A book no Radio Student, Set Builder, Experimenter, or Serviceman can afford to be without.

RADIO PHYSICS COURSE

(SECOND EDITION REVISED & ENLARGED)

By

ALFRED A. GHIRARDI, E. E.

A Complete, Up-to-date, Authoritative Course which Explains, in Simple Language, everything about Sound, Electricity, Radio, Public Address, Phototubes, Television and Sound Motion Pictures . . . for the Beginner Who Wants to Learn all About Them!

RADIO PHYSICS COURSE

An Elementary Text Which Explains the Principles of Electricity and Radio

By

ALFRED A. GHIRARDI, *B.S., E.E.*

Author, "Modern Radio Servicing," "The Radio Troubleshooter's Handbook," "Radio Field Service Data." Contributing Editor, "Radio News" Magazine, "Service" Magazine. Technical Consultant. Member, New York Electrical Society, Radio Club of America, Institute of Radio Engineers, Radio Servicemen of America, Advertising Club of New York.

508 ILLUSTRATIONS

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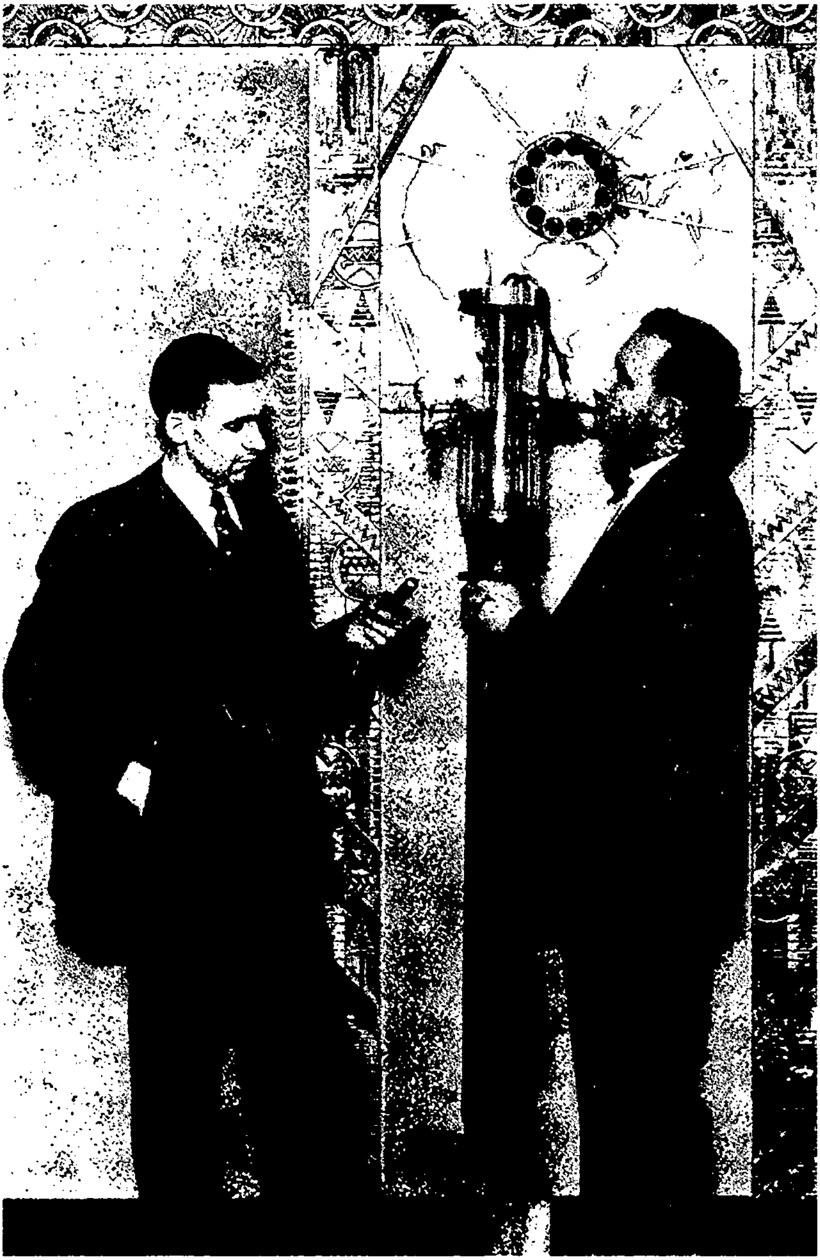


Frontispiece

One of the beneficial results of our increasing knowledge of the behavior of electrons, has been the development of more efficient vacuum tubes for use in radio receivers, and larger tubes capable of handling greater amounts of electrical power for radio transmission purposes. One of the smallest types of vacuum tubes used in radio receiving equipment, is shown at the left. The large water-cooled tube on the right is used for generating the high-frequency carrier current which produces the radiated signals from the broadcasting station. It costs about $1500.

PRINTED IN THE UNITED STATES OF AMERICA

PREFACE

This second revised and enlarged edition, represents the result of an effort to include in a single book, all of the material required for a complete up to date course in radio. It has been written especially for use as a text book for radio courses in technical high schools, trade schools, and by custom radio set builders and the thousands of technical and non-technical persons who desire to gain an insight into the working of radio receivers, sound amplifier equipment, photoelectric cells and devices, television equipment, and sound motion pictures, either for their own knowledge and satisfaction or as a means of earning a livelihood. The book is also adapted for home study by those who cannot attend a school.

The title "Radio Physics" has been applied in the sense that *physics* is mainly an explanation of common things. Radio Physics is then an explanation of the common things in radio. Every attempt has been made to bring this edition up to date with descriptions and illustrations of the modern forms of radio equipment which are now being employed. Those readers who are familiar with the first edition, will quickly see that all obsolete material has been dropped in this edition. Even though this has been done, the addition of a complete electrical course for radio students, and the thorough revision of the radio section and addition of new material which was necessary to keep the book up to date, has resulted in a large increase in the number of pages. Every attempt has been made to further the usefulness of the book as a text on radio for the use of even the most non-technical persons. The topic sections are numbered for easy reference, and larger more readable type has been used throughout this edition. Enough carefully selected review questions for the questioning of entire classes, have been included at the end of each chapter.

In the preparation of the text, the requirements for a thorough practical knowledge of modern radio, have constantly been kept in mind. Involved technical discussions have been omitted wherever possible. An attempt has been made to present the subject matter as clearly, and in as simple language, as possible A complete course in electricity, and some work in sound, has been added, as a result of the suggestions of a large number of radio instructors who have used the first edition in their courses. The author has always felt that a thorough training in the fundamentals of both d-c and a-c electricity should first be obtained, before making any serious attempts to study radio. This is even more necessary now than ever before, because of the refinements in design and almost universal use of electric receivers with associated alternating current power equipment. It is necessary for the student to have a thorough knowledge of the principles of both d-c and a-c phenomena in order to proceed with the study of this equipment with any degree of intelligence. In his own instruction work, the author has always felt a need for a complete electrical course written especially for the requirements of radio students. No satisfactory text for this purpose has heretofore been available. It was felt that this should be written in a manner which was both interesting and in accordance with the modern electron theory.

The author has tried to incorporate in the electrical course in this book, all of the features which he has found helpful in his own instruction work and which meet the above requirements. The modern conception of the electron theory has purposely been introduced early in the book, so that the students may benefit from it to understand and obtain a mental picture of the probable actions taking place in magnetic and electric circuits. This not only makes the subjects more interesting to the student, but removes a great deal of the mystery which is usually connected with the early studies of the force of magnetism and the flow of electricity. The student has been warned not to accept the electron theory as a final explanation of these phenomenas, but rather to look upon it as one which seems to explain better than any other theory yet advanced, the many actions involved. By the time the student has advanced to the study of the vacuum tube, he is on such intimate terms with the electron theory and structure of matter, that very little explanation is required to introduce the conception of the emission of electrons by heating, photoelectric action, etc., and he is able to grasp the operating principles of electronic devices very easily. The order of study of this new electrical course has been laid out in a manner which best leads the student almost unknowingly to the advanced electrical work without sudden jumps or confusion. Any part of the work which the instructor may desire to omit, may be easily left out without seriously breaking up the continuity of the course. The alternating current work has been presented in a way which the author feels is most conductive to proper understanding of the construction and operation of modern radio equipment. This work has been carried sufficiently far to give the student all the knowledge necessary for the study of radio. Electrical measuring instruments of all kinds have been treated in detail on account of their great importance in radio work.

This edition has been revised and enlarged in keeping with the many great advances made in the radio art in the past two years. Many new chapters have been added in order to thoroughly present the theory and description of all the new vacuum tubes and other apparatus which has been developed and to round out the course so it covers the subject completely. The physical principles underlying the construction and operation of the apparatus described have been stressed wherever possible, in order to tie up the theoretical knowledge with its practical application. The chapter on television has also been greatly enlarged with the idea of presenting to the student, the main methods of attack which are being employed by the various workers on the problem of television today. Description and illustrations of actual apparatus now developed are included. These are by no means to be considered the final forms of television equipment, for undoubtedly great changes will be made in them within the next few years.

If some explanations seem unduly long and detailed, it is because the writer has found by practical experience in teaching the subject in classroom and laboratory, that those particular topics require such explanations for proper understanding by the novice. The order of topics and illustrations has been selected with the purpose of leading the pupil into the subject in the most logical and interesting manner. The use of over 500 carefully planned illustrations is in accordance with the author's firm conviction that a good illustration presents more information to the student than several hundred words. Many new, useful tables have been added to the appendix at the rear of the book. The index has been made unusually complete, so that it is an easy matter to look up any subject in the book. Students are advised to develop the habit of making use of it instead of thumbing the many pages to locate some particular bit of information they require.

Grateful acknowledgment is due to the various electrical and radio manufacturers for the kind spirit of cooperation and helpfulness shown in furnishing the illustrations and descriptions of their apparatus for this book. Many helpful ideas have been obtained from time to time from the *Bell Laboratories Record, The Bell System Technical Journal, Aeronautical Engineering, Radio Broadcast, Electronics, Radio Design, Radio Engineering, Radio News, Radio Craft, Q.S.T.* and *The Citizens Radio Call Book* magazines.

The author also wishes to express his appreciation to his many pupils who have been of invaluable assistance in providing questions which were food for thought and explanation; to Mr. M. B. Sleeper, Mr. Robert Hertzberg, Mr. M. Reiner and Mr. F. L. Horman, for their criticisms and valuable help during the preparation of the text; and to Dr. Edgar S. Barney and Mr. W. W. Ker, who have ever been an inspiration in this work. Mr. Edward Buechner, Jr., has supplied invaluable aid in the preparation of the drawings used throughout the book, and Misses M. Schranz and R. Levitan have assisted greatly by their work of proof reading and typing the manuscript. Thanks are also extended to the editors of *Radio Design* for their kind permission to reprint all of the Radio Physics Course articles which appeared in that magazine; and to Mr. L. Cockaday, Editor of *Radio News Magazine*, for the many illustrations and helpful suggestions supplied. To the many friends and radio instructors who have

offered their opinions and criticisms of the first edition, the author feels deeply grateful, for their ideas have proved exceedingly helpful and valuable in the work of revision.

A. A. G.

New York City, September 10, 1931.

PREFACE TO THE SECOND IMPRESSION

The enthusiastic manner in which the first impression of the Second Revised and Enlarged Edition has been received by both students and teachers alike, is extremely gratifying.

In this second impression, an attempt has been made to correct all of the troublesome typographical errors which unavoidably appeared in the first printing. Also, minor changes have been made here and there where a phrase or sentence could be re-worded to clarify the meaning. The vacuum tube characteristic chart on P. 434 and the detailed instructions for aligning the tuned circuits of radio receivers have also been revised in order to present the latest data on these subjects. Some additional material has also been included on the important subject of cathode-ray tubes for television work.

These minor changes are not to be regarded as a revision of the book. No such change has been necessary. Also, these slight changes in no way affect the section or page numbers on which the various topics appear, and should cause absolutely no difficulty in classes where both "first impression" and "second impression" books may be used together.

It is the sincere wish of the author that these corrections will prove helpful to both students and instructors alike.

A. A. G.

March 15, 1932.

PREFACE TO THE THIRD IMPRESSION

In this impression, Art. 313 which deals with the variable-mu screen grid tube (now called "super-control" tube), has been re-written in order to present the latest data on this subject. Also, corrections of additional typographical errors which have been discovered, have been made.

A. A. G.

March 1, 1933.

TABLE OF CONTENTS

Appendixes

RADIO PHYSICS COURSE

CHAPTER 1.

RADIO BROADCASTING SYSTEM

1. Radio broadcasting system: The art of radio broadcasting as we know it today presents a very fascinating subject for study. It has for its main object the transmission of sound programs over long distances and wide areas to the homes of millions of people. The programs usually originate as sound waves (speech and music) created by artists in the studios of the broadcasting stations, although they are sometimes picked up in halls, theatres, restaurants, or other public places and relayed to the broadcasting stations over special telephone wire lines and networks. In addition we have the specialized uses of radio for communication between land, sea and air vessels in commercial work.

It is certain that the popularization of radio television will add to this, the necessity for the transmission of visual scenes, possibly in their natural colors. It is fortunate that our present general methods of broadcasting of sound programs is also satisfactory for transmitting television programs. The major portion of this course is devoted to the sound phase of broadcasting. This lays a foundation for the study of television apparatus which is discussed later.

Considering the purpose of radio broadcasting as outlined above, let us see how and why it is being carried on in the particular way we are all familiar with today. We know that it is possible to transmit sound waves directly. A common example of this is furnished by one person talking to another. The sound vibrations or waves produced by the vocal apparatus of the first person, travel out directly to the hearing or auditory apparatus of the second person and cause the sensation of sound. This is an example of the direct transmission of sound. This method is not suitable for broadcasting purposes for the following reasons: Sound can be transmitted directly only over very limited distances. Even loud whistles and sirens can only be heard over distances of a few miles at the most. A speaker or singer's voice cannot be heard intelligibly over distances greater than a few hundred feet. Our popular musical instruments such as the piano, organ, violin, etc. are similarly limited in their range. Also if several persons or musical instruments were producing sound waves of equal loudness simultaneously we would have no way of listening to one of them to the exclusion of the others. Nature has not equipped us with any means of selecting or "tuning" to the particular sounds we desire to hear. Our ears respond to all sound waves lying within certain ranges of frequency or pitch. Imagine the distressing result of hearing the programs from all of the stations in your vicinity at one time!

It is evident that some method other than the direct transmission of sound waves must be employed for our broadcasting system. The sound programs originating in the many stations all over the world are to be broadcast simultaneously over long distances and wide areas to the millions of listeners; and must be received in such form that the listeners can readily tune to any single station or program desired. These requirements are satisfactorily met by using electricity, and electrical or radio waves as intermediate agents in our radio broadcasting system. It has been found that alternating electric currents of high frequency (carrier current) can be made to produce electromagnetic and electrostatic waves of similar frequency (radio waves) when made to flow in suitable circuits in the transmitting station. These radio waves have the desirable property of radiating or spreading out into space in all directions over great distances without serious decrease in strength. They are propagated at the rate of approximately 186,000 miles per second. Also, it is possible, by erecting a suitable metallic electrical conductor (antenna wire) at any place through which these waves are traveling, to induce in this conductor electric voltages or potentials which can be strengthened or amplified and then converted back into sound waves similar to those originating in the broadcasting studio. By arranging each broadcasting station to operate with a carrier current of different frequency it is possible to operate many stations at one time without interference. By the use of suitable equipment at the receiving station, it is possible to select the signal of any particular station it is desired to hear, from those of all of the other stations broadcasting at the time.

A simple outline picture of this system as it is employed by our broadcasting stations today is shown in Fig. 1. Starting at the left, the person speaking sets up sound waves which are made to act on the microphone M. This changes the varying sound vibrations into corresponding electrical current impulses. These are led into the transmitting apparatus B (which will be studied in detail later) where they are made to control the strength of flow of a more powerful steady high frequency current (carrier current) so that it is no longer steady but varies in strength in accordance with the original sound waves. This varying high frequency current is made to flow into the transmitting aerial A where it produces high frequency radio waves of varying strength which immediately travel outward in all directions to great distances at the rate of 186,000 miles per second. In any receiving antenna C erected in the path of these waves, weak electric potentials or voltages are induced. These are led to the home receiving set R where they are selected, and amplified until they are of sufficient strength to actuate the loud speaker L so as to produce sound waves which are loud enough to be heard by the listener. These sound waves are very nearly an exact duplicate of the original sound waves. An important advantage of this method of transmitting is that it makes it possible to have a number of stations broadcasting at one time and still be able to select the program from any one station desired, without interference from any of the others. It is this feature which makes practical our modern broadcasting system, wherein a large number of high powered stations are operating simultaneously in the same locality, while the listeners are able, with proper receiving equipment, to select any one of them at will by tuning their receivers.

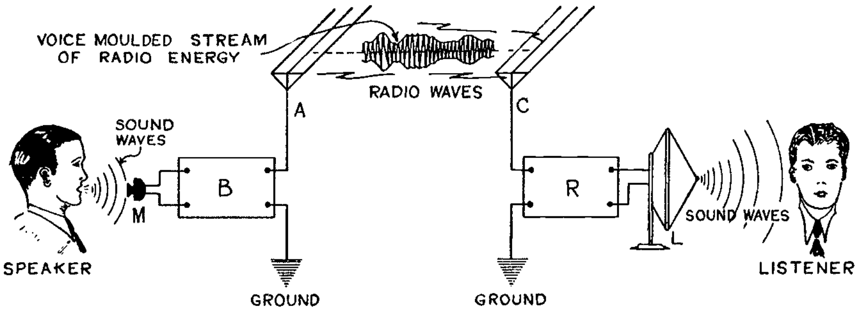


Fig. 1.—Radio Broadcasting System with Transmitter at Left and Receiver at Right.

This outline of the broadcasting system should be studied very carefully, since a thorough understanding of the main function performed by each unit will make the study of the subject more simple and exceedingly interesting. It is evident that the entire structure of radio broadcast is intimately tied up with sound waves, magnetism, electric currents, and electromagnetic and electrostatic waves. The latter are commonly referred to as "radio waves" for simplicity. It is essential therefore that we know something about the characteristics of these things insofar as they affect speech, music, and broadcasting. As a large portion of modern radio broadcasting deals with music, it is essential that the student understand some of the fundamental things about the frequency ranges, types of sound waves, etc., produced by the various common musical instruments since both the radio transmitting and receiving equipment must deal with corresponding sound waves and electrical currents of these frequencies. The characteristics of sound waves, speech and musical instruments will be studied first.

(Review Questions on Next Page)

REVIEW QUESTIONS

1. What is the main purpose of radio broadcasting?
2. What is the purpose of television broadcasting?
3. What is meant by the direct transmission of sound? Give an example of this.
4. State 3 limitations to the broadcasting of speech and musical programs by the direct transmission method.
5. Why are radio waves used in the modern broadcasting system?
6. Draw a simple diagram of the complete system including both the transmitting and receiving stations.
7. Explain the purpose of the microphone, transmitting equipment and aerial in the transmitting station.
8. Explain the purpose of the antenna, receiver and loud speaker in the receiving station.

CHAPTER 2.

SOUND, SPEECH AND MUSIC AS RELATED TO BROADCASTING

SOUND WAVES — SOUND AND HEARING — NOISE, SPEECH AND MUSICAL SOUNDS — PITCH — TIMBRE OR QUALITY — LOUDNESS — SOUND SENSATION — FREQUENCY RANGE REQUIRED — REVIEW QUESTIONS.

2. Sound waves: Sound waves are produced by the mechanical vibration of a material object in an elastic medium. Air is elastic. It can be compressed, and will expand when the pressure is released. Air can be set in motion by a body vibrating in it, and its rate of vibration or frequency will be the same as the rate or vibration of the body which set it in motion. For example, if we ring an ordinary electric door-bell so as to set it vibrating, it will produce a ringing sound. We can prove that the sound is caused by the actual vibration of the bell metal and air around it. If the bell is touched with a finger so as to damp the vibrations, the ringing ceases. If the bell is enclosed in a vacuum, no sound is produced, even though it is vibrated as before, simply because there is no air around it to be set in vibration. The vibrations of a radio loudspeaker can be felt by placing the hand on its diaphragm or horn while playing.

Let us study the motion of the diaphragm of an ordinary cone-type loud speaker as used in radio sets, and see how it produces sound waves in the air. At A, in Fig. 2, the diaphragm is at rest. At B, the diaphragm has moved to the end of its first vibration to the left. The small dots represent a single series of molecules of air moving forward. Air molecule, No. 1, adjacent to its front is pushed onto molecule No. 2. Molecule No. 2 pushes into No. 3. No. 3 pushes into No. 4, etc. These molecules of air are therefore compressed together. Those nearest to the front of the diaphragm are compressed together most. After each molecule has bumped into its neighbor and given up its energy of movement to it, it stops. The wave of compression thus formed, travels along at the velocity of sound. Out some distance in the air, the molecules are not so compressed as yet, and still farther out they have not yet felt the movement, and are their natural distance apart. But they will feel it when this travelling wave of *compression* gets to them at F. During this time, an empty space is left at the back of the diaphragm. The adjacent molecules will move forward into this since air is elastic, and will fill up all the available space. Immediately next to the diaphragm there are few molecules and they are far apart. (Nos. 5, 6, 7, etc.). This area where the molecules are far apart, is called a *rarefaction*. As the molecules rush to fill the spaces successively, the wave of rarefaction travels outward as shown, at the velocity of sound, (about 1130 feet per second in air at 20° Centigrade). (As will be discussed later, in the chapter on loud speakers, a baffle must be put around the edge of the cone so that the compressed molecules at the front will not travel right around the rim of the cone and neutralize the rarefaction wave behind the cone—thus neutralizing the sound wave—when producing sound waves of low frequency.)

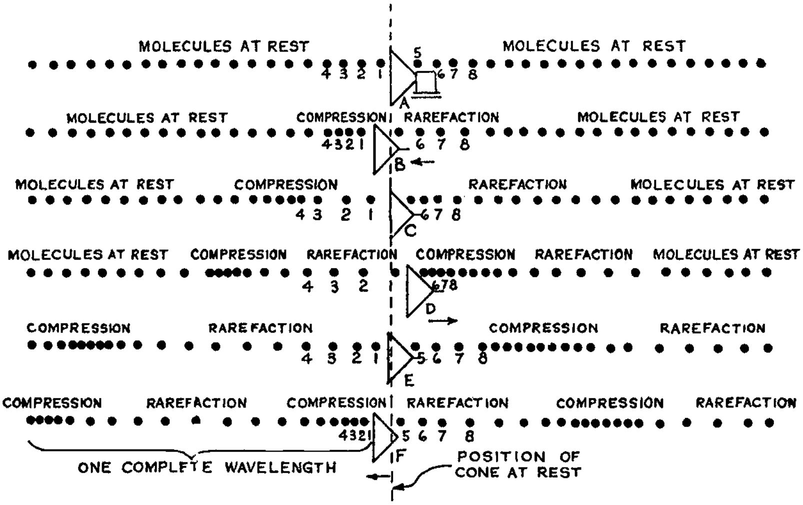


Fig. 2.—Sound Waves Produced by Vibrating Cone of Loud Speaker.

When the diaphragm reaches the end of its first forward push, it moves back to approximately its original position, C. Immediately there is a rushing back of the molecules on the left. They have been tightly pressed together there, but when the diaphragm begins to move back it leaves an open space in its wake into which the compressed molecules rush. At the right, a wave of compression is being produced at the same instant. The diaphragm continues to the end of its swing at D. A full rarefaction is at the left and a compression wave has already started to move along at the right. The movement back to its original position and next forward swing to the left are shown at E and F. This cycle of events repeats itself as the diaphragm continues to vibrate. Sound waves are set up in air by vibrating bodies in this way.

A complete single sound wave includes an area of compression; the adjacent area in which the molecules are their natural distance apart; the adjacent area which the molecules are widely separated (rarefaction); and the adjacent area in which the molecules are their natural distance apart. This is illustrated at F. The exact length of this wave in feet or other unit of length is called the *wavelength* of the sound wave. We may measure the length of a wave from any point to the corresponding point farther on but it is customary to measure it from compression to compression for convenience.

As the diaphragm vibrates, the complete sound waves travel out in all directions from molecule to molecule in the form of expanding spheres of increased pressures and decreased pressures, as shown in

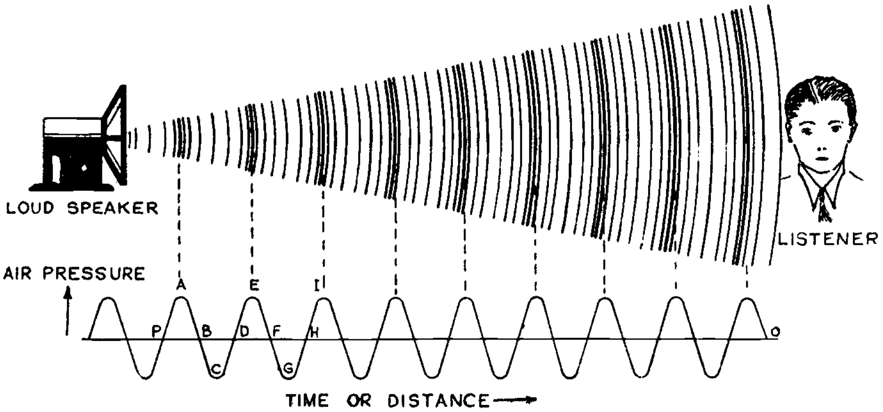


Fig. 3—Sound Wave Propagation and Pressures.

Fig. 3. These moving spheres are commonly called *sound waves.* The number of complete waves created in each second is known as the *frequency* or *pitch* of the sound. This is usually referred to as the number of waves or *cycles* per second. It is important to note here, that the individual molecules themselves move only over very short distances, that is, each molecule does not move out the entire distance to the listener. The action may be compared to that occurring if a number of men stand with feet absolutely fixed in a long line. Now the end man is given a push. He sways forward and pushes against the next man, who in turn pushes against the next, etc. The push, or pressure is carried down along the whole line of men without the lower part of the body of any one of them moving from its original position.

The vibrations of the sounding bodies are usually so rapid, that the human eye cannot see the actual motion. The eye is able to see as separate pictures or impressions, movements up to 10 per second. Movements faster than this blend into a continuous scene. (The motion picture depends upon this principle.) This fact hampers somewhat the visualization of the actions taking place, since we do not see either the movements of the sounding body or the sound waves. Movements of sounding bodies can be studied however, by means of the stroboscope.

Any elastic material such as steel, brass, wood, etc. will transmit sound waves. The speed or velocity at which the sound waves travel depends upon the density of the substance in which they are moving, and the temperature. Accurate experimental determinations show that the velocity of sound in dry air is 1090 feet per second at 0° Centigrade. The velocity increases two feet for each degree increase in temperature. Therefore at 20° Centigrade (normal temperature) the velocity is 1130 feet per second. This value will be used throughout this book in sound calculations. The more elastic the medium, the greater is the velocity of sound in it. In lead at 0° Centigrade, it is 4,659 feet per second; in glass 1,783 feet, and in steel 16,322 feet. In radio broadcasting, we are concerned chiefly with sound waves in air. Contrasting the velocity of sound waves in air, 1130 feet (or about one quarter mile per second) with the velocity of radio waves in air, 186,000 (approximately) miles per second, we can see that radio waves travel about 750,000 times as fast as sound waves do.

If we could devise apparatus for measuring the very small variations in the air pressures caused by a very simple sound wave at any particular point, we would find that these variations could be shown in picture form by the wavy line or curve of Fig. 3, where vertical distances represent pressure and horizontal distances represent time. The axis or horizontal line P—O represents the normal atmospheric pressure. When the sound wave comes along, the pressure gradually increases to a maximum from P to A, then decreases from A to B, further C, then increases again from C to D at which point the pressure is again the same as at the beginning. The next wave would continue similarly along D E F G H. Point A, which is the crest of a wave, represents a point of condensation or compression, at this point the air is condensed or compressed. Point C, which is at the hollow of a wave, is a point of rarefaction since at this point the pressure is lessened or rarefied. It must be remembered that the wavy line of Fig. 3 represents the air pressure, and not the movements of the individual molecules of air.

3. Sound and hearing: The study of radio and sound should include some consideration of the structure, operation, and characteristics of the human ear. There are many ways of producing, recording, transmitting and reproducing sound waves, but we have only one means of making them affect us, that is, through the human ear and associated nerve systems. As the ear is the one common element in any sound system, and since much of the design of our radio and audio systems and equipment is influenced greatly by the characteristics of the ear, we should learn some of the elementary things about its action. When we become familiar with its remarkable construction and actions we cannot help but cease to regard it merely as a decorative flap presented to us by nature. We see it as a highly sensitive mechanism rivalling any man-made piece of delicate machinery for ingenuity of construction.

The ear may be roughly divided into three parts, the outer ear, the middle ear and the inner ear. The outer ear consists of the flap R, and a short tube G, leading to the middle ear, as shown in Fig. 4. The tube is sealed by a thin stretched membrane or diaphragm T, commonly called the ear drum.

When sound waves strike the ear drum of the listener, the terminals of the auditory nerves are stimulated and the sensation of sound is produced in the brain.

In our study, "sound" is held distinct from the term "sound waves". *Sound* is the sensation produced in the brain by the *sound waves.* The sound or *air pressure* waves entering the ear passage G, vibrate the ear drum T in Fig. 4. The number of these back and forth vibrations of the drum per second is the same as the number of pulses of the wave that arrive at the ear per second. The vibrations of the drum are transmitted directly to the first of a set of three oddly shaped bones in the middle ear, the last one of which touches a second diaphragm (oval window) at the entrance to the inner ear. These bones are called the *hammer*, the *anvil* and the *stirrup.* They form a mechanical lever system.

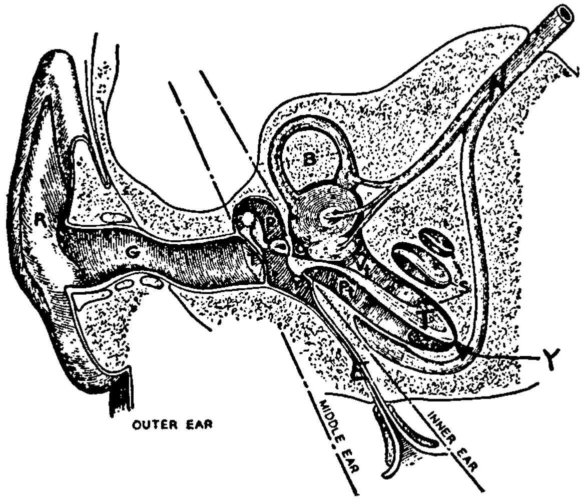


Fig. 4.—Internal Structure of the Human Ear.

The stirrup is attached to the end of the oval window O, which separates the middle from the inner ear. There is another flexible membrane "r" (round window separating the middle from the inner ear).

Due to the fact that the area of the stirrup resting against the oval window of the inner ear is about one-twentieth of that of the ear drum and also due to the lever action of the three bones, the pressure exerted by the oval window of the middle ear upon the fluid of the inner ear is 30 to 60 times that exerted by the air upon the ear drum.

The inner ear is a spiral, snail shaped cavity in the skull bone, and is filled with a liquid. This liquid-filled spiral cavity or *cochlea* is separated into two parts V_t and P_t, by the soft, flexible cone-shaped spiral *basilar membrane* T which extends across its entire length, but leaves a narrow communicating passage Y (*helicotrema*) at the right end for passage of the liquid from the upper to the lower half of the inner ear. This cochlea is encased by the bony structure of the head.

Into the liquid from the walls of the chambers, project thousands of tiny, elastic hairs of varying length and size. The auditory nerve N is divided at its extremity into filaments, one of which is attached to each hair.

The middle ear is entirely closed except for a small duct E leading to the throat. By the process of swallowing we allow air to escape from, or allow it to enter into, the middle ear through this duct in order that the air pressure on both sides of the ear drum shall be the same. When entering a deep tunnel in a subway train the pressure on the outside of the eardrum increases and it is temporarily pushed inward. This causes the common unpleasant sensation in the ear. By swallowing hard, or holding the nose and blowing, air is forced up to the middle ear through tube E to equalize the pressure and allow the ear drum to assume its normal position. When rising to the surface the outside pressure is again decreased and swallowing hard allows some air to escape from the middle ear through tube E. This reverse action also occurs when rising to a high altitude during an airplane flight.

There are several theories as to the exact function of the inner ear. The exact way in which the auditory nerves T act on the brain to produce the sensation of sound is still a mystery. It is of course extremely difficult to obtain any direct experimental observations on these actions.

When sound waves cause the ear drum T to vibrate, this mechanical vibration is transferred across the middle ear by the system of bone linkages P and is impressed on the flexible diaphragm O, which in turn impresses the vibration on the fluid in the cochlea. This fluid being relatively incompressible and being encased in a solid bone container in the head, needs some relief for pressure or there would be no transfer of vibration to the inner ear. The diaphragm r, (round window) opening back into the middle ear provides this. When the diaphragm O is pressed inward, the liquid bends the basilar membrane T downward and this in turn forces the diaphragm "r" outward. The next instant, diaphragm O moves outward and "r" moves back in, etc.

Different tones and sound frequencies affect different parts of the basilar membrane and therefore affect different hair cells and nerve fibres. Low frequency vibrations (low tone) cause a transfer of vibration across the basilar membrane at points near the thick end at the right. High frequency tones affect the thinner end near the diaphragm O. Frequencies between these affect it at points between the extremities. A 1,000 cycle sound wave (1,000 complete to-and-fro vibrations per second) is sensed by the nerve terminals very near the center of the membrane. The motion of the basilar membrane causes the many tiny hair cells to stimulate the nerve endings at their bases. Each tiny hair having a different length, thickness, and mass will respond only to that particular ripple or movement with which it is in sympathy. Thus it is supposed that each tiny hair cell responds only to a certain definite frequency, just as each individual string of a piano or harp will vibrate at its own particular frequency depending on its length, thickness and mass.

The nerve filaments transmit the impression to the brain, where in some mysterious manner the disturbances are interpreted as sound of definite pitch, quality and loudness. The pattern carried to the brain by the nerves of hearing depends upon the particular combination of vibrations or frequencies disturbing the basilar membrane at each instant.

The entire mechanism of hearing is extremely delicate, composed of many parts and is quite complex. There is still considerable controversy regarding the exact function of some of them. Now that we have some idea of the construction and operation of the human ear it is obvious that slight differences in shape and structure of any of the parts can cause different people to hear the same sounds differently. These differences may be inherited at birth or may be caused by some accident or disease. The mechanism of hearing in some people is as nearly perfect as nature intended it should be. As a result of musical training and practice, minute changes of pressure or frequency are distinguished by some ears which would not be noticed by ears and hearing not so delicately adjusted and trained. It is evident that the hearing faculties of different persons may vary greatly. This explains why some radio receivers sound perfectly satisfactory to certain persons and are absolutely unsuited to the delicate and fine appreciation of sound and music of other persons with highly trained hearing faculties. Also the range of sound frequencies which different persons hear and the strength with which certain frequencies are heard vary greatly due to slight differences in ear construction.

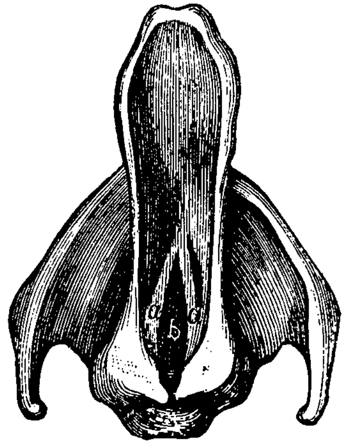


Fig. 5.—Human Vocal Organs. The vibration of the vocal cords a-a varies the size of the opening b thru which air from the lungs rushes.

4. Noise, speech and musical sounds: In radio broadcasting we are concerned mostly with speech and music although at times noises are transmitted as parts of plays and dramas. The dropping of a book on the floor, the crash of a piece of glass, the rattle of a train of freight cars, all produce sound disturbances that have no regularity of vibration and to which we can assign no definite pitch. Such sounds are disagreeable to the ear because of lack of steadiness, regularity or rhythm and are classed as *noises*.

Speech or vocal sounds are produced by the human organs of speech. The main vocal sound wave producing organ is shown in Fig. 5. The lungs supply the streams of air by a bellow-like action. The air presses in and out of the windpipe, vocal passages, the elastic vocal cords "aa" in the larynx, the tongue, the lips and the resonant cavities of the nose and throat. The rapid movement of the vocal cords "aa" stretched across the top of the windpipe changes the size of the slit-like opening "b" through which the air from the lungs passes. This impresses on the air stream, variations which are heard as speech sounds. The pronunciation of the English language is composed of about 39 different sounds located in different parts of the frequency range. The "voiced sounds" are produced as described above by the vocal cords in the larynx. They are located mostly in the lower register and possess most of the volume and energy of speech. The "unvoiced sounds" are produced without using the vocal cords at all. They are caused by the flow of air through small openings, or over sharp edges of the teeth, lips and tongue. They have a hissing rushing sound of the breath, and consist of the sounds like p, f, s, k, sh, ch, th. Most of these sounds are high pitched, and they are much weaker than the voiced sounds. The student is urged to pronounce these sounds in front of a mirror and notice the movements of his tongue, teeth and lips when doing so. These higher unvoiced sounds are absolutely necessary to the clear and distinct rendition of speech. A third class of speech sounds called the "voiced consonents" are produced by a combination of the two processes just outlined.

The length and tension of the vocal cords "aa" can be altered by muscular action with great rapidity, hence the extreme flexibility and great range of tone of the human voice. The vocal cords in men are thicker than in women and children, so they vibrate more slowly and produce the lower tones characteristic of men's voices. The sound waves produced by the vocal cords are greatly modified by varying the shape of the resonant cavity of the mouth. This may be easily proven by uttering all of the five vowel sounds a, e, i, o, u, one after another. The altering of the shape of the mouth produces the change of the voice sound. This is called *articulation.* Changes in the flexibility or size of the openings in any of the air passages, etc. may change the tone of the voice. Thus when a person catches cold, the nose passages are blocked and the throat may be inflamed or swollen. The result of this interference to the free normal passage of the air pulses makes itself evident as "hoarseness" of the voice.

Musical sounds occur in the form of smooth, uniform vibrations of steady duration, until the dying of the sound. A musical sound is produced from a source of regular vibration. Thus when a horsehair bow is drawn across the strings of a violin, they are set into vibration. This vibration is regular and smooth and results in a *musical sound.* Music is pleasing, because of its agreeable combination of sounds, which have been worked out more or less systematically.

Every sound has three identifying properties or characteristics, which distinguish or identify it from all other sounds. These are pitch or frequency; quality or timbre; and loudness or intensity.

5. **Pitch:** The musician's term for frequency of vibration is *pitch.* Pitch is defined as the number of air waves per second produced by the vibrating source, or the number of air waves received by the ear per second. Sounds of low pitch like those of the bass viol, bass tuba, etc., are low in frequency, and therefore vibrate the ear drum slowly. Sounds of high pitch, like those of the flute, piccolo, etc. are high in frequency, and vibrate the ear drum rapidly. In stringed instruments the low notes are produced by the long, thick or heavy strings. For instance, on the piano, the strings which produce the low notes are wound with wire and weighted down so they cannot vibrate so fast.

In the wind instruments we find the low notes produced by the vibration of air in air columns of large volume—either long or of large diameter. The long air columns of the pipe organ Fig. 7 and bass tuba Fig. 9, are illustrative of this. The relative approximate lengths of some common wind instruments are, piccolo (Fig. 10) 12 inches, flute (Fig. 10) 26 inches, trumpet (Fig. 11) 55 inches, trombone (Fig. 11) 107 inches, Sousaphone bass tuba (Fig. 9) 216 inches. The frequency of the lowest notes these instruments can produce can be found from the chart of Fig. 8.

The notes of high pitch are produced by the light, thin, or short strings in string instruments and short or small diameter air columns in wind instruments. In instruments like the violin (Fig. 10), mandolin, guitar, banjo (Fig. 11), and ukelele, a wide range of notes is produced with a few strings by "stopping" or shortening the vibrating length of the string with the finger. The triangular shape of the harp and the grand piano illustrate the application of the law of length by using longer and heavier strings for the lower pitches.

By impressing sounds of various measured frequencies on human ears it has been found experimentally that the normal ear is able to detect sounds of frequency about as low as 16 cycles per second, and about as high as 20,000 cycles per second, but not with the same degree of sensitivity.

Vibrations slower than 16 per second do not sound as one tone, they separate into 16 or less separate noises. Above 20,000 vibrations per second, the vibrations are so rapid, that the ear drum membrane and associated parts cannot follow them. Above this point, we cease to hear. The ear is most sensitive to frequencies between 500 and 4000. Below 16 cycles per second, the sense of feeling occurs before the sense of hearing. The actual frequency range the human ear will respond to varies among individuals. It is narrowed by weakening of the sound and also by advancing age of the person. Some persons cannot hear the chirp of crickets or the high notes sung by some birds and insects. The range of sound frequencies employed in ordinary speech lies between about 200 and 3000 cycles per second.

The effect of the frequency or rapidity of occurrence of the individual sound waves can be demonstrated very convincingly by the use of a simple siren (Fig. 6). This consists of a small circular flat disc mounted on a central shaft so it can be rotated rapidly either by hand, by an electric motor or even in a lathe. A circle of evenly spaced small holes are drilled in the disc. A rubber hose or small metal pipe is arranged directly over the perforations or holes so that a flow of air under pressure is forced through the holes when the disc revolves. This flow of air is naturally cut off or interrupted as each solid portion of the disc passes the air pipe, and as a hole passes the air pipe a puff of air shoots through the hole. Therefore, a vibration of air is produced by each hole. The frequency of the air vibrations depends upon the number of holes that pass the air jet during each second. Multiplying the number of holes in a circle on the disc by the number of revolutions that it makes per second gives the vibration frequency per second. The speed can be measured with a revolution counter or tachometer. By varying the speed of the disc, or by drilling several circles of holes, each circle having a different number of holes, various sound frequencies can be produced. If the number of holes on each circle is ½ the number on the next, each circle will produce a note one octave higher or lower than that on the next circle if the disc is rotated at constant speed. By choosing suitable high and low speeds and numbers of holes it is also possible to determine the upper and lower limits of audible frequencies with this apparatus. This experiment is a very interesting one, especially when made with a number of listeners in a group. Also by perforating some circles with the same total number of holes but with the holes slightly uneven (two closer together, making the next two further apart, as at B) the frequency will be the same, but the succession of air puffs will not occur in the same order. The sound produced will appear different as judged by the ear. This illustrates the effect of "timbre or quality" of a sound (see Fig. 14).

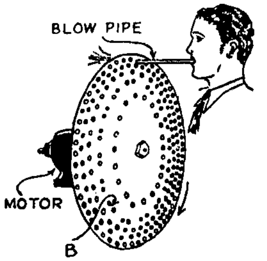
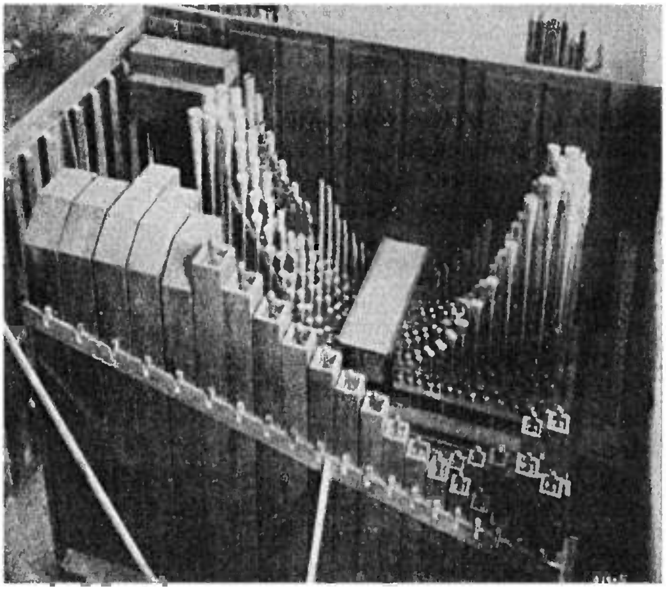


Fig. 6.—Siren Disc. The blowpipe directs air in puffs thru the rotating holes. Sound waves result.

The various musical instruments produce sound waves in different ways. Thus the violin, cello, piano, banjo, etc. produce sound by means of strings which are set into vibration. On the piano, for instance, low notes are produced by the vibration of long, heavy, loose strings, while shrill or high notes are produced by short stretched small strings.

The wind instruments are classified as of two kinds, wood and brass. The commonest of the wood-wind instruments are the flute, oboe, piccolo, clarinet, bassoon and English horn. The brass-wind types are the cornet, trumpet, trombone, French horn, bass tuba, saxophone, alto horn. In all of these, the air is vibrated in a hollow tube either by reeds by blowing against the sharp edge of an opening, or by the



Courtesy Skinner Organ Co.

Fig. 7.—Pipe Organ During Assembly. A mechanical blower keeps the wind chest full of air. When a key is pressed, a valve admits air to the proper pipe. Many sets of pipes of different lengths are employed to give the different pitches and qualities, each set being controlled by a "stop." At the lower left is a bank of closed wooden pipes for the low notes. At the right are several banks of open pipes. The space inside is nearly filled with the shorter, more slender, high-note pipes.

lips of the player. In wind instruments different pitches are obtained by changing the length of the air column by moving a slide as in the trombone Fig. 11, or by opening and closing holes as in the flute, saxophone, trumpet, etc. (Figs. 10 and 11).

The percussion instruments, are those that are beaten, shaken, rattled or jingled. Among these are the kettle drums. bass drum, (Fig. 12) cymbals, snare drums, tambourine, xylophone, bells, and the piano. The pipe organ (Fig. 7) is a wind instrument, and has become a collection of all possible wind instruments controlled by keyboards and stops with possibilities of string tone and percussions as well. The human voice is really of the vibrating air column type.

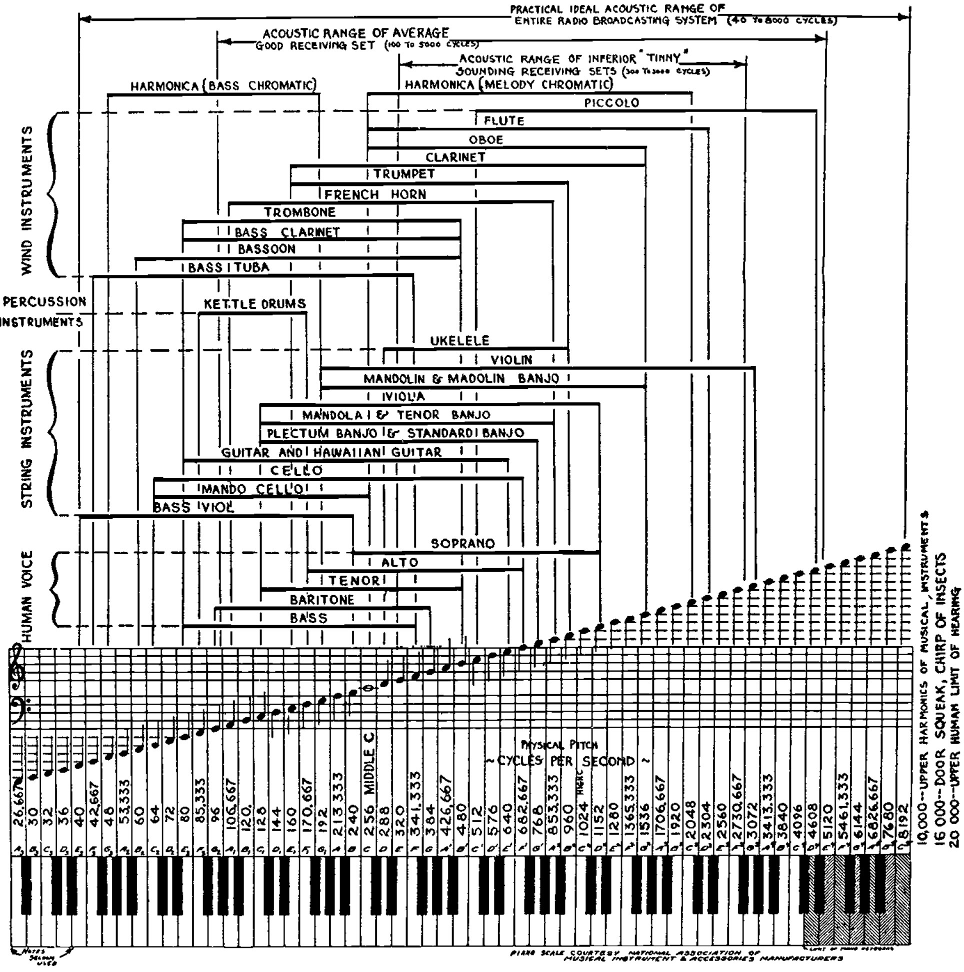


Fig. 8—Chart showing the fundamental frequencies of the various keys or notes on a piano keyboard, as well as the fundamental frequency ranges of the various common musical instruments and the human voice. The comparative acoustic range of the broadcasting station equipment, and that of "average" and "inferior" radio receiving sets are also shown.

Each musical instrument has a definite range of sound frequencies which it can produce. The chart of Fig. 8 shows the fundamental frequencies of the various notes on a piano keyboard. The frequency ranges of the various common musical instruments are indicated above this in direct line with the piano key frequencies. The range of the pipe organ is about the same as that of the piano and is not indicated here. Middle C lies near the middle of the piano keyboard and represents a frequency of 256 cycles per second. The lowest, C_3 is 32 cycles. The C_2 above this is an octave of it and has a frequency of 32×2, or 64 cycles. The *octave* of a frequency is a frequency twice as high. For instance, low C_3 is 32 cycles per second, the second octave of this is $32\times2=64$, the third octave is $64\times2=128$, the fourth octave (middle C) $128\times2=256$, the fifth octave C^1 is $256\times2=512$, and so on.

The horizontal spacing of the chart of Fig. 8 may be rather puzzling to the reader. It is evident that in going from the low notes to the high notes the actual increases in frequency between the adjacent piano keys is not the same. The frequencies of the tones are arranged according to the octaves in such a manner that the various octaves occupy equal horizontal spaces on the chart, irrespective of the actual number of cycles covered by the octave. One octave means doubling of the frequency. Thus we have one octave of tone if we jump from 100 to 200 cycles. We also have one octave if we jump from 1000 to 2000 cycles. The latter jump covers 1000 cycles while the former covers only 100 cycles. Yet both ranges cover just one octave.

In music we are interested in all of the octaves between certain limits. Therefore, in radio reproduction of music we are also interested in the same thing. As will be seen later it is common practice to plot amplification curves of audio amplifiers, etc. in this same way with the frequency scale plotted according to octaves. Mathematically this is known as a logarithmic scale because it is really plotted according to the exponents of the numbers instead of the actual numbers themselves.

Close examination of the chart of Fig. 8 reveals many interesting things about our common musical instruments. The piano, organ and harp produce the greatest range of fundamental frequencies, ranging from about 16 to about 4096 cycles per second on the physical scale of pitches. All of the other instruments have more limited ranges within these values.

Some of the instruments like the bassoon and the bass viol and bass tuba of Fig. 9, produce sounds lying entirely in the low frequency range. Others like the violin, flute and piccolo of Fig. 10 cover the high frequency range. The tenor banjo, trombone, saxophone and trumpet (Fig. 11) produce sounds of the middle range of frequencies. The pipe organ, harp and piano cover the entire range of low, middle and high frequencies. The bass drum, snare drum, tom-tom, traps and cymbals have no definite musical pitch and are used only to bring out the rhythm and add novelty effects. The bass drum and traps are shown in Fig. 12.

The great body of a symphony orchestra is composed of an assembly of practically all of these instruments. Therefore if we are to be able to satisfactorily broadcast and reproduce the music from such an orchestra our electrical apparatus in both the transmitting and receiving stations must be capable of dealing with the complete range of frequencies of all of the instruments.

6. Timbre or quality: Musical sounds are sustained at definite pitches for comparatively long times and the change in pitch takes

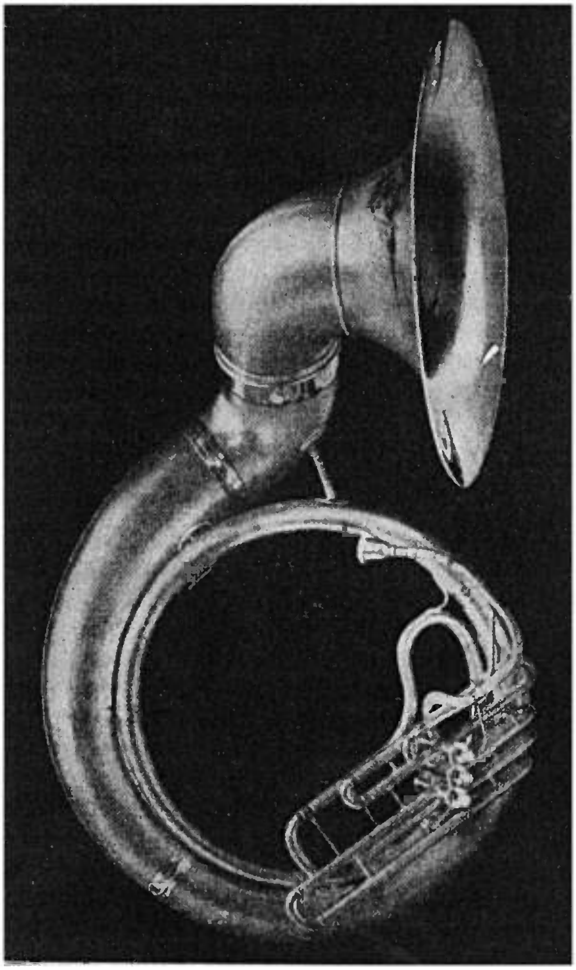
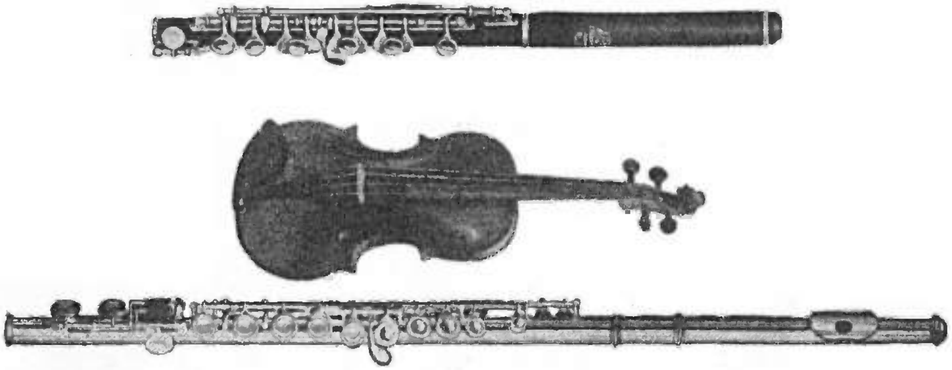


Fig. 9.—Bass Tuba and Bass Viol. These two instruments produce the deep, rich sounds in the low frequency range. The Bass Tuba at the left goes down to 43 cycles and the Bass Viol goes to 40 cycles.

Courtesy Carl Fischer Musical Inst. Co.

place in definite steps called the musical interval—thirds, fifths, octaves, etc. The musical sounds are all agreeable to the ear. However, we can very easily distinguish the sound of one musical instrument from that of another. For instance, middle "C", which is defined as producing 256 air waves per second, may be struck on the piano, blown on a trumpet or played on a violin, yet the sound in each case will be characteristically different, and easily recognized, despite the fact that the pitch or frequency of the fundamental sound waves thus produced is exactly the same in all three cases. We have no difficulty in recognizing the particular instrument which produced it. The voices of different persons can also easily be distinguished and recognized. The characteristic which enables one to recognize the tones of the different



Courtesy Carl Fischer Musical Inst. Co.

Fig. 10.—Top—Piccolo; Middle—Violin; Bottom—Flute. These instruments produce the fundamental sounds in the high frequency range. The highest fundamental sound frequency of the Flute is about 2300 cycles; Violin, 3000; and Piccolo about 4,600 cycles.

instruments, or to assign a sound to its source, is called the *quality* or *timbre.*

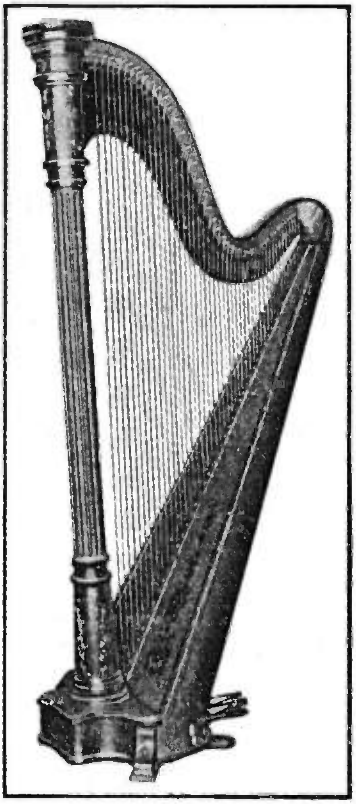
The physical explanation of quality or timbre, is that most sounding bodies vibrate not only as a whole, but also in various parts as well. When the string of a musical instrument is plucked so as to make it vibrate as a whole (A of Fig. 13) the production of the musical note is easily understood. When a bow is drawn across it or the string is plucked at the proper point, it may not only vibrate as a whole, but in parts as well. This may easily be seen by plucking the strings on a piano. Thus in B of Fig. 13 a string is vibrating as a whole between points A and C and is also vibrating in halves between AB and BC. In C of Fig. 13 a string is vibrating as a whole and in five segments. The same action occurs in vibrating air columns. When a string or an air column vibrates as a whole, it produces its lowest tone or *fundamental* (A of Fig. 13). When it vibrates in two segments (B of Fig. 13) it produces its first *overtone,* or *second* harmonic. This harmonic is double the frequency of the fundamental. A *harmonic* is an integral multiple of the fundamental frequency. Thus the second harmonic of middle C (256) is, $256 \times 2 = 512$ cycles, etc. When the string vibrates in fifths, (C of Fig. 13) the fourth overtone or fifth harmonic results, etc. A string or air column of a musical instrument can be vibrating as a whole and at the same time be vibrating in segments. It will then give out its fundamental frequency and a number of multiple higher, (harmonic), frequencies at the same time. The harmonics are usually weaker than the fundamental, but in some musical instruments they may be stronger.

The fundamental and harmonic sound waves do not exist separately in the air, but combine to form a resultant wave which is different from any of its components. This is the wave which affects the ears of the listener. The combination is responsible for the "quality", "timbre", or "tone color" of the tone and gives each musical instrument its individual characteristic sound. The general "wave-form" of a musical note of a given frequency maintains a similarity easily recognized as being of a certain fundamental frequency regardless of the instrument which produced it. Fig. 14 shows the actual wave-forms of the sound waves produced by sounding the note middle C on the piano, cello organ pipe, and trombone organ pipe. These curves were

Courtesy Carl Fischer Musical Inst. Co.

Fig. 11.—Tenor Banjo, Saxophone, Trombone, Trumpet. These instruments produce the middle range of frequencies.

determined by Dr. Harvey Fletcher of the Bell Telephone Laboratories. At the top is the wave-form of a "pure" fundamental or sine-wave sound of the same frequency. Note the difference in the little zigzag lines of the sound wave curve of note C originating on the piano and the same note originating on the cello organ pipe and trombone organ pipe. These little zigzag lines or ripples, are caused by, and represent the number, position and loudness of the harmonics in the sound waves



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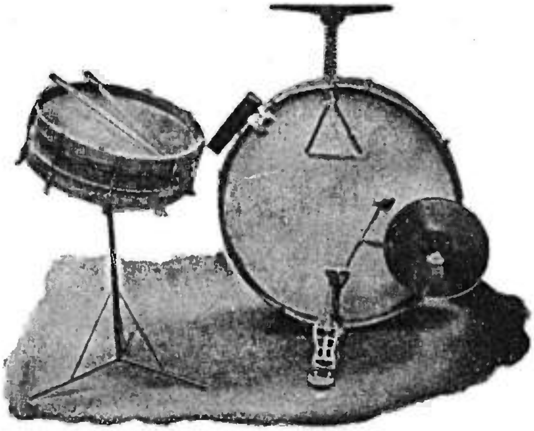


Courtesy Carl Fischer Musical Inst. Co.

Fig. 12. Left: Harp with long, thick strings for low frequency notes, and short strings for high notes.

Right: Base Drum and Traps. These have no definite pitch and are used only to bring out the rythm and add novelty effects.

produced by these particular instruments. The height or amplitude of these lines indicates the loudness of each harmonic note. Notice that the general form or shape of the wave is similar in all three cases. A low-pitched piano tone has a large number of harmonics; the third harmonic of the cello organ pipe has about five times the amplitude of the fundamental; the trombone organ pipe is also very rich in harmonics.

Pure tones (tones without harmonics) are very rare and lack individuality. They seem flat when heard by the ear and have little musical value. Higher harmonics than the fourth are seldom encountered in ordinary practice. Harmonics higher than the third are not important. It is the abundance of strong harmonics that produces the "quality", "tone color" or richness of musical sounds, but the pitch depends entirely on the fundamental frequency. Those musical instruments which have a deep rich tone are the ones which produce strong harmonic frequency air vibrations as well as the fundamental. Musical tones are quite complex because of these harmonics.

The harmonics are influenced greatly by the difference in the physical make-up, characteristics of the material, etc. of the musical instruments. Thus a violin made of wood has a pleasing, mellow sound and certain harmonics. If it were made of sheet metal it would sound metallic because the intensity of the individual harmonics produced would be different. A cornet made of wood would sound like a clarinet, etc. "Muting" of a saxophone, cornet, trumpet or clarinet is a familiar procedure especially in dance orchestras. These instruments are muted simply by inserting a plug in the opening of the horn. The resulting tone has a decided wheeze because the mute damps out certain of the overtones of the instrumental notes. This changes the character of the tone because the wave-form of the sound is changed. In speech, cavities in the head and upper part of the chest resonate to affect the timbre or quality of the tone. The roof of the mouth and the lips also affect this by varying the shape of the resonance cavity of the mouth. Interference with the free passage of this vibrating air (such as stopping of the nasal passages or irritation of the throat when suffering from a cold) causes a harsh rasping sound or hoarseness due to the suppression of the harmonics and overtones.

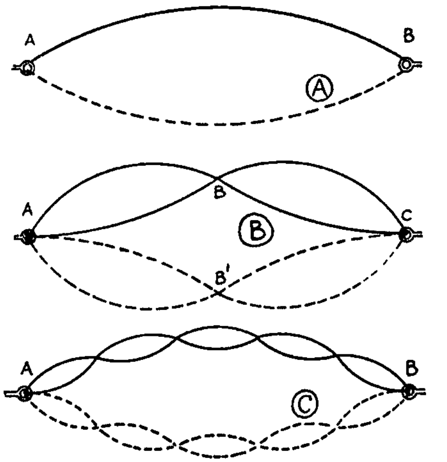


Fig. 13.—Vibrating Strings and Harmonic Vibrations. Showing how a string may vibrate as a whole and in several parts at the same time.

7. Loudness or intensity: The harder we strike a bell, or a drum, the louder will be the sound because the body vibrates over a greater amplitude. The "loudness" of a sound depends upon how violently the air is set in motion. The loudness is determined by the intensity of the sound sensation as produced in the brain by the ear. Loudness of sounds can usually be controlled greatly by the sound producing body. Thus the human speech organs can control the sound of the voice from a very low whisper (barely audible) to a loud shout. Musicians refer to the loudness of musical sounds by special terms such as "pianissimo" for very soft; "piano" for soft; "forte" for loud and "fortissimo" for very loud.

It must be remembered that the actual air pressure variations due to sound waves are very small. The variations due to the weakest sound which a person with average hearing can hear is in the order of .000000015 pounds per square inch. A painfully loud sound would produce a pressure variation of about .015 pounds per square inch, or 1,000,000 times as great. The average power of normal speech is about 10 microwatts (0.00001 watts). In music the variation of sound power between a "fortissimo" passage and a "pianissimo" passage may be as great as 100,000 to one. The intensity just sufficient to be heard is called the "threshold of audibility". The intensity which stimulates the sensation of feeling is called the "threshold of feeling." Both the threshold of feeling and threshold of audibility vary greatly with the frequency of the sound. A consideration of these figures shows that the human ear is an extremely sensitive and delicate instrument and will operate over a wide range of frequencies (about 10 octaves) and a large range of intensity of sound.

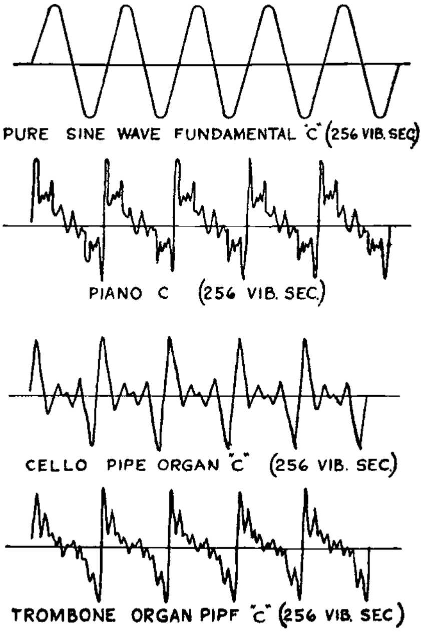


Fig. 14—Wave-forms and Harmonic Frequencies for Piano C, Cello Organ Pipe C, and Trombone Organ Pipe C.

8. Sound sensation: The sensation of sound as relayed to the human brain by the auditory nerves presents an interesting and important study. Dr. Harvey Fletcher has covered this subject thoroughly in his excellent book "Speech and Hearing". Two sounds having the same physical amplitude but differing in frequency do not sound equally loud. It requires a much greater amplitude in low frequency than in high frequency sounds to produce equal loudness sensation because, the human ear hears sounds of high frequency better than those of low frequency and sounds around 2000 cycles better than either. Thus it is evident that a radio loudspeaker emitting the low sounds of an organ selection is really handling a greater amount of energy, and is vibrating over a greater amplitude, than when emitting the high notes of a violin selection so as to produce equal loudness sensation in the ear. Other characteristics of the ear will be studied in Articles 419 to 421.

9. Frequency range required: In radio broadcasting we are interested in transmitting and reproducing as naturally as possible, both speech and music. We have seen that the sound waves are first changed into electric currents and then into radio waves at the transmitter. At the receiver the electric waves are transformed into electric currents and finally back into sound. It is essential that all of these changes be so made that the final sound issuing from the loud speaker will be an exact counterpart (insofar as the human ear can judge) of the original program. From the foregoing studies of the characteristics of speech and musical sounds we can see that true reproduction of music and speech in the home depends on maintaining with exactness the frequency loudness, pitch and quality or wave-form of the sounds. When we realize the complexity of the sounds occuring in music and speech it seems almost impossible that they could undergo so many transformations in the radio broadcasting system and still reach our homes in almost perfect condition. It is true that some changes may occur without being noticed by the average ear.

The average fundamental frequency of the male voice is around 120 cycles per second, while the female voice is about 240 cycles (an octave higher). However, harmonics exist in some speech sounds up to about 8000 per second, and while female speech has less overtones than male, they extend up to 8000 and the richest overtone area of the male voice is between 3000 and 5000 cycles. Cutting off the frequencies above 6000 eliminates the characterizing features of the unvoiced sounds such as s, f, sh, th, z, etc. These are absolutely necessary for the clear and distinct rendition of speech. Most of the energy of the voice occurs in the frequencies below 1000 cycles, most of the intelligibility above that frequency. The frequencies transmitted over the ordinary telephone lines range only from about 250 to 2700 cycles. That is the reason why it is difficult or impossible to understand sounds like th, z, sh, etc. in telephone conversation.

The playing of a musical selection by an orchestra, an organ or a piano involves the production of a large number of fundamental sound frequencies and accompanying higher harmonic frequencies. The musical tones are more or less complex. Speech does not involve as large a range of frequencies as does music, so that a system designed to satisfactorily transmit and reproduce the entire useful musical scale will generally be satisfactory for speech also.

The range of "fundamental" frequencies which must be transmitted in the reproduction of music from an entire orchestra will ordinarily range from about 40 up to 4000 cycles per second. The orchestra is composed of four choirs, the strings, the wood-wind, the brass and percussion. The lower and higher strings or keys on the harp and piano are seldom used. However, satisfactory transmission requires that the important "harmonics" of these frequencies also be transmitted and reproduced, otherwise the reproduction will not possess the characteristics of the original sound.

A certain amount of low frequency suppression is possible without serious effects due to the fact that the ear has the power of supplying to our consciousness many of the fundamental frequencies, provided the harmonics are reproduced. However, it is much better if these missing fundamental frequencies are transmitted and reproduced, for the ear soon grows tired of performing this function and the listener becomes mentally fatigued. This tiring action is very marked when listening to old radio receivers which do not reproduce either the low or the high frequencies correctly. When the harmonics are not reproduced the personal element in either the human voice or musical instrument is lost. A violin tune may sound like a whistle, the high pitched tones of the piccolo may not be heard at all. The *ideal* frequency range for perfect speech, music, important harmonics and most noises as tapping, hissing, etc. is about 30 to 10,000 cycles. However, it has been definitely established experimentally, by progressively eliminating high and low frequencies by means of electrical filters, that exceedingly good reproduction is possible if the range extends from about 40 to 8000 cycles. We must remember that harmonics higher than the third can be cut off without seriously affecting the music.

Examination of the chart of Fig. 8 shows that only four major instruments produce fundamental sound frequencies above about 2500 cycles. These are the pipe organ, piano, piccolo and the flute. Fundamental notes of higher frequency than this are rarely played in ordinary music excepting on the piccolo and flute. It would appear then that a radio transmitting and receiving system designed to handle sound vibrations up to about 8000 cycles would satisfactorily handle the fundamental and first three harmonics of all notes up to about 2500 cycles. (The third harmonic of 2500 cycles is $2500 \times 3 = 7500$ cycles.) Only the very high notes of the flute, piccolo, piano and organ would be eliminated.

At the lower end of the musical range we find that only the pipe organ and piano can produce notes lower than 40 cycles per second. These lower notes are seldom played, and even if they are, their harmonics are reproduced and the ear unconsciously tends to supply the missing fundamental frequencies. The lower limit of 40 cycles therefore seems satisfactory. At the present stage of the radio art, the cost of apparatus increases greatly with the attempt to increase the frequency range below and above these limits.

At the present time, most of the powerful broadcasting stations in the United States, transmit all sound frequencies from slightly below 100 cycles to about 5,000 cycles per second due to the present 10 kilocycle band basis for assigning broadcast station carrier frequencies as we shall see later. Broadcast engineers have been pushing into the higher frequencies however, and many of the latest transmitters are capable of transmitting a complete range of sound frequencies from 30 cycles in the bass to 8,000 cycles in the high notes in order to obtain better transmission of the low notes and harmonics. It is interesting to note that many telephone wire circuits which link radio stations into chains or networks for programs of common origin, are capable of only the range from 75 cycles to 4,800 cycles at present. This is the reason for the noticeable poorness in quality of programs originating from some chain station hookups.

The telephone engineers have developed special telephone wire circuits which will pass everything from 30 or 40, to 8,000 cycles. When such lines are in general use, we may expect the programs originating in distant cities and put out over chain station hookups to be of just as good quality as those originating directly in the studio of the local station we are listening to. At the present time, radio receiver design has not kept up with the improvements in radio transmitters, from the standpoint of sound-frequency range. Very few receiving sets reproduce below 100 and above 4000 cycles.

It is almost certain that the next few years will witness great improvements in loud speakers and receiving equipment, with the complete important sound-frequency range reproduced for full tone quality and realism. The extending of the frequency range is simply a question of improvement at reasonable cost of the radio and audio-frequency amplifiers, vacuum tubes and loud speakers in the receiver. It is essential that every part perform its function properly. Early types of transmitters, radio receivers and loud speakers did not reproduce the low and the high notes simply because we did not know enough about them at that time to be able to construct them properly at reasonable cost. As our knowledge of these things increases we can expect finer and more realistic reproduction.

It is true that some persons have a distinct aversion to really faithful low-note or high-note reproduction. Very high notes cause the sensation of feeling rather than that of hearing.

Loud high notes may cause severe irritation or pain. Also static and many other electrical interfering noises are most prevalent on the high frequencies. The latter consideration has been a very important factor in the question of high-frequency reproduction. It seems that best all-around satisfaction can be obtained by high quality transmission and reception with provision in the radio receiver for some form of tone control which can be adjusted to reduce either the high, low, or middle frequency response to suit the musical taste of the individual listener and to make up for the acoustic difference in the rooms in which receivers are operated.

When one fully realizes and understands the task of the radio broadcasting transmitter and receiver, one must really marvel at its simple design and almost perfect accomplishment. The complex audio frequency sound waves must be faithfully transformed into audio-frequency electric currents and waves, varying in intensity at these audio frequencies. These waves are in turn radiated out into space. The transmitter as a whole must be capable of responding to a whisper or a pianissimo, as well as to a shout or a fortissimo. It must be impartial in its transmission of the complex sound waves of all the different instruments. It must not introduce frequencies which are not present in the original sound waves, and must accurately reproduce even the most delicate tone shadings.

REVIEW QUESTIONS

1. How could you prove that sound is produced by mechanical vibrations?
2. Describe what occurs when a body vibrates in air.
3. Do the particles of air actually travel outward the entire distance from the sounding body to the ear of the listener?
4. Describe two common devices for producing sound waves, and explain just how these sound waves are produced in each case.
5. Why is the vibration of a sounding body usually not visible to the human eye?
6. What is the velocity of sound in air?
7. Is the velocity the same in all substances?
8. What kind of waves are sound waves? Of what does each wave consist?
9. Explain how sound waves produce the sensation of sound when impressed on the human ear.
10. When a bottle of soda water is opened, a sound is heard. Explain this.
11. Distinguish between noise, speech sounds and musical sounds.
12. What are the three identifying characteristics of all sounds?
13. Explain the operation of the human organs of speech.
14. Define "pitch". What is a low pitched sound; a high pitched sound?
15. What is the approximate range of sound frequencies which the average person is able to hear?
16. Describe an experiment which proves that the pitch of a sound depends upon the frequency of vibration.
17. Describe an experiment which shows the exact upper and lower limits of sound frequencies audible to the human ear.
18. Explain the various methods used to produce sound waves in musical instruments.
19. Name three musical instruments able to produce sound waves lower than 100 cycles per second. Name three able to produce fundamental sound waves above 2,000. Name two able to produce the entire range of musical sound waves.
20. Why are the strings of a bass viol and a cello heavier than those of a violin?
21. Why does increasing the speed of rotation of a phonograph record change the character of the music produced? Would this raise or lower the pitch of the music?

22. Why is the length of the horn or air-column in the bass tuba much longer than in the piccolo?
23. Distinguish between (a) fundamental (b) overtone or harmonic (c) octave.
24. What is the second octave of a 200 cycle note? The fourth octave?
25. What is the second harmonic of a 200 cycle note? The fourth harmonic?
26. Upon what does the quality or timbre of a sound depend?
27. Why does a 200 cycle note sounded on a piano sound differently than a 200 cycle note sounded on a violin?
28. What would be the effect on the sound wave produced by a loud speaker diaphragm whose amplitude of vibration was not proportional to the current through its winding?
29. What determines the loudness of a sound?
30. Since the complete range of important fundamental sound frequencies occurring in speech and music is only from about 40 to 4,000 cycles, why is it necessary to transmit a range of 40 to 8,000 cycles for real good reproduction of speech and orchestral music?
31. What musical instruments would not be heard in their entirety if the loud speaker or some other part of the transmitting and receiving equipment cut off at 3,000 cycles?
32. A symphony orchestra composed of over 100 instruments is performing in a broadcasting studio. What determines the actual movement of the microphone diaphragm,—the resultant sound-pressure wave produced by the combination of the sound waves of each individual instrument, or does each individual sound wave act on the diaphragm separately?
33. Why is the rattling of paper, squeak of a door, chirp of an insect, etc., difficult to transmit and reproduce over the radio?
34. Why are ordinary telephone lines unsuited for the transmission of sound pickups for broadcast programs of symphonic music?
35. In what direction do sound waves normally travel? How may they be directed in some particular direction?
36. Why does the sound from a radio loud speaker diminish in strength as you move farther away from it?

CHAPTER 3.

ELECTRON THEORY, ELECTRIC CURRENT

ELECTRICITY IN RADIO — USE OF ELECTRON THEORY — ELECTRICAL CHARGES — LAWS OF ELECTRICAL CHARGES — MATTER AND MOLECULES — COMPOUNDS, ELEMENTS, ATOMS — ELECTRONIC STRUCTURE — ATOMIC STRUCTURE — CHEMICAL ACTION — CHARGED BODIES — ELECTROMOTIVE FORCE — SOURCES OF E. M. F. — CONDUCTION CURRENT — NUMBER OF ELECTRONS — VELOCITY OF PROPAGATION — DIRECTION OF ELECTRONS AND CURRENT — ELECTRIC CONDUCTORS — ELECTRIC INSULATORS — INSULATION BREAKDOWN — DIELECTRIC STRENGTH — REVIEW QUESTIONS.

10. Electricity in radio: Every piece of electrical apparatus used in radio work has an electric circuit in some conducting material, and a magnetic circuit either in air or some magnetic material. Transformers, choke coils, loud speakers, etc. used in radio receivers, depend for their operation on the proper use of electricity and magnetism. Invisible electromagnetic radiations manifest their actions by magnetic and electrostatic fields. It is desirable and necessary therefore, for every student of radio to know something of the nature of electric current and magnetism, the properties of the common electric and magnetic materials, and the laws governing electric and magnetic action in order that he may understand the design, operation, servicing and limitations of radio apparatus. It is interesting to note that in a complete radio system we are dealing with almost every form of electric current known.

Another important consideration which is too often overlooked, is the fact that the student who thoroughly understands, and has a good mental picture of, the fundamental actions associated with the flow of current and magnetism, is excellently prepared to keep abreast of all the new developments which are coming almost daily in the radio art. He finds that the new things are merely new adaptions and arrangements of the fundamental principles he is already familiar with, and he is usually able to quickly understand their operation and put his fundamental knowledge to practical use.

Since the most recent scientific discoveries and investigations in science indicate strongly that the manifestations of electricity and magnetism are really due to actions of tiny electrical charges called electrons, it is necessary that our study of these two important servants of man be preceded by a study of the behavior of the electron. This is really the most interesting subject in the study of electricity and not at all difficult if it is pursued in a logical manner.

11. Use of electron theory: The flow of electricity through a wire is always a very puzzling thing to the novice, possibly because the action is not directly visible to the naked eye. However, by making use of the information brought to light in recent discoveries, and employing our powers of imagination and visualization, a rather complete picture of what goes on inside the wire can be presented. Like many other things we can learn to use and control electricity by studying its various actions and effects. Many theories have been advanced to explain the reasons for the observed behavior of electric currents. The one most commonly accepted at present, because it explains the observed actions most satisfactorily and completely, is the *electron theory.* The student is reminded here, that the electron theory is simply an explanation of these things which fits and explains most of the observed facts. It has not been definitely proved in its entirety, for then it would have become *a law* of science. It does however, explain more satisfactorily and more thoroughly than any other theory thus far presented, the observed behavior of the flow of electric current, magnetism and electromagnetic waves. While there are still a few things about the behavior of light that the electron theory does not satisfactorily explain, it seems that the necessary slight changes to be made in it in the future, or a different point of view on these questions will settle them satisfactorily.

We do not have definite and positive answers to every question that might be asked about electricity today. There is however, a growing mass of exact fundamental data proved by precise and really beautiful experiments, that is leading rapidly to a satisfactory solution and explanation. This work has opened the door to a new physics, a new way of looking at, and explaining, familiar things. It is extremely absorbing and interesting. When Madame Curie through her remarkable patience and skill succeeded in discovering and isolating radium, she opened the door to the innermost minute particles of matter and revealed to us the workshops of nature where heat, light, electricity, magnetism and the many rays and radiations have their origin. It really seems a pity that nature did not provide us with eyes capable of looking into this atomic and electronic world so that we might appreciate the wonders and the beauty of the actions locked up therein.

12. Electrical charges: The word "electricity" is derived from "elektron", the Greek word for amber. About 600 B.C., Thales, a Greek philosopher, recorded the fact that if amber is rubbed it will attract objects of light weight. As no satisfactory explanation was forthcoming at that time, the action was looked upon as being rather mysterious.

Benjamin Franklin investigated this phenomenon of the electrical action of various substances and combinations of substances when rubbed together. For instance a glass or a rubber rod when rubbed with a piece of fur or a cloth became electrified and would attract light objects. (This experiment may easily be repeated by the reader by rubbing an ordinary hard rubber comb, rubber rod, or fountain pen with a piece of silk or flannel cloth. The comb will then attract small pieces of paper, or balls made from the dried pith of the elder bush, as shown in Fig. 15.) As a result of his work, Franklin concluded that there are two kinds of electrification or "electricity", *positive* and *negative.* Bodies that behave like the rubbed glass rod, he said, possessed *positive* electricity, and those behaving like the rubbed rubber rod, possessed *negative* electricity. It should be noted that he chose the terms positive and negative arbitrarily without any definite reason except possibly the fact that these two charges could be made to neutralize each other, and thus made the terms seem justifiable. Any substance capable of being electrified in this manner, he called an electric; our modern name for such a substance, is *insulator.*

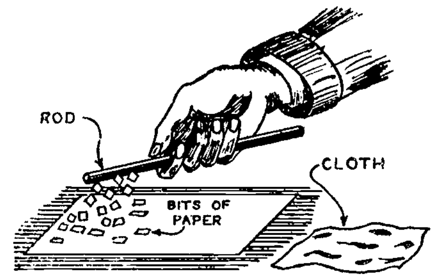


Fig. 15.—A Body Electrified by rubbing attracts light objects.

After an insulator like hard rubber or glass has been electrified by rubbing, or some other means, the electricity does not move through it as it does in an ordinary conductor like copper, but remains at rest in the form of a stationary (static) charge. The electricity remaining at rest in an insulator is called a static charge, *static electricity,* or just an *electrical charge.* When the body is very small, the body itself is called a charge, and it may be referred to as a positive or negative charge. If it has a large excess or deficiency of electrons it is said to be highly charged.

13. Laws of electrical charges: It has been determined by experiment that a field of force exists around every charged body, and that *like charges repel each other,* and *unlike charges attract each other.*

Thus, a negative charge *attracts* a positive charge.

Two negative charges *repel* each other.

Two positive charges *repel* each other.

The more highly charged the bodies are, the greater is the force of attraction or repulsion between them. Also, the closer together the charged bodies are, the greater is the force of attraction or repulsion. The force is directly proportional to the product of the strength of the charges, and is inversely proportional to the square of the distance between them. Thus, tripling the distance between the two charged bodies makes the force of attraction or repulsion $\frac{1}{3^2}$ or $\frac{1}{9}$ as great, etc.

A single body on which there is an equal amount of positive and negative charge is said to be *neutral*, or in equilibrium. If a single body has an excess of either positive or negative electricity it is said to be *charged* either *positively* or *negatively*.

An understanding of the actions between electrical charges is important in radio work for it has direct application when considering the design of condensers, vacuum tubes, hand-capacity effects in tuning, etc. Bodies may be charged electrically in many ways. One of the common methods, known for a long time, is by friction. Whenever one body is rubbed by a dissimilar one, one of the bodies takes on or assumes a positive charge and the other assumes a negative charge. The charge on either body may be transferred to another body under proper conditions. Charging a body by friction is a familiar trick. During cold dry weather, the friction of one's shoes on a rug will charge the body so that sparks can be drawn from the finger tips. A rubber fountain pen rubbed with a piece of fur or cloth will become charged and attract bits of paper. A rubber comb drawn briskly through the hair on a cold dry day, will charge it and it will emit crackling sounds.

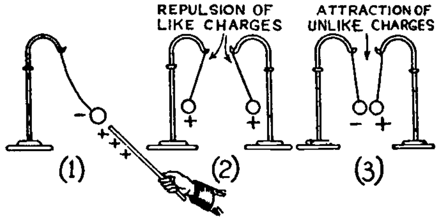


Fig. 15A.—Attraction and Repulsion of Charged Bodies.

Charged bodies may be studied by the simple apparatus shown in Fig. 15A. A small piece of paper or a piece of pith from a dry cornstalk, elder, or sunflower stalk, is suspended from a stand by a short silk thread. The stand should be well insulated from the table by a sheet of clean glass or other good insulator. Stands for the purpose are made with a glass rod for a shaft.

Experiment. Briskly rub a rod of glass or hard rubber with a flannel cloth or piece of fur. Bring the glass near the pith ball. It should be strongly attracted, proving that the pith ball must also have acquired an electrical charge. If the glass rod is allowed to touch the pith ball and is then pulled away from it, the ball will immediately be repelled from it. Now suspend two similar pith balls from two independent threads hung from separate stands. Rub the glass rod briskly and touch each pith ball with it. They will both receive a similar charge from the glass rod. Now bring the stands close together and the balls will immediately repel each other as shown at (2) in Fig. 15A (like charges repel). Now rub the glass rod again. Touch one ball with it and touch the other pith ball with the piece of flannel. The two balls then assume the opposite charges of the two opposite charged objects, and are attracted to each other when brought near one another, as shown at (3) in Fig. 15A, (bodies having unlike charges attract each other).

The two charges of electricity are called *positive* and *negative*, but there is no really good reason for this. If a glass rod is rubbed with silk, the rod assumes a positive charge, if a stick of sealing wax is rubbed with a piece of flannel cloth, the wax will assume the negative charge. Thus the charge induced on the rubbed body depends on the two materials used.

The forces of attraction or repulsion between charged bodies may be considered to act along imaginary lines called *electrostatic lines of force.* The sum total of the lines of force around a charged body constitutes the *electric field.* Every charged body is surrounded by such a field.

14. Matter and molecules: The word "electron" is generally familiar and is usually understood to represent a very small particle of matter. Beyond this very elementary conception the average person's ideas on the subject are vague and usually altogether too jumbled to be useful to him.

Let us first consider *matter.* Matter is any substance having weight, volume and other physical characteristics. The water we drink, the clothes we wear, the earth we live on, the air around us, our own bodies, all constitute matter. It has been found that all matter really consists of numerous very tiny particles instead of single large chunks. The smallest possible portion to which a substance (compound) can be divided, and yet retain all its individual characteristics is called a *molecule.* The molecule is too small to be visible even under the most powerful microscopes we have, due to the grossness of our sense of sight. The smallest portion of matter we can see under even the most powerful microsope still contains several hundred molecules.

15. Compounds, elements, atoms: Those readers who have already studied physics or chemistry will remember that there are 92 different chemical elements, (see Art. 223), from which all matter in the entire world is made up. Among the more common are oxygen, hydrogen, gold, silver, copper, iron, etc. An *element* contains nothing other than the single material itself. The smallest particle of an element is an *atom.* Single elements such as the above are common in our daily lives but most of the substances and materials with which we are familiar consist of a chemical combination of the atoms of two or more elements to form a new substance or *compound* whose physical and chemical properties are entirely different from those of any of the constituent elements. Examples of common compounds are, table salt, (sodium and chlorine), iron rust (iron and oxygen), water (hydrogen and oxygen), etc. The smallest portion into which a compound can be divided without splitting it up into its element atoms is called a *molecule.* Of course if a substance is a simple single element, then its molecules and its atoms are identical. The term *molecule* is usually associated with compounds, whereas *atom* is associated with the elements.

In general each molecule of a compound is made up of two or more smaller atoms of the simpler elements entering into its composition. The properties of a compound prove to be due to the particular way in which the atoms are architecturally grouped. The strength and elasticity of metals, their power of conducting electricity, heat, etc., can be explained in terms of their structure as it is revealed by the actions of X-rays upon them. Much experimental work on the determination of the arrangements of atoms in substances has been carried on by means of X-rays by Sir William H. Bragg and Prof. W. L. Bragg. It is thought that the atoms arrange themselves in regular geometric forms, which in some substances are extremely complicated. Fig. 16 shows the structure or arrangement of the atoms of sodium and chlorine in sodium chloride (ordinary table salt).

The innumerable possible combinations of the 92 chemical elements explains why it is possible for us to have so many different kinds of materials in existence today. Thus two atoms of the element hydrogen will combine with one atom of the element oxygen to form each molecule of a new substance, water. The chemist uses a special simplified method for expressing this elementary combination of atoms, thus $H_2+O=H_2O$. One atom of sodium combines with one atom of chlorine to form each molecule of sodium chloride (table salt). Thus, $Na+Cl=NaCl$. The salt does not look, taste or act like either of the two constituent elements, it is a new material entirely. Hydrogen and oxygen are both gases under ordinary conditions; water formed by their chemical combination is a liquid. Fig. 16 shows the arrangement of the atoms in salt. The black spots represent the atoms of sodium and the white spots represent the atoms of chlorine as they are arranged inside of a crystal of the salt.

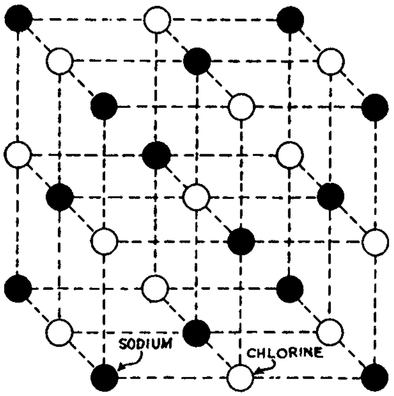


Fig. 16.—Arrangement of the atoms in sodium chloride. The black spots represent sodium atoms and the white ones chlorine.

16. Electronic structure: Molecules are extremely small, so small that we cannot see them with the lenses of the most powerful microscopes. Lenses are themselves composed of molecules and atoms. To see molecules, the lenses and our eyes themselves would have to become molecular in size. Still, the empty space between the molecules of a substance is thousands of times greater than the space actually occupied by the molecules themselves! A molecule however, is a relatively huge affair compared to the size of an atom.

Up to the time that radium was discovered, atoms were considered to be indivisible units of matter. We now know them to be very simple or very complicated structures (depending on the chemical element). Every atom consists of a miniature planetary system with a central nucleus or "sun", around which constantly revolve in regular orbits, one or more tiny particles or planets. This is somewhat like our solar system, of the earth, sun, and moon. The nucleus or core of each atom contains one or more particles called *protons*; each proton having a definite positive electrical charge. The little bodies revolving around the nucleus were called *electrons* by Johnston Stonly in 1891 because of their electrical nature. These electrons are simply infinitesimally tiny *negative* electrical charges. The number of negative electrons revolving around the central core or nucleus of each atom varies in the different chemical elements. Also the number of positive protons in the nucleus is different in each chemical element. In some elements the nucleus consists of both protons (positive charges) and a few electrons (negative charges) with additional electrons revolving in concentric rings around the core, as shown in (B) of Fig. 17. The latter revolving electrons are commonly called *planetary electrons* to distinguish them from the electrons which remain in the core.

Under normal conditions each atom is electrically neutral as a whole, that is, the sum total of the negative charges of all its electrons just balances and equals the total positive charge of its protons. Under this condition the body is uncharged electrically, so far as any outside effects are concerned.

It is evident then, that acording to the electron theory, the final analysis of all elements and compounds of which all matter is composed, reveals them to be made up of but two things, positive electrical charges known as protons, and negative electrical charges known as electrons. The atom is pictured as a core or nucleus of positive charge (with a few electrons in it also, in some elements) surrounded by a number of negative electrons rapidly rotating in circular or slightly elliptical orbits which form more or less concentric rings around it. The atoms and the molecules in matter are constantly in motion, carrying within them in their movements, the electrons that constitute them. In the bumping of one atom against another, electrons may be gained, lost, or interchanged.

Why then, do the various chemical elements such as gold, silver, iron, oxygen, chlorine, etc. differ in weight, taste, color, strength, electrical conductivity and other characteristics? The difference is due to the difference in the number and position of the electrical charges (protons and electrons) which constitute each tiny atom. The atoms of some elements contain only a few protons and electrons arranged simply, as in the case of hydrogen, helium, etc. The atoms of the other substances like copper, gold, uranium, etc. contain many electrons and protons arranged to form very complicated systems. The simplest of all atoms is that of hydrogen (one of the constituent elements of water). This consists of a nucleus composed of one revolving proton, around which rotates a single planetary electron as shown in (A) of Fig. 17. The circle indicates one of the several orbits the moving planetary electron may take. It is difficult to represent the real structure of atoms by diagrams, since the element of motion and relative sizes is lost. In all diagrams of this kind, the nucleus in the center and the electrons around it are drawn several thousand times too large relative to the actual distance and space between them, because the actual distance between the electrons and protons is many times as large as they are. There is a relatively large amount of empty space around the protons within the boundaries of the electron orbits. This is one of the astonishing things about matter, this great emptiness of it. A piece of copper wire seems solid to us because of the grossness of our sense of sight. It is really the openest kind of a sponge. Only about two-one-hundred trillionths of the space inside a piece of copper is occupied by anything solid, by the electrons and nucleus. All the rest of the space so far as we know is absolutely empty. While the proton seems to be extremely small compared to objects with which we are familiar, the electron is a mere dwarf compared to the proton. Almost the entire mass of every atom is due to the mass of the protons.

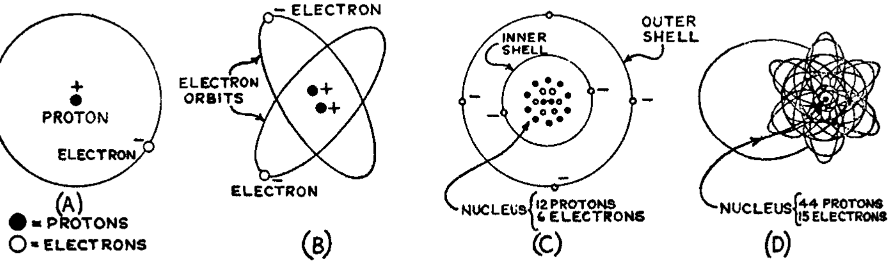


Fig. 17.—Structure and Electron Orbits of Atoms of Hydrogen, Helium, Carbon and Copper, according to Bohr. The Hydrogen Atom is the simplest.

The next simplest atom is that of helium (the gas used in lighter-than-air craft) having a rotating nucleus of two positive protons with two electrons revolving about it as shown in (B) of Fig. 17. In this way we conceive the atoms of different masses to be made up by progressively adding one electron and a corresponding proton to the element of lower mass and lower atomic weight. The heavier atoms are those having the greatest number of protons and electrons, (see Art. 223).

17. Atomic structure: The grouping of the electrons in the more complicated atoms is still in the stage of hypothesis and the pictures shown here are merely those which today most satisfactorily account for the largest number of known phenomena. It is imagined that in the more complicated atoms the electrons are arranged around the nucleus as if they lay in a concentric series of spherical shells. In the first shell are two planetary electrons (except in the case of hydrogen) revolving around the nucleus. In those atoms which contain more than two planetary electrons all those planetary electrons in excess of these first two are arranged in shells external to the one just described. The next outer shell is supposed to be twice as far from the nucleus, and thus has four times its area. In it a maximum of 8 electrons may be revolving. If the total number of planetary electrons in the atom is greater than 10, an additional outer shell is required; for electrons greater than 18, a fourth shell is required, etc. More complicated atoms then have electrons revolving in additional shells. Two elements may have the exact same number and arrangement of planetary electrons in these outer shells, but may differ simply because the proton and electron arrangement in the nucleus is different.

In (C) of Fig. 17, the internal structure of an atom of carbon is shown. This consists of 12 protons and 6 electrons in the nucleus. Around this are two planetary electrons in the first outer imaginary shell, and four electrons in the second outer shell. In this figure, only the boundaries of the shells are indicated, as an attempt to show the individual orbits of the electrons would make it too complicated for our purpose.

The internal arrangement of each atom in a piece of copper wire is shown in (D) of Fig. 17. Here the central nucleus contains 15 electrons and 44 protons. Flying about in planetary orbits ouside of this are the other 29 electrons: distributed in four concentric spheres or shells (a total of 44 electrons). The orbits of these planetary electrons are shown in the diagram.

The atoms of all the 92 different chemical elements are formed by various combinations of protons and electrons. The most complicated of all the 92 different atoms or chemical elements known at the present time is that of uranium (one of the radio-active substances). This has a nucleus into which are tightly packed 238 protons and 146 electrons, around which revolve 92 planetary electrons distributed systematically in seven concentric shells or spheres. The story of how uranium atoms are constantly emitting electrons and thereby changing themselves into simpler atoms and elements and at the same time supplying energy (radio-activity) is a most interesting one.

It is evident from the foregoing descriptions that the atom is somewhat like a miniature solar system, with the sun corresponding to the nucleus and the several planetary orbits corresponding to the rings in which the electrons revolve. One difference between these however, is that in our solar system each orbit contains only one planet, whereas a single electronic orbit may contain as many as 32 and as few as a single electron. The electrons are grouped about the nucleus as if they occupied individual cells in concentric shells of successive diameters which are related as 1:2:2:3:3:4:4: and of capacities or quotas for electrons 2, 8, 8, 18, 18, 32 and 32 respectively. No electrons exist in outer shells unless those within are completely filled.

18. Chemical action: Those chemical elements whose atoms contain outer shells having their complete quota of electrons, are satisfied inert substances which do not enter into chemical combination easily. Those chemical elements whose atoms contain outer shells only partially filled with electrons tend to combine chemically with other substances in like condition, (either losing electrons to, or gaining electrons from the other substances) so as to form a more stable and satisfied system. This is the basis of all chemical combinations and explains why some elements like neon (eight electrons actually in the second shell which has a capacity for only 8 electrons) and helium (two electrons in first shell) are chemically inert. Other elements like hydrogen (one electron in first shell), fluorine (seven electrons actually in the second shell which has a capacity for 8 electrons), etc. are chemically active because the number of electrons in the outer shells are not enough to completely satisfy the full capacity of the shell for electrons as given in Art. 17.

19. Charged bodies: Up to this point in our discussion of the structure of the atom, we have considered only the condition where the sum total of all the positive charges of the protons in the nucleus is equal to the total negative charge of all the electrons in the atom, and the atom does not exhibit any electrical manifestation outside. A body composed wholly of such atoms is said to be neutral or uncharged. The electrons and protons because of their opposite charges have a great attraction for each other, and this normally tends to keep the electrons revolving inside the atom.

If by some means, a body is made to have an excess of electrons or protons, its electrical charges are unbalanced, (having more positive charges than negative or vice versa) and it exhibits the external effects commonly associated with electrically charged bodies. Whenever a body has an excess of protons, (whether the body is of atomic size or as large as the earth) we say it is "positively charged" with electricity; similarly, when it has an excess of negative electrons, it is "negatively" charged.

Note: It must be understood that this does not necessarily mean that a change in the chemical nature of the substance has taken place, for in those bodies which can be charged, an electron can be added to or subtracted from each atom without changing the arrangement of the atom to what it would be for some different substance. It must be remembered also that in order to change one element having say, four protons and four electrons in each atom into an element having five electrons and five protons, in each atom, we must add not only an electron to the first, but must also add a proton to it and re-arrange the electrons so they are in the same order as in the second element. Simply adding or taking away one electron from each atom as during the process of charging a body does not satisfy this condition for change of element or substance.

There are various ways of charging a body with electricity, the most simple one is by the so-called "frictional method" as described in Article 12. When the two dissimilar substances are rubbed together, although their surfaces appear smooth, the structure of their atoms is such that the act of rubbing the two bodies together is really the act of crowding one planetary system into another or causing one to pass through the other. This presents a splendid opportunity for some of the electrons to be displaced from their own planetary systems and join those of the nuclei in the other body. In general, the molecules of that substance which has the greater need for electrons, will gain them and become negatively charged; that substance which will willingly assume an electron arrangement with fewer electrons, will lose them and become positively charged. Those substances which already have their outer shells completely filled with the proper number of electrons (see latter part of Article 17) will not lose or take on additional electrons easily and so are not electrified by rubbing together. When glass and silk, or cat's fur and sealing wax, are rubbed together, the first of each pair loses electrons and thus becomes positively charged, and the second gains these electrons and becomes negatively charged, as shown in Fig. 18. The rubbing is simply a means of bringing more points into intimate contact so the exchange of electrons can take place. Since the number of electrons gained by one body is just equal to the number lost by the other body, they became equally and oppositely charged. A charged body may contain millions of normal

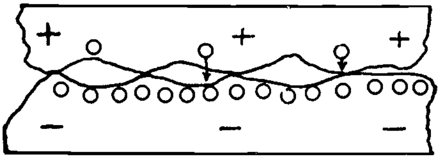


Fig. 18.—Charging Bodies by Rubbing. The upper body is positive because it has lost electrons to the lower body which became negative.

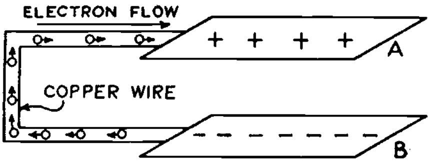


Fig. 19.—Flow of Electrons (current) through a wire connecting two charged bodies.

atoms for every atom that has either an excess or a deficiency ot electrons.

The act of separating the two charged bodies after they have been rubbed, is done against the force of attraction of the unbalanced charges of the atoms of one body for the excess electrons which were put on the other body. A certain amount of work is done to effect this separation. If free to move into contact again they will do so, and the excess electrons will return to the atoms deficient in electrons and restore the electrical equilibrium. The return of the electrons need not be brought about by touching the two bodies together again. Any method which will transfer the electrons from the negative body will tend to bring about the original, stable condition. There are several methods of doing this, but to all of them we give the general name of "electrical conduction", and we say the medium through which conduction takes place possesses "electrical conductivity". We will see later that this medium may be a suitable solid, liquid, gas, or even a vacuum. Conduction through solids like copper, brass, etc., represents the more common instances of electrical current flow, but in radio we are also interested greatly in conduction through liquids (storage batteries), conduction through gases (rectifier tubes, neon tubes), and through a vacuum (vacuum tubes). Conduction through solids and liquids will be studied first.

If we take two charged bodies A and B of Fig. 19, A being charged positively, (deficiency of electrons) and B being charged negatively (excess of electrons) and connect them together by a piece of copper wire, an immediate re-distribution of charge will take place. The excess electrons from B will start a flow of electrons through the wire to A. This will continue until A has gained enough and B has lost enough electrons so as to bring them to their normal uncharged condition or to the same electrical potential. Meanwhile, a flow of electrons has taken place through the wire. This is an electric current, of exactly the same nature as that furnished by batteries, dynamos, etc. It will produce exactly the same effects as the current found in ordinary power and electric light wires. This experiment can be performed by charging the plates of a 1 or 2 mfd. condenser used in radio receivers, by connecting it across a 110 volt electric light circuit. The condenser is then removed, and a short wire is connected across its terminals. A spark will be produced due to the flow of current between the terminals.

20. Electronic force: We have shown that electrons can be transferred from one body to another by rubbing or frictional contact. We have also shown that electrons can be made to move from one end of a body to the other end, as in the case of the copper wire in Fig. 19. Electrons can be made to flow continuously if a proper closed circuit through some suitable material (particularly metals) is provided, as in Fig. 21. This is commonly called a flow of electricity, or simply an "electric current". In practice the circuit is usually arranged in the form of a wire. In order to make the electrons flow in a definite direction, through the wire, an external force must be applied to it. This force is called electron-moving force, or simply *electromotive force.* The usual abbreviation for this rather long word is e.m.f. This will be referred to often in our work.

There can be no definite flow of electrons or flow of electricity without the application of electromotive force, just as there can be no flow of water through a pipe unless a pressure is applied to it. As a matter of fact, electromotive force is sometimes called "electrical pressure" since it causes the flow of electrons, but of course it is really not a pressure in the same sense as applied to water.

21. Sources of e.m.f.: Electromotive force which will force electrons to flow through a suitable conductor (flow of electricity) can be developed or generated in several ways. We have already studied the process of creating an electron flow by friction. This is not used in practice to any extent. Other more practical methods consist of moving an electrical conductor in a magnetic field as in the case of the electric dynamo or generator; by creating chemical changes in suitable substances as in the case of primary batteries and during the discharge of storage batteries; and by heating the junction of two dissimilar metals as in the case of the thermocouple. These methods will be studied in detail later. The common sources of e.m.f. employed in radio receivers are shown in Fig. 20.

22. Flow of electric current by conduction: Let us see just what happens when current flows through a solid conductor. The atoms in solid bodies are more or less restricted in their motion and do not wander around from one part to another as much as do the molecules of gases and liquids. They are constantly in a state of agitation however, depending on the temperature of the body. Through solids therefore, the conduction of electricity results simply from the motion of electrons through the body, since they are very small. The smallest known atom, that of hydrogen, has a weight about 1845 times that of an electron.

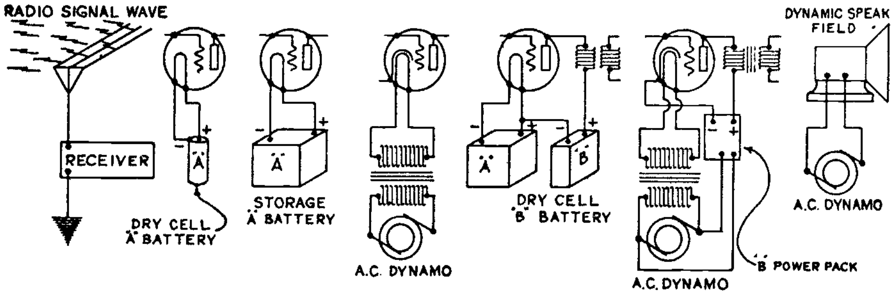


Fig. 20.—Common Sources of E.M.F. used in Radio Work. Radio Signal Wave; Dry Cells or Storage "A" Battery sends current through filaments of tubes; Filament Transformer Operating from A-C Line furnishes Filament current; Dry Cell "B" Batteries or "B" Eliminator furnishes E.M.F. for plate circuits; Electric Light Line furnishes E.M.F. for Electro-dynamic Speaker Field.

The solid substances which conduct electricity best, are the metals, and these are the ones whose atoms will most easily part with an electron. Thus each atom of copper normally has 11 electrons in its outside (fourth) shell. The capacity of this shell is 18 electrons. Therefore it is relatively easy to release at least one electron from each atom and make it move through copper. Copper is therefore said to be a good conductor of electricity, that is, a comparatively small e.m.f. applied to it will cause a large number of electrons (large current) to flow through it. The same is true with the other good electrical conductors, such as gold, silver, etc.

When visualizing the flow of electrons through an apparently solid body such as copper it should be remembered that actually the body is very empty, that is, there are comparatively large spaces between the atoms. Thus if a copper penny were enlarged so as to cover the earth's orbit, (to a great copper disc 189,000,000 miles in diameter) the distance between the individual atoms would be about three miles; the cores of the atoms would be about 11 inches in diameter and the electrons would be about 3 inches in diameter! In the whole of a copper cent there are about 700,000,000,000,000,000,000,000 electrons. For convenience this can be written $7x10^{23}$, which means that 7 is to be multiplied by 10 twenty three times.

It is evident then, that even in solid objects the tiny electrons have plenty of empty space in which to move around. Imagine the large amount of room a particle about four-thousandths of an inch in diameter would have for movement within a sphere 1 meter (over three feet) in diameter!

When an e.m.f. is applied to a wire as in Fig. 21, those electrons which can be taken from their atom families easily are driven from one atom to another through the wire towards the source of the force. This movement of electrons results in a drift of electrons around the complete circuit and is called *conduction current or electronic drift.* The number of electrons flowing past any point in the circuit depends upon the strength of the applied e.m.f. and the resistance which the conductor offers to the flow of the electrons through it.

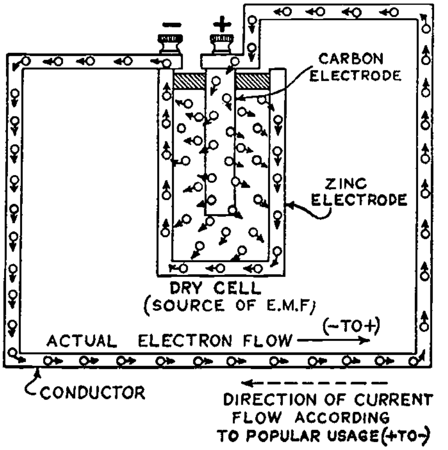


Fig. 21.—Actual Direction of Electron Flow, and direction of current flow according to popular usage, in an electric circuit.

If a copper wire is connected to a source of e.m.f., such as the dry cell battery in Fig. 21, at the positive terminal of the battery an attraction occurs for those electrons in its immediate vicinity because the chemical action between the materials in the cell has forced many of its electrons out to the negative terminal, leaving the positive terminal with a scarcity of electrons. As copper is a good conductor, that is, electrons can be freed from its atoms by comparatively small electric forces, some of them will be set free ("free electrons") and will immediately start to rush toward the positive terminal. (According to some investigators a large number of electrons are free in conductors even before any e.m.f. is applied.) As soon as they are set free their atoms have unbalanced positive charges and will tend to attract electrons from the atoms behind them. When these lose electrons they attract some from the atoms behind them, etc. At the same time, since at the negative terminal of the battery there is a surplus of electrons, some electrons in the atoms of the wire in its immediate vicinity are freed from their atoms and repelled forward in a direction through the wire toward the positive terminal of the battery. The chemical changes taking place in the dry cell, tend to maintain the charge at each terminal, that is, maintain the e.m.f. or propelling force in the circuit. There is then a drift or circulation of electrons around through the conductor from the negative to the positive terminal of the source of e.m.f., and *through* the source of e.m.f. from positive to negative as shown in Fig. 21. This drift of electrons constitutes the flow of electric current by *conduction.*

It is thought that the flow of electrons through the conductor really takes place in several ways. Some of the electrons may flow from one atom to another thus releasing electrons which flow on to the next adjoining atom, etc.; some may flow between the atoms, some even flow through the relatively large empty spaces in the atoms in the same way that a bullet can be fired through the empty spaces between the planets of our solar system without hitting any of them. The electrons may dash in and out without attaching themselves to the atoms. It must be remembered that while there is a general drift of *electrons* through the wire, the *atoms* continue their haphazard vibration in the wire. Whatever the individual electrons may do, we may assume that an electric current through a conductor consists of a stream of electrons drifting through the wire.

23. Number of electrons: In order to produce a perceptible effect of current flow, it is necessary that a large number of electrons be transferred through the wire. Thus when one ampere of current flows through a wire, about 6,280,000,000,000,000,000 or 6.28×10^{18} electrons (over 6 quintillion) are drifting or flowing past any point in the circuit every second. This however, is only a very small fraction of the total number of electrons contained in the wire. It has been estimated that only one in 5000 electrons resident in a conductor actually is used when current is flowing through the conductor. The others remain in their respective atoms.

24. Velocity of propagation: In the usual electric wires the electrons revolve around their protons at very high velocities. However, the *free* electrons are darting around from atom to atom and they actually move or drift *along* the wire very slowly, probably only a few inches a minute, but of course they move in enormous numbers. This slow movement of the electrons should not be confused with the speed of electricity or electrical disturbances which is 186,000 miles per second. The latter means that when the electrons at one end of a very long electrical circuit for instance, are set in motion by the application of an e.m.f., the electrical disturbance of the electrons would reach to a point 186,000 miles from this end in one second; so that in one second, electrons in that whole 186,000 miles section of wire would start to move toward the positive terminal (at a comparitively low speed). Any change or variation in the current flow also takes place at this rate.

The effect may be roughly compared to a long column of soldiers standing still. At the instant of the command "forward march" the front row advances and starts to march, at say two miles per hour. The next row then moves forward, then the next, etc. It may take a fraction of a second before the last row in the column will start to move forward after the first row has started. The steady forward movement of the soldiers is only two miles per hour, whereas the initial wave of disturbance or movement proceeded along the column at a very much faster rate.

Now if for some reason the first row of soldiers decided to speed up their marching to four miles per hour, this wave of speeding up would proceed back along the line very rapidly (velocity of propagation) so that within a fraction of a second all the soldiers up to the last row would have speeded up. The four miles per hour corresponds to the slow rate of drift of the electrons in a wire, the wave of speeding up or starting up, proceeding back along the column, corresponds to the rate of propagation of electrical disturbances and electrical waves, 186,000 miles per second.

25. Direction of electrons and current: The atoms cannot drift freely in metals because of their relatively large mass. Consequently the flow of electricity through metals is due solely to the *drift movement of the electrons.* Obviously the direction of movement of the electrons is continuously from the negative terminal of the source of e.m.f., around through the circuit to the positive terminal of the source of e.m.f., and through the e.m.f. source to the negative terminal as shown in Fig. 21. It is unfortunate that in the early experiments with primary batteries (before the electron theory or the flow of electrons had even been thought of), the electric current was supposed to be a fluid like water and was arbitrarily said to flow from the positive terminal of the battery (point of high pressure or level) to the negative terminal (point of low pressure or level). This purely arbitrary terminology has been carried down from that time and is in universal use among electrical workers. Nowadays we know that the electron flow (which is really the current) is actually from the negative terminal around to the positive terminal of the source of e.m.f. This unfortunate apparent discrepancy need not cause any serious difficulty however, if the student will keep the electron theory in mind and remember how and why the terminology of current flow now in popular use, originated. In this book, confusion will be avoided by accepting the common positive to negative direction of flow when speaking of "electric current", and specifically stating "electron flow" when speaking of the actual direction of the electrons. The reader is urged to do likewise.

For instance when studying the electron flow in vacuum tubes, we will find that the *electrons* actually flow from the filament or cathode to the plate inside the tube, whereas the *plate current* is said to flow from the positive terminal of the B supply source of e.m.f., up to the plate, across from plate to cathode, and back to the negative terminal of the B supply of e.m.f.

26. Electric conductors: It is well known that certain materials like copper, silver, gold, brass, aluminum and other metals and certain solutions will readily permit the passage of electric current through them while other materials like rubber, Bakelite, porcelain, silk, cotton, etc. do not. The former are called *conductors* of electricity. The reason why metals are such good conductors is that their atoms apparently have such weak attraction for electrons that large numbers of them are either in practically a free state throughout the body of the metal, or else are capable of being shifted readily by any outside electric forces. The more easily the electrons can be shifted, in a given material, the better are the current conducting qualities of that material i.e., the lower is its *resistance* to current flow. Good conductors like copper, brass and aluminum are used extensively in the construction of radio receivers for wires, condenser plates, coil shields, etc.

The electrons in ordinary *metallic conductors* at ordinary temperatures are moving around at random from one atom to another. They have no definite direction, their directions at any instant being determined by the attractive forces of adjacent atoms having deficiencies of electrons. As soon as an e.m.f. is applied to the ends of the conductor the electrons may still continue their movements among the atoms but they also begin to move or drift in a more or less definite direction along the wire, urged on by the electromotive force. They move from the negative to the positive end of the conductor. This action may easily be likened to the condition existing in a slowly moving stream of water in which are thousands of tiny young fish darting to and fro between, and to, the larger fish. The larger fish (atoms) may keep themselves from travelling downstream, but while the tiny fish, (electrons), are darting to and fro in all directions, they are also drifting slowly in a definite direction downstream.

27. Electric insulators: Materials in which the atoms hold on to their electrons very strongly so that it is difficult to free any electrons and make them flow along in a definite direction, are known as *non-conductors* or *insulators*. There is no sharp distinction between conductors and insulators. Substances that for some cases would be regarded as fair insulators would in other cases be regarded as fair conductors.

For instance, the grid leak resistance employed with the ordinary detector tube in a radio receiver usually has a resistance of 2 million ohms. In radio work this is considered as offering a conducting path for the charges on the grid of the tube to leak off slowly, so it is a conducting path. In ordinary electrical work a body having a resistance of two million ohms would be considered a pretty good insulator.

Some substances which are good insulators at one temperature, become fairly good conductors when their temperature is raised. Glass acts like this. The resistance of carbon also decreases as the temperature is increased. We do not know of any perfect insulator. All practical insulators will allow some electrons to flow through them, (conduct some current) if e.m.f. is applied to them. The actual rate of current flow through a body having a given resistance and given e. m. f. applied to it can be calculated. This will be studied later. Thus a piece of Bakelite of certain dimensions, having a resistance of say ten million ohms will have flowing steadily through it a small current of .00001 (one-hundred-thousandth) ampere if an e. m. f. of 100 volts is applied to it. As this current is very small, we can say that a piece of Bakelite is a good insulator, since a medium amount of e. m. f. cannot make many electrons move through it. However, if 1,000,000 volts is applied to this same piece of Bakelite (provided it does not break down) a current of 0.1 ampere would flow through it and if we were particularly interested in employing this as an insulator to prevent leakage of current at this voltage, it might not be considered a good insulator under these conditions.

It is fortunate that certain substances do not conduct electricity freely and may therefore be used as insulators, for if this were not so, we would find it impossible to conduct electricity from one place to another through metallic conductors. If we did not have insulators, we would not be able to isolate one electric circuit from another.

The ohmic resistance which an insulating material offers to current flow or leakage through it is called the *resistivity* or *insulation resistance.* It is measured in ohms, and is usually expressed as the resistance of a cube of the material measuring 1 centimeter on each side, at a certain temperature. The following table shows the values of the volume-resistance of dielectric materials determined by tests at the Bureau of Standards.

RESISTIVITY OF SOLID DIELECTRIC MATERIALS

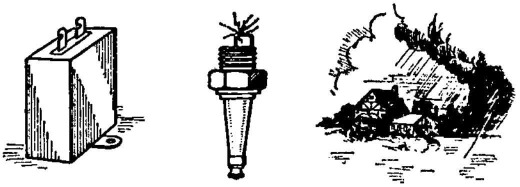
Resistivity of a centimeter cube at 22° Cent. or 71.6° Fahr. in billions of ohms (1,000,000,000 or 10^9)

Material	Resistivity
Bakelite	
No. 1	200
No. 150	4000
No. 190	100
No. L-558	20,000,000
micarta	50
Celluloid, white	20
Condensite	40
Fibre, hard	20
red	5
Glass, ordinary	90,000
plate	20,000
Lavite	20
Marble	
Italian	100
Tennessee	5
Vermont	1
Mica	
African, spotted black	40,000
African, brown clear	2,000,000
colorless.	200,000,000
India ruby, stained	50,000
India, slight stains	50,000,000
moulded	1,000,000
Porcelain, unglazed	300,000
Quartz, fused	5,000,000,000
Rosin	50,000,000
Rubber, hard	1,000,000,000
Shellac	10,000,000
Sulphur	100,000,000
Waxes	
beeswax, yellow	2,000,000
beeswax, white	6,000,000
ceresin (over)	5,000,000,000
halowax No. 1001	20,000
halowax No. 5055B	20,000,000
paraffin	50,000,000
parowax	10,000,000
sealing	8,000,000
Woods, paraffined	
mahogany	40,000
maple	30
poplar	500
walnut	10

Note: The surface resistivity of any material is lowered by humidity, and by the presence of moisture. For example, the surface resistivity of hard rubber which is 10^{16} ohms at a relative humidity of zero drops only to 10^{15} at a humidity of 60; but it then drops to 10^{12} at humidity of 80 and to 10^{9} at a humidity of 90.

28. Insulation breakdown: If a sufficiently high e. m. f. is applied to an insulating material, the electric forces acting on the free electrons in the material become very great. Under these forces the free electrons are speeded up to very high velocities, proportional to the forces acting on them. As this velocity becomes very high, the velocities acquired by the electrons in the short paths between collisions with molecules becomes greater and greater, and finally, at an intensity (voltage) which is fairly definite for any particular insulating material, the few free electrons acquire such high velocities that upon colliding with neutral molecular or atomic structures they tear away the more easily detached electrons, giving rise to a greatly increased number of free electrons. This destructive process rapidly increases the supply of free electrons and thus a conducting channel or path is formed through the insulating material. This intense destructive bombardment results in failure, *breakdown* or *puncture* of the insulating medium, during which condition the material fails to insulate. This breakdown is indicated by the formation of a brush discharge or by the passage of an electric spark. Upon breakdown, sufficient heat is produced to char a path through such insulating materials as wood, silk cotton, tape, Bakelite, etc. Materials like porcelain or glass will be cracked open, or a small channel will be melted through them due to the concentration of the energy. Fig. 21A illustrates three common instances of insulation breakdown.

This is what happens when the insulation on wires or the waxed paper or mica dielectric between the tinfoil sheets of fixed condensers



(a) (b) (c)

Fig. 21A—Three common instances of breakdown of insulation due to the application of sufficiently high voltage. (a) In a condenser due to breakdown of the dielectric between the plates; (b) in the spark gap of a spark plug, (here it is intentional); (c) lightning due to breakdown of the air insulation between charged clouds and the earth.

used in radio sets breaks down. Practically the same action takes place when a high voltage is applied between the spark gap points in an automobile spark plug, or when a lightning discharge takes place between two electrically charged clouds or between a cloud and the earth. The *breaking down* of insulating material should be distinguished from the simple current flow or *leakage* through it discussed in Article

27. The breakdown action makes the insulation worthless, thereafter, unless the insulating property can be healed or restored upon removal of the high e. m. f. as in the case of the air path in the spark plug, or between clouds, or in the oxide films formed in electrolytic condensers. In these cases the insulation is not permanently damaged.

29. Dielectric strength: The electric intensity at which an insulating material fails or breaks down is called the *dielectric strength* or *breakdown voltage* of the material. It is expressed in volts per centimeter length of conducting path in the insulator, or sometimes in "volts per inch." The breakdown voltages of a few of the common insulating materials are listed in the following table. The voltages are expressed as the number of volts required to pierce a given thickness of the material (.001 inch).

TABLE OF BREAKDOWN VOLTAGES

Material	Dielectric strength or Breakdown Voltage in volts per .001 inch thickness of material
Cotton (single covering)	260—340
Cotton (double covering)	210—240
Silk (single covering)	350—565
Silk (double covering)	320—420
Mica	2000—8000
Micanite (cloth)	175—310
Micanite (paper)	280—390
Paraffined paper	800—1000
Asbestos	60—100
Glass	150—300
Dry process porcelain	1000
Dry Manilla paper	110—320
Press board	200—330
Untreated pure para rubber	300—500
Air (dry)	50

The breakdown voltages are difficult to measure exactly, for they vary greatly with the particular samples tested and the conditions of test. The upper and lower limits of breakdown voltage which may be reasonably expected for the particular materials are given in the table above.

Dry air is a fairly good insulator, but its dielectric strength is not exactly directly proportional to the thickness of the layer. The values given in the table above, are useful in determining approximately how thick a certain insulating material must be made in order to safely stand a given voltage without breaking down, remembering that the thicker the insulator is, the higher is the voltage required to break it down. Thus if a piece of mica .001 inches thick can stand 2000 volts, a piece .003 inches thick can stand approximately 6000 volts. Of course a factor of safety must be allowed to take care of possible weak spots in the insulator, etc. Also, the properties of most insulating materials are very different when subjected to low frequency alternating current voltages than when subjected to high frequencies. A piece of insulating material capable of withstanding 100,000 volts at 60 cycles (commercial electric light frequency) may deteriorate and become conductive very rapidly when subjected to only 20,000 volts at 150,000 cycles per second (radio frequency current).

In radio transmitting and receiving equipment, porcelain, pyrex glass, and dry treated wood are used as insulators in the antenna system. In the station equipment, Bakelite, formica, hard rubber, mica, paraffin wax, bees-wax, cotton, silk, glass and treated papers and cloths are used extensively as insulators. Each one has its own particular properties such as hardness, flexibility, adaptability to molding, cheapness, thinness, etc., which make it best suited for use in a certain part of the equipment.

The common conducting materials used are copper, aluminum, brass, tungsten, tin-foil, etc., each being employed where it is most suitable.

REVIEW QUESTIONS

1. Why is it important for a student of radio to have a good knowledge of the fundamentals of electricity and magnetism?
2. The entire electron theory has never been proved to be correct by actual experiments. Why then, is it accepted as an explanation of the actions existing in all bodies?
3. If someone proved that a part of the electron theory was incorrect, would that make the entire theory useless? Why?
4. Why does a body become charged when it is rubbed?
5. Define in accordance with the electron theory, (a) a charged body. (b) a positively charged body. (c) a negatively charged body.
6. Describe a simple way of determining if a body is charged.
7. How would you determine if two charged bodies had like charges or unlike charges? State the rule upon which your method depends.
8. How did the words "electricity", "positive charge", "negative charge", "electron" originate?
9. What factors affect the force of attraction and repulsion between two charged bodies? State the quantitative relations.
10. Name three elements and six compounds. In each case give your reason for classifying the substance as an element or compound.
11. According to the electron theory, what is an atom of any material supposed to consist of? Draw a simple picture to illustrate your answer.
12. Why is it that electrons can flow or drift through iron which is apparently a hard, dense, solid substance?

13. A piece of copper wire contains negative charges (electrons) and positive charges (protons). Why doesn't every piece of copper then exhibit all the external properties or effects of a charged body?
14. A substance contains 20 protons and 4 electrons in the nucleus, with two additional planetary electrons in the first outer shell, eight electrons in the second outer shell, and six electrons in the third outer shell. Draw a picture of the internal arrangement of this atom. Will this substance be chemically active?
15. Of what does a current of electricity consist?
16. What is the difference between static electricity and a current of electricity? What similar features do they have?
17. What is necessary besides a conducting path in order to have a flow of electricity?
18. Describe in detail the flow of electricity in a wire connecting two oppositely charged bodies.
19. Make a diagram showing the conditions existing in question 18 and show on it the direction of both the electron flow and the current flow.
20. Name three sources of electromotive force.
21. Why is the direction of electric current flow according to popular usage, just opposite to the actual direction of the electron flow?
22. Explain why copper is a good conductor, and Bakelite is a very poor conductor of electricity.
23. Why is it that exchanges of electrons can take place between the atoms of a conductor, and electrons can move through the conductor, during the flow of electricity without any change of chemical composition of the material taking place?
24. Describe in detail, the actions taking place during the flow of current in a complete closed circuit consisting of a dry cell battery with a piece of copper wire connected across its terminals.
25. Draw a diagram to illustrate your answer to question 24, and mark on this the positive and negative terminals of the dry cell, and the direction of flow of both the electrons and the current.
26. Distinguish between (a) the resisting action of an insulating material to current leakage through it and (b) actual voltage breakdown of this material.
27. Equal thicknesses of the five following materials are simultaneously subjected to a gradually increasing voltage. In what order are they likely to break down: rubber, air, paraffined paper, glass, porcelain?

CHAPTER 4.

ELECTRICAL UNITS, OHM'S LAW.

NEED FOR UNITS — QUANTITY OF CURRENT (COULOMB) — RATE OF CURRENT FLOW (AMPERE) — MILLIAMPERE, MICRO AMPERES — E. M. F. (THE VOLT) KILOVOLT, MILLIVOLT — RESISTANCE (THE OHM) — MICROHM, MEGOHM CONDUCTANCE, THE MHO — ABSOLUTE AND INTERNATIONAL UNITS — OHM'S LAW — VOLTAGE DROP, FALL OF POTENTIAL — ELECTRICAL POWER — E. M. F., RESISTANCE, CURRENT — LENGTH, AREA, MATERIAL AND RESISTANCE — WIRE GAUGES — CIRCULAR MEASURE — TEMPERATURE AND RESISTANCE — RESISTORS IN RADIO EQUIPMENT — WATTS DISSIPATION — REVIEW QUESTIONS.

30. Need for units: We have now reached a point in our study of electricity where it is necessary to establish definite units and relations to express electric current flow, e. m. f. and resistance quantitatively. In our everyday lives we are accustomed to using common units and their subdivisions to express lengths, time, forces, etc. Thus the foot, meter, etc., are employed to measure and express lengths or distances; the second, minute, hour, etc., are used to express intervals of time. In electrical work also, certain units of current, e. m. f. and resistance are in common use. Furthermore these units have been adopted as standard by the many countries of the world so that an ampere, for instance, in the United States represents exactly the same rate of current flow as an ampere in Australia, England, Germany, etc. Also the units used by the electrical worker or electrician are the same as those employed in radio work. This standardization of units is of course absolutely essential to a simplified electrical practice. In the early days of the electrical art, before the electron theory was known, several systems of units were proposed and used in different countries. This led to confusion. At the present time the International Units have become standard in all of the civilized countries of the world.

31. Quantity of current (coulomb): It was explained in Chapter 3 that an electric current flowing through a conducting circuit really consists of a large number of tiny electrons moving rapidly in complex paths from atom to atom, but at the same time flowing or drifting through the conductor. Since these electrons are tiny negative charges, it follows that an electric current really consists of the motion of a large number of tiny electric charges, through the circuit, so that a measure of the *quantity* of current really resolves itself into a measurement of the quantity of electric charges. We cannot feel, see, smell, or hear these tiny electric charges and therefore cannot count or measure them by any of our senses. Also we cannot measure an electric charge by any of our common standards of measurement such as length, weight, etc. However, we can measure a charge by measuring the force of attraction or repulsion which will always exist between it and some other charge. Since the force of attraction or repulsion depends not only on the strengths of the charges themselves, but also on the material and the distance between them, these factors must also be considered when defining our units.

A very natural method of procedure in establishing a unit of electric charge would be to specify a standard medium and distance between the charges and the force acting between two unit charges under these conditions. Thus the original *Electrostatic* unit of quantity of electricity was defined as "that quantity with which a very small body must be charged so that when placed in a standard medium at a distance of one centimeter (2.54 centimeters equal one inch) from a similar body charged with an equal quantity, a force of repulsion of one dyne (1 lb.= 444,827 dynes approximately) will exist between the two." This was the unit of quantity in the *electrostatic system of units*, evacuated space (a vacuum) being selected as the standard medium. This condition is represented graphically in Fig. 22. However, this unit and the associated units for e. m. f. and resistance were later found to be entirely too small for conveniently measuring and expressing the quantities of electricity, e. m. f., and resistance dealt with in the applications of practical batteries and generators and in practical electrical devices. For instance, the quantity of electricity flowing through a 100 watt, 110 volt incandescent lamp every second is about 2,700,000,000 electrostatic units.

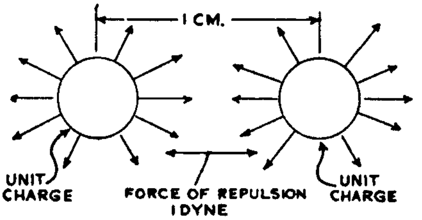


Fig. 22. — Conditions specified for unit quantity of electricity in the original electrostatic system of units.

As it was found inconvenient and unwieldly to use the large numbers necessary to express in this system of units the values of quantities of electricity dealt with in practice, the so-called *practical units* were defined to be certain multiples of these original units. The practical units are those in common use today. The fundamental unit of quantity of electricity in the practical system is the *Coulomb*, (named after Charles A. Coulomb, the celebrated French Physicist). The *Coulomb* is approximately 3,000,000,000 (3×10^9) times as large as the electrostatic unit defined above.

We may define the *Coulomb* as that quantity of electrical charge with which a very small body must be charged so that, when placed in a vacuum at a distance of one centimeter from a similar body charged with an equal quantity of electricity, it will repel that body with a force of approximately $(3\times10^9)^2$ dynes (since the force is proportional to the product of the strengths of the charges, as explained in Art. 13).

The coulomb represents a definite *quantity* or *amount* of electrical charge, just as a gallon of water represents a definite quantity of water as represented in (A) of Fig. 23. It is independent of all other units. Since the electron theory has come into use it has been estimated that since each electron contains a definite quantity of electricity a coulomb is the total amount of charge contained by 6.28×10^{18} electrons (6,280,000,000,000,000,000 electrons).

32. Rate of current flow (ampere): In the cases of storage of electric charges as in the charging of condensers, or charges at rest as in static electricity, we are interested in the bulk or quantity of electricity or charge stored. The coulomb is useful in expressing this. In the case of current flow through wires and other conductors, we are not usually much interested in the total quantity of electricity flowing through the circuit, (coulombs), for this does not take into account the time during which the electricity flows All of the effects of electric current (heating, chemical, magnetic, etc.) with which we commonly deal, depend for their intensity on the *rate* at which current flows through the conductor. For instance, 100 coulombs of current might flow through a wire in one hour. This would produce a certain total quantity of heat in the wire during that time. During the hour the wire would have plenty of time to lose this heat by radiation, etc. If the 100 coulombs were sent through the wire quickly, say in one second, the same total quantity of heat would be produced, but since it is now all produced in one second, it heats the wire up to a higher temperature. Thus the intensity of the heating effect in the wire depends on the *rate* of current flow rather than on the total quantity of current flowing through it. It is more important then for us to know the *rate* of *current flow.*

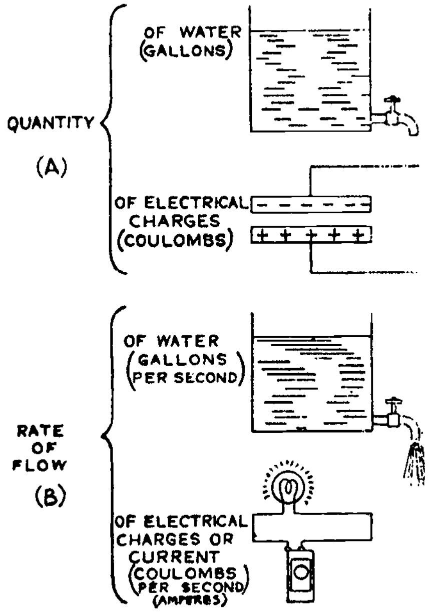


Fig. 23.—Analogous units of quantity and rate of flow for water and electrical charges.

Instead of expressing the rate of current flow as so many coulombs per second it is convenient to use a separate short term. The name *ampere* has been adopted in honor of the famous French scientist André Marie Ampere, to represent the practical unit of rate of flow of electricity. The current flowing past any given point in a circuit is one "ampere" (commonly abbreviated as "amp.") when electricity passes through at the net rate of one coulomb per second. (This is analogous to the term "gallons per second" when expressing the rate of flow of water, as shown in (B) of Fig. 23.)

Since one coulomb equals 6.28×10^{18} electrons, when a current of 1 ampere is flowing through a circuit, 6.28×10^{18} electrons are drifting past any given point in the circuit every second. It can be seen from this that in our common electrical circuits carrying tens, hundreds, and

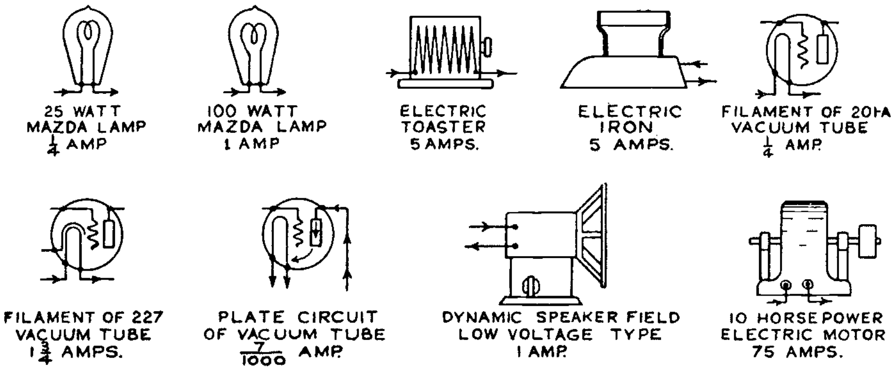


Fig. 24.—Rates of current flow through common electrical devices.

thousands of amperes of current, billions and billions of electrons are circulating through the conductor every second.

33. Milliampere, microampere: For measuring very small electric currents, (for instance the plate current in a vacuum tube) it is convenient to use a smaller unit than the ampere. In this case the *milliampere* is employed. Milli is French for $\frac{1}{1000}$. Therefore, 1 milliampere is .001 ampere. Conversely, one ampere equals 1,000 milliamperes. (See Appendix C on page 942.)

A still smaller unit sometimes used is the *microampere*. This is $\frac{1}{1,000,000}$ ampere; or 1,000,000 microamperes equal one ampere.

The student may perhaps gain some idea of just how much an ampere of current is by studying Fig. 24. Here several common electrical devices are represented together with the rate of current flow in amperes required for their proper operation. Some devices take currents considerably less than one ampere, some take currents of many amperes. In radio receiving equipment most of the parts are carrying rather weak currents. Meters have been developed for measuring the rate of flow of electric current. They are called ammeters, milliammeters or microammeters, depending upon the strength of the currents they are designed to measure. Their construction and operation will be studied later.

34. E. M. F. (the volt): During our study of the electron theory we found that the free electrons could be made to drift in a definite direction along a conductor by applying an external electric force which we call "electromotive force", (abbreviated to e. m. f.). This electrical force or pressure exists between any two bodies that have a different intensity of charge or a different polarity of charge. It is sometimes called "potential difference."

Electromotive force may be developed or generated in several ways in practice. Common sources of e. m. f. are, primary cells or batteries, storage batteries on discharge, electric dynamos, etc. These devices produce a continuous difference of electric potential or pressure between their terminals. If a complete conducting path is provided. this difference of electric potential will cause a flow of electrons, or electric current. The practical unit of electromotive force is the *volt.*

When a coulomb of electricity is transferred between two points by an expenditure of one joule of energy (10^7 ergs) the points are said to differ in electrical potential by one volt.

Because of the term *volt* the e. m. f. or source of electric potential is often referred to as "voltage".

The e. m. f. developed by a single dry cell is 1½volts. That developed by the three cells of a lead-acid storage battery on discharge is slightly over 6 volts. Incandescent lamps are usually operated from 110 volt sources of e. m. f. The filaments in the 201-A, 171-A, and 112-A tubes are designed to operate on 5 volts. Those of the 224 and 227 tubes require 2.5 volts. The plate voltage employed on radio receiving tubes varies from 45 to 450 volts, depending on the type of tube. The e. m. f. of a standard B battery is 45 volts. Voltages as high as 2,000 are employed on electrical transmission lines. Thus it is seen that a large range of voltages is employed for various devices.

35. Kilovolt, millivolt: Sometimes it is more convenient to use larger or smaller units of electric potential than the volt. In such cases the kilovolt (equal to 1,000 volts), the millivolt, (equal to $\frac{1}{1,000}$ volt), and the microvolt (equal to $\frac{1}{1,000,000}$ volt), are used. For instance, 5,000 volts=5 kilovolts; .003 volts=3 millivolts; .00005 volts= 50 microvolts.

Measuring instruments called *voltmeters* have been devised for indicating directly in volts, the values of e. m. f. Where the e. m. f. is small, (few thousandths of a volt), a *millivoltmeter* is used. This will be studied later.

36. Resistance, (the ohm): All conductors of electricity oppose the flow of current through them, that is, they have electrical *resistance.* The unit of resistance is called the *Ohm* in honor of George Simon Ohm, a German mathematician.

A conductor has a resistance of one ohm if the ratio of the applied e. m. f. in volts to the current flowing through it in amperes is unity. That is, an ohm is the resistance through which an e. m. f. of one volt will send a current of one ampere (6.28×10^{18} electrons per second). The common symbol for resistance is "R". "ohm" is sometimes represented by the symbol "Ω" (the Greek letter Omega). Thus 5 ohms may be written 5Ω. This representation has been standardized by the Radio Manufacturers Association (R.M.A.) for use in radio work.

The resistance of a body varies with its length, sectional area and material. Further consideration of the laws of resistance will be studied later.

37. Microhm, megohm: The resistance in a conducting path is usually kept as low as possible. Resistors however, are often employed to control the amount of current flowing in a circuit, to produce heat, etc. It often happens that very small resistances are to be considered, for which the ohm is an inconveniently large unit. Therefore to facilitate calculations and recording, a smaller unit, the *microhm* is often used. A microhm is equal to one millionth, $\left(\frac{1}{1,000,000}\right)$, of an ohm. For example, .00031 ohms equals $.00031 \times 1,000,000 = 310$ microhms. Also, 4500 microhms equals $4500 \div 1,000,000 = 0045$ ohms.

Where large resistances are dealt with, the megohm is employed. (often abbreviated Meg. or represented by the symbol MΩ). One megohm equals 1,000,000 ohms. (see appendix) Thus a 5 megohm grid leak has a resistance of $5 \times 1,000,000 = 5,000,000$ ohms. Also, 30,000 ohms equals $30,000 \div 1,000,000$, equals .03 megohms or .03 MΩ.

Note: Authorities differ in their use of the symbols ω and Ω. The American Institute of Electrical Engineers, in their March, 1928, Proceedings, propose a complete group of electrical symbols in which the ohm is shown as Ω, and the megohm as ω. Prominent electrical corporations such as the Bell System and allied organizations use the letter ω exclusively for ohms, and of the various diagrams in a large number of publications which have been scrutinized, about half of them use ω as the symbol for ohms, and the other half use the letter Ω. To prevent confusion, we are identifying all resistances in this book with the word "ohms" spelled out. In the diagrams the letter Ω is used for ohms and MΩ for megohms.

38. Conductance (the mho): In some calculations and considerations of electric circuits it is convenient to consider not the resistance of a circuit, but its *conductance.* The conductance of a circuit is numerally expressed by taking the reciprocal of its resistance, $\frac{1}{R}$, and expressing it in *mhos.* (Mho is ohm spelled backward.) Thus if the resistance of the filament of a vacuum tube is 20 ohms, its conductance is $\frac{1}{20}$ or .05 mhos.

39. Absolute and international units: The units of current, e. m. f. and resistance (ampere, volt, ohm) have been derived entirely through consideration of the unit quantity of electrical charge. This system of units may be called the *electrostatically derived practical system.*

Because of the difficulty in precisely standardizing or calibrating electrical instruments such as ammeters and voltmeters in terms of the fundamental units by absolute methods, the International Electrical Congress at Paris in 1881 recommended that a commission be charged with formulating from the results of carefully made absolute measurements, specifications for practical standards to represent certain units of the practical system. These standards could then be constructed by anyone at any place and they would serve as exact references. This commission drew up specifications for practical physical standards of electric current, and resistance. These are known as the *International Standards* and the units derived from them are known as the *International Units.* By legislative actions of the various governments these International Standards have been made the legal standards of all the civilized governments of the world. The physical specifications for the International Standards as drawn up by this commission follow:

The International Ampere is the unvarying current, which, when passed through a solution of nitrate of silver in water in accordance with standard specifications, deposits silver at the rate of 0.001118 grams per second.

The International Ohm is the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice (0° C), 14.4521 grams in mass, of a constant cross-sectional area, and having a length of 106.300 centimeters.

The volt is the e. m. f. which will send a current of one ampere through a resistance of one ohm. Notice that this is defined in terms of the ampere and ohm.

While the International Standards were intended to represent in a practical form certain of the units of the Electrostatically Derived Practical System, they fail to do this precisely. Later absolute measurements carried on by the National Standardizing Bureau indicates that the greatest discrepancy is about 0.05 of one per cent. For all industrial purposes, this discrepancy is negligibly small, and these standards may be taken as being correct.

40. Ohm's law: When thinking about the flow of electrons in a conductor it must be evident that the greater the e. m. f. is, the more electrons will flow past any point in the conductor each second. Also the greater the resistance of the conductor the less the number of electrons which will flow through. Dr. George Simon Ohm found that there was a definite simple mathematical relationship between the e. m. f. applied to a conducting circuit having a certain resistance, and the current which would flow in the circuit. This relationship is now known as *Ohm's Law*. The law is stated thus: *The intensity of current in any circuit is equal to the electromotive force divided by the resistance of the circuit.*

Expressed in the common electrical abbreviations this law becomes:

$$I=\frac{E}{R} \quad \text{.................................} \quad (1)$$

where I=current in amperes.
E=e. m. f. in volts.
R=resistance in ohms.

Equation (1) enables us to calculate the current (I) which will flow when an e. m. f. (E) is applied to a circuit having a resistance (R).

Example: What current will flow through the filament of a 201-A vacuum tube having a resistance of 20 ohms, when an e. m. f. of 5 volts is applied?

Solution: The current in a circuit may be calculated by Ohm's Law using the equation $I=\frac{E}{R}$. By substituting 5 for E and 20 for R we obtain $I=\frac{5}{20}=\frac{1}{4}=0.25$ Amp. Ans.

To find how much pressure or e. m. f. must be applied to a circuit to make a given current flow through a conductor having a known resistance, equation (1) can be put in more convenient form by simple mathematical transformation.

$$\text{Thus since } I=\frac{E}{R}, \text{ then } E=I\times R \quad \text{.................................} \quad (2)$$

Example: The resistance of the filament of a 201-A vacuum tube is 20 ohms, and it requires 0.25 amperes for proper operation. What e. m. f. should be applied to obtain the correct operating current?

Solution: E=I x R. Since I=0.25 amp, and R=20 ohms, the E=0.25 x 20=5 volts. Ans.

When the e. m. f. (E) and the current (I) are known, the resistance R of the circuit may be calculated very easily by placing equation (1) in more convenient form

$$\text{Thus since } I=\frac{E}{R}, \text{ then } R=\frac{E}{I} \quad \text{.................................} \quad (3)$$

Example: An e. m. f. of 5 volts applied to the filament of a 201-A vacuum tube sends a current of 0.25 amperes through it. Calculate the resistance of the filament.

Solution: $R=\frac{E}{I}=\frac{5}{0.25}=20$ ohms. Ans.

Ohm's Law is one of the most useful and important principles in all radio and electrical work and the student should study it carefully and commit it to memory. While it applies only to direct current circuits, a special form of this law is also used in alternating current work. The student should remember when using Ohm's Law that the current

(I) should be expressed in *amperes*. So many current values in radio work are expressed in *milliamperes*, that one often forgets and uses milliamperes in the formula. This results in incorrect answers.

41. Voltage drop—fall of potential: Current can flow in a circuit only as a result of the application of electromotive force. Whenever a current flows through a resistance there must be a difference of electrical potential (p. d.) or pressure between the ends of that resistance tending to make the current (electrons) flow through it. This difference of potential is equal to the product of the current in amperes times the resistance in ohms. In practice, when a source of e. m. f. is applied to a circuit containing resistances, the part of the e. m. f. used up in sending the current through each resistance is called the *"voltage drop"* or *"fall of potential"* through that resistance. Both of these expressions are commonly used. In some devices the voltage drop occuring in resistance is made use of to reduce voltages which may be too high, as in the case of filament circuit and plate circuit resistors in vacuum tubes shown in (A) and (B) of Fig. 25. In other cases the current is made to flow through a resistance purposely in order to create a difference of potential for some definite use as in the case of C bias resistors in electric radio receivers, shown in (C) of Fig. 25. As the current flows from A to B through the resistance, there is a fall of potential from A to B. Therefore point B is at a lower potential than point A. That is, B is negative with respect to A. In other cases, the voltage drop in resistors is harmful, and is kept low by keeping the resistance of the circuit as low as possible. It is the *pressure* and not the current that is used up in maintaining a flow of electricity (electrons) through a circuit.

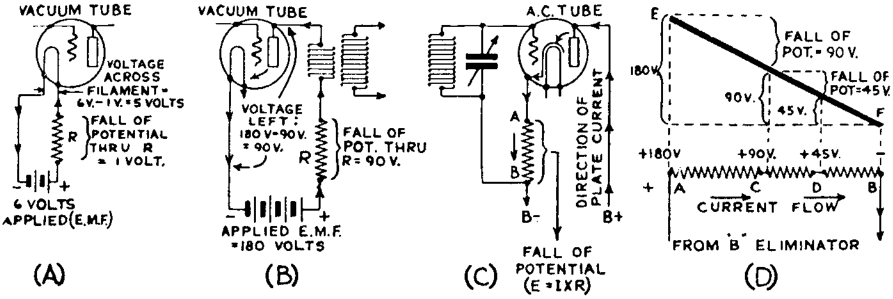


Fig. 25.—Examples of fall of potential along a resistance.

The end to which the current flows is at a lower electrical potential (—) than the end from which it flows (+). This condition is shown in (D) of Fig. 25 which represents an output divider resistance employed in B power packs used in electric radio receivers. This is made up of several resistors connected as shown, or else a single resistor with taps taken off the resistance wire at various places. The current flows out of the B power pack at A, and back into the negative terminal at B. Thus A is the positive terminal (point of highest potential). We will assume that all of the current flows down through the resistance from A to B. There will be a fall of potential from A to C equal to the resistance in ohms from A to C multiplied by the current in amperes flowing through ($E=I\times R$). Point C is at a lower electric potential than point A by this amount. Similarly point D is at a lower potential than C by an amount equal to the fall of potential from C to D ($I\times R$). Point B is at a lower potential than point D by an amount equal to the resistance B multiplied by the current flowing through it. We will assume that the resistances have been so chosen that the potentials at these points are as indicated in the diagram, i.e., 180, 90 and 45 volts. The fall of potential along the resistance may be indicated graphically by the sloping line EF whose vertical height above the horizontal axis line at any point indicates the potential at that point. Notice how the electrical potential decreases as we go from end A to end B of the resistance.

The fall of potential through a resistance may be looked upon somewhat similarly to the case of the fall or drop in pressure of water flowing through a pipe. The friction between the individual molecules of water and between the water and the inside surface of the pipe causes a gradual loss of pressure along the pipe.

42. Electrical power: Electricity flowing through a conductor is really a source of power because it can be made to do work if it is made to flow through suitable apparatus. A familiar application of this is in the use of electricity to drive electric motors of all kinds. Power is the rate of doing work. In considering power, we consider not only the amount of work done but also the length of time during which it is done, that is, the *time rate*. It requires more power to do a certain amount of work in a short interval of time than in a longer time.

The unit of electric power is the *watt*. The watt is the power in a circuit in which one ampere is flowing under a pressure of one volt. The number of watts in a circuit is equal to the volts multiplied by the amperes.

$$W=E\times I \qquad (4)$$

Thus, the filament of a 224 type vacuum tube has flowing through it 1.75 ampere under a pressure of 2.5 volts in order to heat it to a red heat. The filament is therefore using electric power at the rate of $2.5\times 1.75=4.37$ watts.

The watt is a rather small unit of electrical power for use in practical work. The *kilowatt*, (K. W.), equaling 1,000 watts, is used when expressing larger amounts of power. To change watts to kilowatts, divide by 1,000. To change kilowatts to watts, multiply by 1,000. 746 watts, (or nearly ¾ kilowatt), equal one horsepower. These relations are useful to remember.

Equation (4) enables us to calculate the watts if the voltage and current are known. There are two other convenient forms of this power equation which can be easily derived from this one. These enable us to calculate the electric power used up in sending current through a resistance. The electric power used up in this manner is converted into heat. The ordinary incandescent lamp filament or vacuum tube filament are common illustrations of the practical application of this. Current sent through the filament against its resistance, produces enough heat to raise the temperature of the filament to a point where it gives off light. The heat is produced by the collision of the moving free electrons with the many atoms in their path. The energy of the moving electrons is thus converted into heat energy which raises the temperature of the conductor. The heating effect of electric current is also made use of in the electric stove, electric iron, electric furnace, etc.

From Ohm's law (equation (1) we have $I=\frac{E}{R}$

Substituting this value of I, for I in the power equation (4), we obtain:

$$W=E\times I=E\times\frac{E}{R}=\frac{E^2}{R} \qquad (5)$$

This gives an expression for the electrical power in terms of the voltage and resistance.

From equation (2) we have $E=I\times R$.

Substituting this value of E, for E in the power equation (4), we obtain:

$$W=E\times I=I\times R\times I=I^2R \qquad (6)$$

Examination of this last equation shows that in a circuit in which the resistance is kept constant, the electric power consumed in forcing current through it is proportional to the square of the current. For instance if we consider the filament of a 201-A type vacuum tube again, its resistance is 20 ohms. Its normal current is 0.25 amperes. This heats the filament to a dull red heat. If now, we triple the voltage applied to this same filament, the current flowing through it becomes 3 times as great (Ohm's law). Therefore, the heat produced is 3 × 3, or "nine" times as much (varies as the *square* of the current). This of course would raise the temperature above the melting point of the filament wire, and it would melt.

The electrical power can be measured by measuring the current with an ammeter and the voltage with a voltmeter. The amperes and volts are then multiplied together to obtain the watts. The wattmeter is an electrical instrument for measuring the watts directly.

43. Relation of e. m. f., resistance and current: In every branch of electrical and radio work it is very important to have a clear understanding of the relation between e. m. f., resistance and current. The student must learn to look at any electric circuit as a combination of three factors. First, we have the e. m. f. which is able to cause a flow of current (electrons) if a conducting path is provided. Second, we have the conducting path, which offers a certain amount of resistance or opposition to the flow of current (electrons), depending entirely upon its material, length, cross section area, and temperature. Third, we have the resulting flow of current, whose value depends upon the applied voltage and the resistance of the conducting path. Note that the resistance of the path really is independent of the voltage and the current. The resistance really depends upon the *physical* characteristics of the conducting circuit, i.e., the material, the length, the area and the temperature. The current is the result of the application of the e. m. f. to the conducting circuit. The current depends upon the applied e. m. f. and the resistance. The e. m. f. depends on the amount

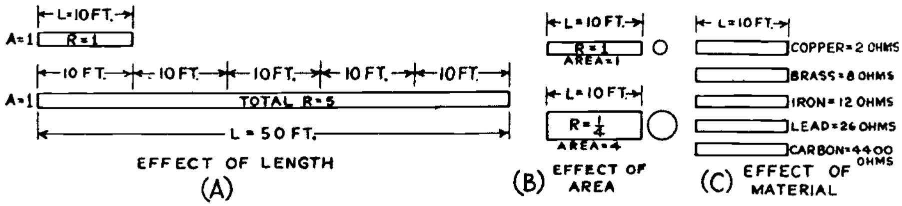


Fig. 26.—Illustrating how resistance depends upon the length, area and material.

of e. m. f. which is provided by the e. m. f. generating or producing device (battery, dynamo, etc.) applied to the circuit.

It has been stated several times that the resistance of any conductor depends upon its length, cross-section area, material and temperature. We will now study these factors in detail.

44. Length and resistance: Just as a long pipe offers a greater resistance to the flow of water than a short one, so a long electrical conductor has a greater resistance than a short one. The resistance is *proportional* to the length. Thus a wire 50 feet long has five times the resistance of a similar wire ten feet long. This becomes evident when we realize that every 10 foot section of the 50 foot wire offers the same opposition (resistance) to the flow of electrons through it as the original 10 foot piece of wire does. Therefore the total resistance of the 50 foot piece is 5 times as much. This is shown in (A) of Fig. 26. We may then state the rule:

The resistance of a conductor is directly proportional to its length.

45. Area and resistance: Just as the internal diameter or cross-section area of a water pipe determines how much water can flow through it, so the cross-sectional area of a conductor determines its resistance to the flow of current (see (B) of Fig. 26). The larger the diameter or cross section area, the less will be its resistance. *Thus, the resistance of a conductor is inversely proportional to its cross-sectional area.* The areas of two similar circular conductors are proportional to the squares of their diameters. Hence the resistances of two wires of similar material and length are inversely proportional to their diameters squared. The larger the cross section area of the wire, the more electrons there are available to flow past any point every second under the influence of a given applied e. m. f. Therefore the resistance to the electron flow must be less.

46. Wire gauges: The standards by which the various sizes of wire are designated are called *wire gauges.* Unfortunately several standards of wire gauges differing from each other have been adopted by various manufacturers and are in use.

In each gauge, a particular number refers to a wire having a certain diameter, the gauge number *increasing* as the size of the wire *decreases.* The law by which this decrease occurs is not the same in the different gauges. In the United States, copper wire is usually designated by the Brown and Sharpe (sometimes called American) wire gauge. This is generally termed B. & S. G. or A. W. G. (*Note*: the common B. & S. wire gauge sizes together with the corresponding diameters and resistances of the wire will be found in the Copper Wire Table in Fig. 288 of Article 402, and in the Bare Copper Wire Table in Appendix F.) In the B. & S. gauge, the ratio of the *areas* for two successive gauge numbers is 1.26. The diameter of a wire may be measured accurately with a micrometer.

47. Circular measure: When calculating the resistance of round wires for electrical purposes, it is convenient to use a *circular* measure to express the cross-section area of the wire, rather than the old method of measuring the area of circles in square inches. A *mil* is a unit of length used in measuring the diameter of wires, and is equal to $\frac{1}{1,000}$ inch; that is, 1 mil equals .001 inch.

The circular mil area of a wire is equal to its diameter in mils squared. For instance, No. 36 wire is .005 inches in diameter, that is, it has a diameter of 5 mils (see wire table Fig. 288 on page 591, or the one on page 948). Its circular mil area is therefore $5 \times 5 = 25$ circular mils.

48. Material and resistance: It must be evident from our study of the electron theory, that since all materials have a different electron arrangement, the ease with which the free electrons can be made to drift along through the material (flow of current) by the application of an e. m. f., must vary with the different materials. That is, *different materials offer a different amount of resistance to the flow of current (electrons) through them.* In order to compare the resistance offered by different materials, some standard sample of unit dimensions must be considered, since the resistance depends not only on the material, but on the cross-section area and length also. In practical work, it is common to consider a piece of the material having a unit cross-sectional area of one circular mil, and a unit length of one foot.

"The resistance of a piece of a material having a cross-section area of one circular mil and a length of one foot, is called the "specific resistance" of that material."

This unit size is commonly referred to as a "mil-foot". As we shall soon see, the "specific resistance" is the basis of formula (7) which enables us to calculate the resistance of any object if its material, area and length are known.

The fact that copper has a low specific resistance (see table of specific resistances) and is rather cheap, makes it used more than any metal in electrical work. Aluminum is also a good conductor, but its specific resistance is higher than that of copper. However, it is lighter in weight and where this factor must be considered, it is used. Part (C) of Fig. 26 shows graphically the resistances of five wires of similar dimensions, but made of different materials.

The values of specific resistance (k) in ohms per circular mil-foot for several common conducting metals and special resistance alloys are listed below. Notice that silver has the lowest resistance, and copper has but a slight bit more. The lower cost of copper makes it used for electrical conductors instead of silver. Notice that the specially manufactured high resistance alloys such as "Climax", "Excello" and "Nichrome" have from 30 to 60 times as much resistance as copper wire. These are employed especially to purposely place resistance in a circuit. German silver is an alloy of copper, nickel and zinc. The per cent stated in the table below indicates the percentage of nickel in the alloy.

If the specific resistance (k), in ohms per mil-foot, of a material is known, it is very easy to calculate the resistance of a wire of that material by multiplying the specific resistance (k) by the length (L) of the wire in feet, and dividing by the area (C.M.) of the wire in circular mils. The formula is:

$$R=\frac{k\,L}{C.M.} \qquad (7)$$

Note: See Bare Copper Wire Table (Appendix F) for cross-section areas of round wires.

Specific Resistance in Ohms per Circular Mil-Foot at 20° C.

Copper (annealed)	10.35	Lead	132.35
Copper (hard drawn)	10.60	Manganin	264.
"Advance" (alloy)	294.	Mercury	576.
Aluminum	17.	Molybdenum (drawn)	34.
Brass	42.	Monel metal (alloy)	252.
Carbon (coke, lampblack)	22,000.	Nichrome (alloy)	675.
"Climax" (alloy)	480.	Nickel	60.
"Constantin" (alloy)	294.	Platinum	60.
Excello (alloy)	552.	Silver	9.56
German Silver (18%)	198.	Steel (soft, carbon)	96.
German Silver (30%)	294.	Steel (cast)	115.
(Constantin)		Steel (transformer)	66.
Gold	14.6	Tantalum	93.
Graphite	4,300.	Therlo (alloy)	282.
Iron (pure, annealed)	61.	Tin	69.
Iron (Cast)	435.	Tungsten (drawn)	34.
Ia Ia, hard (alloy)	300.	Zinc	35.

49. Temperature and resistance: Since the temperature of a conductor may be greatly changed by its surroundings or by the heat developed in the wire itself due to the passage of current through it, the temperature must be taken into account when calculating the resistance if accurate results are desired. The resistance of pure metals and most alloys *increases* as the temperature *rises*. The resistance of carbon and electrolytes (fluid conductors) decreases as their temperature rises. The amount of change of resistance varies with the different conductors, but for *pure metals* the increase in resistance is nearly 0.4% for each change of one degree Centigrade.

Manganin is an alloy of 84% copper, 12% nickel and 4% manganese, developed especially for use in the shunts of ammeters and for precision resistances. Therlo is a similar alloy. Their change in resistance per degree is only one part in 100,000. "Constantin" is another alloy whose resistance does not change materially. It consists of approximately 60

Courtesy Ward Leonard Elect. Co.

Fig. 27.—Stages of manufacture, and construction of vitrified fixed resistance unit from the bare porcelain tube at the left to the completely vitrified resistor at the right.

per cent copper and 40 per cent nickel. It is used in rheostats and measuring instruments.

The amount in *ohms*, that a piece of the material having a resistance of *one ohm* changes for each change of one degree in temperature is known as the *temperature coefficient of resistance* ("a"). Thus if a conductor has a resistance of one ohm at 20° C. temperature, at 21° C. it will have a resistance of one ohm plus the amount equal to this coefficient. At 19° C. it would have a resistance of one ohm minus the coefficient, etc. Values of the temperature coefficients of various metals and alloys are given in the Table of Properties of Metals in Appendix G.

The *average temperature coefficient* between 0° and 100° C. (32° to 212° F.) is roughly the same for all *pure* metals (not alloys). It is about .004 per degree Centigrade, or .0023 per degree Fahrenheit (since one degree C. represents a larger change in temperature than one degree F.).

The temperature coefficient for annealed copper is 0.00218 at an initial temperature of 68° F. (on the Fahrenheit scale), or 0.00393 at an initial temperature of 20 C. (on the Centigrade scale). The value of the temperature coefficients of the various resistance alloys used in radio work for winding fixed or variable resistors must be obtained from the manufacturers of the resistance wire, in any case when exact calculations are to be made.

Since the specific resistance of the conducting materials is usually given for the material at the standard temperature of 20° C., formula (7) must be altered if we are to take into account the change of resistance caused by the fact that the conductor may be operating at a temperature above or below 20° C. in actual practice. To calculate the true exact resistance of any metallic conductor at any temperature (up to 100° C.) use the formula:

$$R=\frac{k\,L}{C.\,M.}\left[1 \pm (a\times t)\right] \quad \text{(8)}$$

where R=resistance of the conductor in ohms at operating temperature.
k=specific resistance of the conductor at 20° C.
L=length of conductor in feet.
C.M.=cross section area of conductor in circular mils.
a=temperature coefficient of the material per degree C.
t=difference in degrees between the operating temperature and the standard temperature at which the specific resistance k is specified (20° C. in most cases).

The ± sign inside the bracket means that if the temperature of the conductor is above the standard of 20° C., the resistance increases, so the *plus* sign is used. If the temperature is below 20° C., the resistance is less and the minus sign is used. (For carbon and liquids, the reverse is true.)

Example: A piece of No. 18 B. & S. gauge copper wire 600 feet long is wound up to form a circular field coil for an electro-dynamic loud speaker. When the normal current flows through the coil its temperature rises to 60° C. What is the exact resistance of the coil during normal operation?

Solution: From the Copper Wire Table we find that a No. 18 wire has a cross-section area of 1624 circular mils. The specific resistance of annealed copper is 10.35 at 20° C. Its temperature coefficient is 0.00393 per degree C. t in formula (8) is therefore equal to 60—20=40 degrees. Substituting these values in formula (8) we obtain

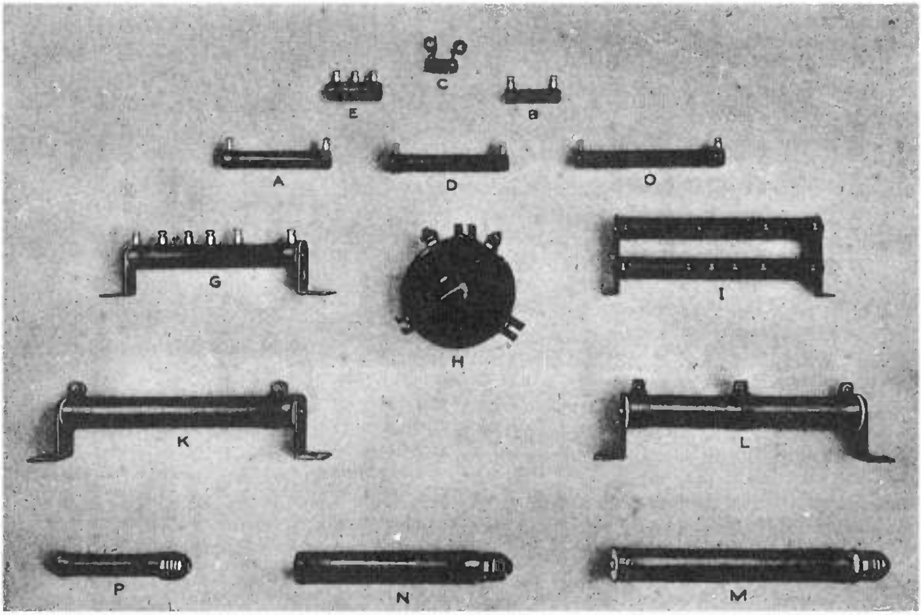
$$R=\frac{k\,L}{C.\,M.}\left[1\pm (a \times t)\right]=\frac{10.35 \times 600}{1624}\left[1+(.00393\times 40)\right]$$

from which R=4.42 ohms. Ans.

50. Resistors in radio equipment: There is naturally a certain amount of resistance in every electrical circuit due to the resistance of the connecting wires, joints, contacts, etc. The resistance of a circuit can be kept low by making it as short as possible, using a good electrical conductor (such as copper), and making its cross-section area large. (Due to the fact that very high frequency currents travel only through a thin surface layer of the wire (*"skin effect"*), wires for conducting this type of current are often made up of a number of very small conductors insulated from each other by an enamel, cotton or silk covering. This is called Litzendraht wire. See Art. 406.)

In radio equipment, resistance is purposely introduced at various places in the circuits in order to reduce or control the amount of current flowing, reduce the effective voltage applied to a device, or cause differences of potential which are utilized for some definite purpose (C bias resistors), etc. A *resistor* is a device whose purpose is to intentionally provide resistance in an electrical circuit. Resistors may be made either fixed or adjustable (variable). *Fixed* resistors are those whose value cannot be changed readily while in use. *Adjustable* resistors may be varied in value. Fixed resistors are used in the filament circuits of battery operated vacuum tubes, in the voltage dividers of B power units, for leaks, resistance couplings, for furnishing grid or C bias voltages, etc. Variable resistances are not used as much in radio receivers nowadays as they formerly were, due to the tendency to eliminate as many control knobs from the panels as possible. They are still employed as rheostats, potentiometers, volume controls, etc.

Vitreous enamelled resistors are used extensively in power packs of radio receivers. They are made by space-winding the resistance wire on a special porcelain tube base. The base, including the terminal connections is then coated with a powdered glassy enamel, and



Courtesy Ward Leonard Elect. Co.

Fig. 28.—Several forms of wire-wound resistors for use in radio receivers.

fired at red heat. The result is a resistor unit covered with a vitreous enamel coating which protects the fine resistance wire from mechanical injury, and serves as an excellent heat conductor to rapidly conduct the heat from the resistive element to the outside surface. This construction permits the finest resistance wire to be used without danger of oxidation or other chemical depreciation. The enamel also holds the resistance wire in place without any mechanical strain, and no strains can be set up by heating or cooling, as the vitreous enamel and the wire expand and contract together. Fig. 27 shows a resistor of this type during the various stages of manufacture, from the bare porcelain base tube at one end to the completely vitrified resistance winding at the other end. This is a voltage divider resistance used in power packs.

Special resistance wires made from alloys of nickel and iron have been developed for winding these resistors. They have very low temperature coefficients of resistance and therefore their resistance does not change very much when they get warm in service. Several resistors of this type made up in special forms for use in radio receivers are shown in Fig. 28. Resistor H is variable in value.

Fixed resistors of high resistance (several hundred thousand ohms or more), and which are to carry very little current, are made by depositing either carbon, or a metal such as tungsten, on glass or other insulating material. The deposit may be placed on a thin glass filament placed within a protecting glass tube or may be deposited on the inside wall of a glass tube. A metal cap at each end serves as a connection to the deposit as shown in the upper part of Fig. 29. Such units have practically no inductance and have very little capacity. They are used as grid leak resistances or as plate coupling resistors, for vacuum tubes. It is possible to make these resistors in high resistance values at considerably less cost than the wire-wound types.

Fig. 29.—Upper: Metallized grid-leak type high resistance fixed resistor.
Lower: Carbon type fixed resistor with pigtail leads.

Fixed resistors of small size are also made by compressing powdered carbon with a binding material into thin solid rods. Flexible pigtail connection wires are provided at each end as shown in the lower part of Fig. 29. These can also be manufactured very cheaply and are being used extensively now in radio receivers.

Fig. 30 shows several variable or adjustable resistors (A, B and C). Resistances B and C are made of a resistance wire wound on a fibre strip. A metal contact arm is arranged to slide over this resistance to vary the amount of resistance wire included between it and one end of the winding. A bakelite form supports the arm, bushing and resistance wire strip. Very high variable resistances used for volume and tone controls (where very little current must be carried) usually have a special adjustable wiping or rolling contact moving over a paper strip impregnated with graphite. The graphite acts as the high resistance.

Adjustable high resistances for controlling B power unit output voltages, vacuum tube plate currents, etc., are usually constructed from a mixed mass of carbon powder which is a conductor, and mica flakes which are insulators. The resistance is lessened by compressing the mixture (by turning a knob) to force the carbon particles into closer contact, and is raised by releasing the pressure, whereupon the springiness of the mica separates the carbon particles and reduces the area of contact. The mica also prevents "packing" of the carbon particles when compressed. Resistance A of Fig. 30 is of this type. A porcelain case encloses the inside parts. More recent resistors of this type use a metal case in order to dissipate the heat more readily. They are therefore able to handle more power without overheating.

Resistances D, E and F of Fig. 30 are ballast resistors used to maintain constant filament current in battery-operated tubes. They consist of pieces of fine iron wire enclosed in airtight glass tubes with metal connecting caps at the ends.

Ordinary commercial resistors are accurate to within 10 per cent of their marked value. Precision resistors are more expensive and are made more carefully. They are usually baked at 120°C for several hours to prevent slow change of resistance with time, and are finally covered with paraffin wax.

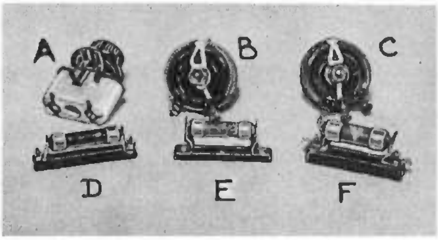


Fig. 30.—Several forms of resistors used in radio receivers.

51. Watt dissipation of resistors: When current flows through a resistance, the electrical energy is converted into heat. This heat must be dissipated to the surrounding air as fast as it is produced, if the resistance is to operate at a steady temperature. The heat developed is proportional to the product of the resistance in ohms and the square of the current in amperes. (equation 6)

$$W = I^2R.$$

This product equals the number of watts of electric power being used up in the development of heat in the resistor, and because of this fact, resistors which are to handle any appreciable current are generally rated according to the number of watts they will safely dissipate, as well as the number of ohms resistance they have. The standard definition of the *maximum wattage rating* of resistors of the vitreous enamel type is; "the input in watts required to produce a temperature rise of 250 degrees Centigrade (482 degrees Fahrenheit) at the hottest point of the resistor, when the resistor is surrounded by at least one foot of free air, the surrounding air being at a temperature not exceeding 40 degrees C. (104 degrees F.)".

This is a standard adopted by the National Electrical Manufacturers' Association (N.E.M.A.) and the Radio Manufacturers' Association (R.M.A.).

The heating of resistors in radio receivers, while chiefly due to the electric power dissipated in them, is also increased by their proximity to other warm or hot parts such as vacuum tubes and other resistors, and to lack of sufficient air circulation.

The safe current in amperes which may be carried by a resistor of given rating in watts and resistance is found by the equation:

$$I=\sqrt{\frac{W}{R}}$$

where W=allowable wattage dissipation rating of the resistor
R=its resistance in ohms.

Example 1: A certain 2,000 ohm resistor has a rating of 80 watts. How much current will it safely carry?

Solution:

$$I=\sqrt{\frac{W}{R}}=\sqrt{\frac{80}{2,000}}=0.2 \text{ amps. or 200 milliamperes. Ans.}$$

If the resistance and the current to be carried are known, the wattage rating of the resistor to be used can be calculated from the formula. $W=I^2R$.

Example 2: A C-bias voltage of 4.5 volts is to be obtained by having the plate current of 3. milliamperes of a 224 tube flow through a resistance. What must be the resistance in ohms and the minimum watts dissipation rating of the resistor used for this purpose?

Solution: $R=\frac{E}{I}$, 3 milliamperes$=\frac{3}{1000}=.003$ Ampere.

$$R=\frac{4.5}{.003}=1500 \text{ ohms. Ans.}$$

$$W=I^2R=.003\times.003\times1500=.0135 \text{ Watts. Ans.}$$

As a matter of safety and to insure long life, resistors are generally operated at about 25% of their maximum watts dissipation rating and at about three fourths of their maximum current carrying capacity rating. Such use makes plenty of allowance for poor ventilating conditions such as are found in the usual installations.

Where there is no danger of damage to other parts from the heat developed by the resistors, or where the ventilation is very good, it is permissable to use them at the higher "Maximum" ratings.

It should be remembered that the watts dissipation rating of a resistor is based on the supposition that the current flows through the entire resistor. In case the resistor is provided with taps, and the full current flows only through part of the resistor, the watts dissipation rating is proportionately lowered.

The student should familiarize himself with the symbols used on radio circuit diagrams to represent the various types of resistors; fixed variable, tapped, etc. These will be found in the Radio Symbol Chart in "Appendix A" at the back of this book. Possibly the best way to do this is to draw the circuit diagrams for all problems worked out, and for other additional problems which the student should formulate and solve for himself. In this way he will become thoroughly familiar with this sign language which is used so extensively in all branches of technical work.

REVIEW QUESTIONS

1. Why are standard electrical units of e. m. f., resistance and current necessary in electrical and radio work?
2. Name and define the practical units of current, resistance and e. m. f.
3. The plate current of a certain vacuum tube is 7 milliamperes. Express this current in (a) amperes; (b) microamperes.
4. The signal voltage applied to the grid circuit of an amplifying tube in a radio receiver is 15 microvolts. Express this in (a) millivolts; (b) volts.
5. The grid leak resistor used with a detector tube has a resistance of 5 megohms. Express this in ohms. What is the conductance of this resistor?
6. It is desired to produce a fall of potential of 90 volts in a circuit through which 45 milliamperes of current are flowing. This is to be accomplished by connecting a resistance in the circuit. (a) What must be the value of the resistor in ohms? (b) What must be the maximum watts dissipation rating of the resistor assuming that it is to be operated at 50% of its maximum rated value?
7. The field coil of a dynamic speaker is connected across a B eliminator having an output voltage of 300 volts. The resistance of the field coil is 1500 ohms. Calculate the electric power in watts supplied to the field coil.
8. State Ohm's law. Write the formula for it.
9. Write the three formulas for electrical power in watts.
   (a) in terms of e. m. f. and current.
   (b) in terms of e. m. f. and resistance.
   (c) in terms of current and resistance.
10. Calculate the power supplied to the filament of a 280 type rectifier tube which takes a current of 2 amps. at 5 volts.
11. State the four factors upon which the resistance of a conductor depends and explain just how each one affects the resistance.
12. The diameter of 1000 ft. of No. 24 B. & S. copper wire, used for the winding on a filament transformer is .0201 inches. What is its diameter in mils? What is the circular mil area? If the specific resistance of copper wire is 10.35 at 20° C. what will be the resistance of this wire at a temperature of 20° C.?
13. What is the resistance of the wire in problem 12 at an operating temperature of 80° C. if the temperature coefficient of copper is .004?
14. From the table of specific resistances of various materials in your book, write down the ten metals having the highest

specific resistances. Next to each, write down how many times greater its resistance is than that of annealed copper.

15. Describe the construction of the vitreous enameled type of wire-wound resistor.
16. Describe the construction of two forms of high resistors used in radio receivers in places where very little current will be flowing.
17. Describe the construction of a variable high resistor designed to carry a small amount of current without overheating. What is the purpose of the flaked mica in this?
18. Describe the construction of a variable wire-wound resistor.
19. What installation conditions affect the power in watts which a resistor can dissipate in the form of heat?
20. Draw the symbol for (a) a fixed resistor, (b) a variable resistor, (c) a resistor tapped at the middle, (d) a resistor tapped at three places.

CHAPTER 5.

ELECTRIC CIRCUITS, BATTERIES.

SERIES CIRCUITS — PARALLEL CIRCUITS — SERIES PARALLEL CIRCUITS — COMBINATION OF RESISTANCES — SOURCES OF E. M. F. — CELLS, BATTERIES — THE ION — WET PRIMARY CELL — THE DRY CELL — CONNECTING DRY CELLS — "B" BATTERIES — LAYERBILT "B" BATTERY — "B" BATTERY RATING — AIR CELL BATTERY — PRIMARY AND SECONDARY BATTERIES — THE LEAD-ACID STORAGE CELL — TESTING STORAGE BATTERIES — CHARGING STORAGE BATTERIES — CARE OF LEAD STORAGE BATTERIES — BATTERY RATING AND LIFE — EDISON NICKEL-IRON-ALKALINE BATTERY — REVIEW QUESTIONS.

52. Series circuits: In order to have current flowing in any conductor the circuit must form a complete conducting path from the positive terminal of the source of e. m. f. around to the negative terminal, (except in the case of a circuit with a condenser). In actual electrical circuits, electrical devices are connected in either of two ways—or a combination of the two. When they are connected one after the other in such a way that *all* of the current flows through each of them, they are said to be in *series*. Thus, in Fig. 31 the filaments of all three of the vacuum tubes shown are connected in series with each other and with the resistor R_4, across the 110 volt electric light circuit whose e. m. f. is maintained by the electric dynamo G. In such a circuit, the total resistance of the entire circuit is equal to the sum of the separate resistances. Thus in Fig. 31 if the resistances of the individual parts are as marked, the total resistance is:

$$R=R_1+R_2+R_3+R_4+ \text{ etc.} \qquad (9)$$

The total resistance is $R=380+20+20+20=440$ ohms.

The current I flowing in the circuit is:

$$I=\frac{E}{R}=\frac{110}{440}=0.25 \text{ amperes.}$$

Another important fact regarding the series circuit is that the current is the same through every part of the circuit since there can be no accumulation of current at any point along the circuit. If five ammeters were connected at the points marked I in Fig. 31, they would all indicate the same current I, of 0.25 amperes. Also if a series circuit is opened or broken at any point the current stops flowing.

A voltage drop occurs across each of the various resistances in a series circuit, depending on its resistance. If a voltmeter were connected across the filament of tube A it would indicate $E = I \times R_1 = 0.25 \times 20 = 5$ volts. This is the voltage drop or fall of potential across this resistance. Similarly the voltmeter would read 5 volts if connected across the filaments of tubes B, and C, since they both have resistances of 20 ohms. If it were connected across resistance R_4 it would indicate $E = I \times R = 0.25 \times 380 = 95$ volts. The sum of all these voltage drops around the circuit is equal to $5 + 5 + 5 + 95 = 110$ volts. This of course is equal to the voltage of the source of e. m. f. (G) which is causing the flow of current through the resistances. This illustrates another law of the series circuit: "The total voltage applied to the circuit is equal to the sum of the

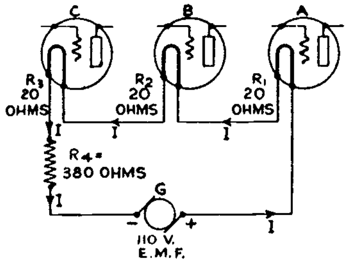


Fig. 31.—Series circuit. The same current flows through every part of the circuit.

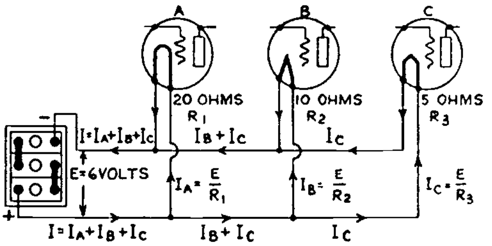


Fig. 32.—Parallel circuit. The current divides and part flows through each branch.

voltage drops across the individual resistances in the circuit." If any unit in a series circuit should become "short circuited", the current will increase because the total resistance of the circuit would be decreased.

Notice from Fig. 31 that the voltage drop across any resistance in the circuit depends upon its resistance. Thus even though the same current flows through all parts, the voltage drop across the 380 ohm resistance is 95 volts, whereas that across each 20 ohm resistance is only 5 volts.

In radio receivers series circuits are very common in the plate circuits of vacuum tubes as we shall see later. The adding of resistances in series is equivalent to increasing the length of the conductor, so that the total resistance is equal to the sum of the separate resistances.

53. Parallel circuits: When parts of a circuit are connected in such a way that they form separate paths through which the current can divide they are said to be connected in *parallel*, *multiple*, or *shunt*. Only a portion of the total current flowing from the source of e. m. f. flows through each path.

Fig. 32 shows a parallel circuit consisting of the filaments of three dissimilar vacuum tubes supplied with current forced through the circuits by the e. m. f. of the storage battery, E. Only a portion of the total current circulating through the battery passes through each of the circuits, but of course the sum of the number of amperes of current flowing in the three circuits is equal to the number of amperes of current circulating through the battery, since all the currents combine again. The actual current in each wire of the circuit is indicated on the diagram. Notice how the current coming out of the positive terminal of the battery divides to go through the tube filaments and then combines again at the negative line.

Any number of electrical devices or circuits may be connected in parallel. The current returning to the negative side of the source of e. m. f. is exactly equal to the current leaving the positive side. The current is merely circulating through the circuits. The electrical devices connected in parallel may all have the same resistance or they may all have unequal resistances. If the resistances are equal, then it is evident that the total current will divide equally among the various paths, and the combined resistance of all the paths considered together is equal to one of the resistances divided by the number of resistances. Thus, if five resistances of 100 ohms each are connected in parallel, the combined resistance will be $\frac{100}{5} = 20$ ohms, since five paths are being presented to the flow of current instead of only one.

When the parallel resistances are not equal, the combined resistance must be found by another method, in which the conductances of the various paths are considered. When resistances are arranged in parallel, since several paths are being offered for the passage of the current, the effect produced is the same as if we were to increase the cross-sectional area of the original conductor. The current passing through the separate resistances is proportional to the conductivity of each path.

In Article 38 it was stated that the *conductance* of a circuit is equal to $\frac{1}{R}$. That is, the less the resistance of a wire, the greater is its *conductance* or ability to conduct current. Conductance is expressed in *mhos.* Thus if the resistance of a conductor is 5 ohms, its conductance is $\frac{1}{5} = 0.2$ mho.

The conductance of the entire parallel circuit is equal to the sum of the conductances of its individual branches. Thus if R stands for the combined resistance of the parallel circuit, and r_1, r_2, r_3, ...etc., stand for the individual resistances of the parts of the parallel circuit, then

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \text{ etc.} \qquad (10)$$

from which the combined resistance R may be calculated if the resistances of the individual branches are known. Thus in Fig. 32, the combined resistance of the three filaments in parallel is:

$$\frac{1}{R} = \frac{1}{20} + \frac{1}{10} + \frac{1}{5} = 0.05 + 0.1 + 0.2 = 0.35$$

Therefore, $R = 1 \div 0.35 = 2.9$ ohms. *Ans.*

Notice that the combined resistance is less than the resistance of any of the paths. This should be expected of course since even the path of the lowest resistance is having several additional conducting paths connected in parallel with it so that the resistance must be less. Additional paths increase the current carrying ability of the circuit, that is, they decrease the resistance.

We see that two or more *equal* resistances in parallel is merely a special case of parallel circuits. Equation (10) can be used for any condition of equal or unequal resistances.

In a parallel circuit the voltage across each branch is the same as that across every other branch and is equal to that supplied by the source of e. m. f. The current which flows through each branch is simply equal to this voltage divided by the resistance of the branch. Thus in Fig. 32, if the battery supplies an e. m. f. of 6 volts the currents in the various branches are:

$$Ia = \frac{E}{r_1} = \frac{6}{20} = 0.3 \text{ amps.}$$

$$Ib = \frac{E}{r_2} = \frac{6}{10} = 0.6 \text{ amps.}$$

$$Ic = \frac{E}{r_3} = \frac{6}{5} = 1.2 \text{ amps.}$$

Therefore $I = 0.3 + 0.6 + 1.2 = 2.1$ amps. (this is the total current supplied by the battery).

As a check on this calculation we may calculate the total current directly from the value of the combined resistance of 2.9 ohms obtained above for the circuit. Thus $I = \frac{E}{R} = \frac{6}{2.9} = 2.1$ amps (which checks with the value just calculated).

In a parallel circuit, if any one of the branches is opened, current will continue to flow through the others. The conditions existing in parallel circuits may be summed up as follows:

1. The voltage is equal across all branches of a parallel circuit.
2. The combined resistance is less than the resistance of any branch of the circuit.
3. The total current is equal to the sum of the currents through all the branches.

Parallel circuits are very common in radio receivers. In battery operated receivers the filaments of the various tubes are usually connected in parallel across the source of e. m. f. (battery). In a-c electric receivers the filaments of the tubes are connected in parallel across the filament winding of the power transformer. The plate circuits of the tubes are all connected in parallel across the B power supply unit.

54. Series — parallel circuits: Circuits may consist of several devices so connected that some of them are in parallel with each other, and others are in series with each other and the parallel combination. Connections of this kind are referred to as *series—parallel* circuits, since they are a combination of series and parallel circuits. A circuit of this

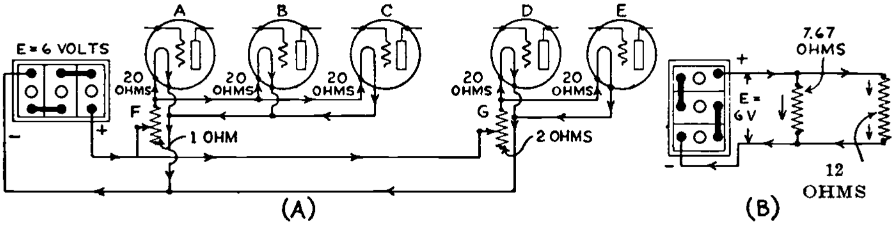


Fig. 33.—Series—Parallel circuit. The circuit at (a) can be considered to be equivalent electrically to the simple circuit at (b).

kind is shown in (A) of Fig. 33. Here the filaments of three 201-A vacuum tubes A, B and C (each having a resistance of 20 ohms) are connected in parallel with each other. A resistance F of 1 ohm is connected in series with the group. The filaments of two other tubes D and E are connected in parallel with each other. A resistance G of 2 ohms is in series with them. This second group is in parallel with the first group across the battery.

The total resistance of the entire circuit can be found by reducing each series—parallel combination to an equivalent single resistance.

The combined resistance of the resistances A, B and C is found from,

$$\frac{1}{R}=\frac{1}{20}+\frac{1}{20}+\frac{1}{20}=0.05+0.05+0.05=0.15. \text{ Therefore, } R=6.67 \text{ ohms.}$$

As this is in series with resistance F, the total resistance of this group is R=6.67+1=7.67 ohms. Therefore this group is equivalent to, and could be considered as, a single resistance of 7.67 ohms connected across the circuit as shown in (B) of Fig. 33.

Likewise the combined resistance of resistances D and E is found

$$\text{from } \frac{1}{R}=\frac{1}{20}+\frac{1}{20}=0.05+0.05=0.1. \text{ Therefore, } R=10 \text{ ohms.}$$

As this is in series with resistance G, the total resistance of this group is R=10+2=12 ohms. Therefore this group could be considered as a single resistance of 12 ohms connected across the circuit as shown at B.

Therefore the combined resistance of the entire circuit (from B of Fig. 33) is $\frac{1}{R}=\frac{1}{7.67}+\frac{1}{12}=0.13+0.083=0.213$. Therefore R=4.7 ohms.

The total current drawn from the 6 volt source of e. m. f. is then

$$I=\frac{E}{R}=\frac{6}{4.7}=1.3 \text{ amperes.}$$

The individual voltage across each filament, or the current through it, could be calculated from these values by applying Ohm's law.

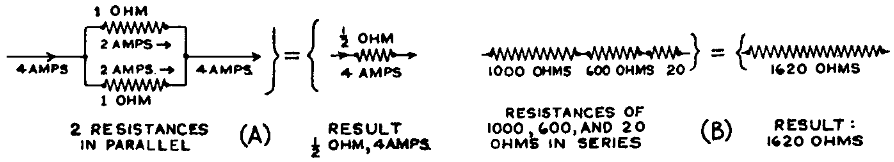


Fig. 34.—How standard size resistors may be combined to obtain odd values of resistance.

Series-parallel circuits are encountered in the plate circuits of modern a-c tube electric receivers where the plate circuits of all the tubes in the receiver are in parallel with each other across the source of B voltage supply, but each individual complete plate circuit consists of several resistances in series. Such circuits may be very complicated when considered as a whole, but when they are split up and attacked as above they may be solved very simply by the formulas for series and parallel circuits. The scheme of substituting equivalent single resistances in the computations for series-parallel connected resistors, makes this work simple.

55. Combination of resistances: Resistances are sometimes purposely connected in series, parallel, or series-parallel in order to obtain odd resistance values or current carrying capacities which are not obtainable commercially in single resistances. For instance, suppose a resistance of ½ ohm with a current carrying capacity of 4 amperes is required for the filament circuit of a radio receiver. We will assume that ½ ohm resistors with a current carrying capacity of 4 amperes are not readily available, but that 1 ohm resistors having a carrying capacity of say 2 amperes can be obtained. By simply connecting two of these in parallel as in (A) of Fig. 34, a joint resistance of ½ ohm is obtained and since each resistor can safely carry 2 amp. the combination of the two in parallel can handle the 4 amperes.

As another simple illustration of connection of resistors to obtain some desired value, let us suppose that we require a resistance of 1620 ohms for some purpose. Now resistors are not made in standard sizes of 1620 ohms. But standard resistors of 1,000, 600 and 20 ohms are available. By connecting one each of these in series as shown in (B) of Fig. 34, a total resistance of 1620 ohms can be obtained.

56. Sources of e. m. f.: We have found in our study of electricity that electrons can be made to drift or flow in a definite direction through any conductor (current flow) by the application of an external electrical force which we call *electromotive force.* The e. m. f. is really the force which keeps the electrons moving in a definite direction around the circuit. It is sometimes called *electron-moving* force. Electromotive force may be produced or generated in a number of different ways, among which are the following:

1. By friction between two bodies, and electrostatic induction.
2. By chemical action as in the dry cell or storage cell.
3. By electromagnetic induction, such as produced in a dynamo when conductors are moved across a magnetic field.
4. By thermo-electric action produced by the contact of two dissimilar materials and the application of heat at the junction. The e. m. f. produced in this way is often called thermo-electromotive force.

The first and fourth methods are not used commercially. The third method is used for producing e. m. f. on a large scale for commercial electric light and power supply. This method will be studied later. The second method finds use where no electric light service is available, as in the case of rural districts. This method will be studied first. We will confine ourselves to the use of chemical changes occuring in primary and storage cells for its production.

57. Cells, batteries: A cell is usually considered to be a single unit in which electrical energy is produced by chemical action. A *battery* is a combination of two or more cells, either in series or in parallel, for the purpose of obtaining either more e. m. f. or more current than a single cell will provide. Thus an ordinary 6 volt storage *battery* consists of three 2-volt *cells* connected in series to give 6 volts.

The terms E. M. F., potential difference, fall of potential and voltage are often used interchangeably by the layman. It is perhaps better to reserve the term e. m. f. to denote the *total* electrical pressure actually *developed* by the source, whether it be a dry cell, storage battery, electric dynamo, thermo-couple, etc. no matter how it may be caused. As we will find out later, all generators of electric energy have some internal resistance of their own. When current is being delivered there is a fall or drop of potential in the generator due to this resistance. The result is, that the voltage actually available at the terminals when current is being supplied, is less than the e. m. f. generated, by an amount equal to the internal $I \times R$ drop in the generator. This resulting voltage actually available at the terminals is called the terminal voltage or p.d.

58. The ion: Electrons or negative charges of electricity may be added to, or removed from normal atoms in several ways. If by some means an electron is removed from an atom as shown in B of Fig. 35, the balance between the strength of the total positive charge of the nucleus or protons and the total negative charge of the electrons in the atom no longer exists, and the positive charge of the excess proton left in the atom predominates. This unbalanced electrical state of an atom due to the removal of one or more of its electrons changes the atom to an *ion.* The process of accomplishing this result is known as *ionization.* As the excess electrical charge remaining on the ion is positive, this ion is known as a *positive ion.* The electron which has been removed from the atom becomes a *free electron,* free to move about wherever it is attracted

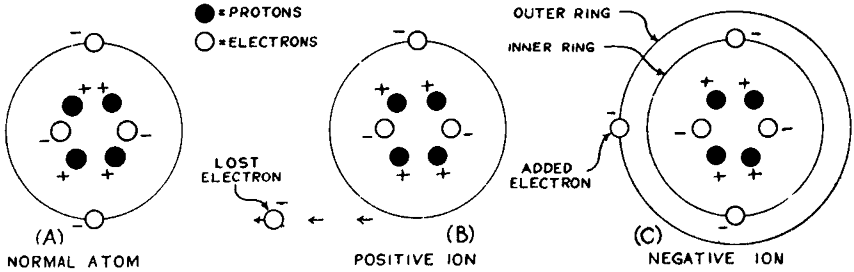


Fig. 35.—A normal atom has as many electrons as protons. A positive ion has one less electron than protons. A negative ion has one more electron than protons.

by the charges. Of course the unbalanced positive charge remaining in the ion exerts a force tending to attract it back, this force diminishing as the square of the distance between them. If the free electron becomes attached to a neutral atom, the amount of negative charge or electricity in the atom becomes excessive, and this atom exhibits a resultant negative charge as in C of Fig. 35. It is then known as *a negative ion.* The actual substance of an ion remains the same since the protons—which contain the mass of the atom—are not removed or combined. However, some substances exhibit increased chemical activity when in an ionized condition. It is evident that the more electrons that are removed from each atom during ionization of a substance, the greater becomes its unbalanced electrical charge.

When salts or acids are dissolved in water, the act of solution separates or *dissociates* many of the salt or acid molecules, each molecule yielding a negatively charged atom (— ion) and a positively charged atom (+ ion). Thus when sulphuric acid (H_2SO_4) is mixed with water, there are present in the solution the positive hydrogen ions H^+, H^+ and the negative SO_4 ions $SO_4^{=}$. We might say that the SO_4 ion takes an electron from each hydrogen ion.

59. Wet primary cell: A simple primary cell may be made of a platę of zinc and one of carbon dipping into a jar of ammonium chloride (NH_4Cl—sal ammoniac solution). A conducting circuit connects the two plates outside of the solution as shown in Fig. 36. In the electrolyte (ammonium chloride) there are present the ions NH_4^+ (ammonia) and Cl^- (chlorine). When zinc is immersed in the solution, Zn^{++} ions enter the solution. The Zn^{++} ions are positive because each has left behind on the zinc plate two electrons (-). This accumulation of negative electrons constitutes a negative charge on the zinc plate, as shown in Fig. 36. The Zn^{++} ions, on entering the solution, repel the H^+ ions and the $NH4^+$ ions that are already present. In this simple cell, the H^+ and the $NH4^+$ ions are repelled toward the carbon plate. The

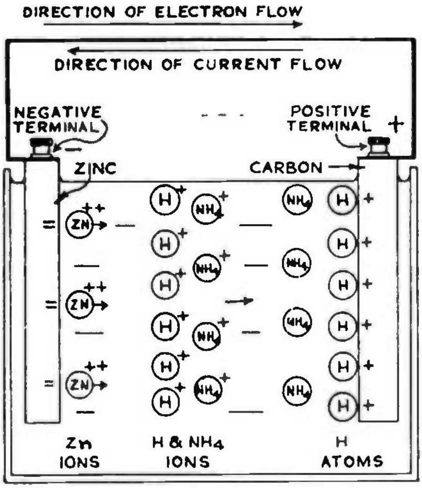
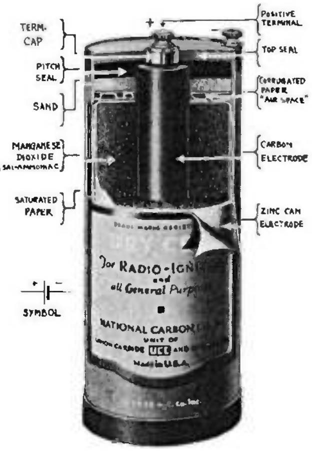


Fig. 36.—Wet primary cell.



Courtesy National Carbon Co.

Fig. 37.—Interior of an ordinary 6-inch dry cell.

H^+ and the $NH4^+$ ions reaching the carbon plate take electrons from its atoms and form neutral hydrogen and ammonia atoms which collect on the surface of the carbon plate in the form of hydrogen and ammonia bubbles. The loss of electrons to the hydrogen leaves the carbon plate with a positive charge. The zinc ions, Zn^{++} combine chemically with the chlorine ions Cl- to form zinc chloride ($ZnCl_2$) (a white substance). Thus the zinc plate is gradually used up to form zinc chloride during the normal operation of the cell. This zinc chloride stays in the solution.

The chemical action in the cell results then, in leaving too many electrons on the zinc plate and too few on the carbon. The overcrowded electrons on the zinc plate repel each other and try to push each other off the plate. This push, together with the attraction of the positive carbon plate, is the electromotive force of the cell. This e. m. f. will cause an electron flow around through the external circuit from the negative zinc plate through the wire to the positive carbon plate. This is equivalent to saying that an electric current flows from the carbon plate through the external circuit to the negative zinc plate (see article 25). Thus the chemical action in the cell really produces electric charges which act like a pump in producing a continuous flow of electrons in any conductor joining its plates. The carbon is the + terminal of the cell and the zinc is the — terminal.

The accumulation of hydrogen bubbles over the carbon plate reduces both the voltage and the current. The hydrogen tends to set up an electromotive force in a direction opposite to that of the cell and thus decreases the effective e. m. f.; and it also reduces the conducting area of the plate and so increases the *internal resistance* of the cell. This action is called *polarization.*

Polarization may be remedied either by constructing the cell so that the electrolyte is mechanically agitated to free the hydrogen bubbles, or else to remove the hydrogen by causing it to combine chemically with a substance rich in oxygen, to form water. Manganese dioxide ($Mn\ O_2$) is commonly used for this purpose, and it is called a depolarizer. (In the recent Eveready Air Cell "A" battery, oxygen is drawn directly from the surrounding air for this purpose.) The manganese dioxide is placed around the carbon plate. When hydrogen combines with its oxygen, water (H_2O) and Mn_2O_3 are formed.

If the zinc plate contains on its surface, any impurities, such as iron, carbon, etc., each little particle of these impurities forms a tiny local cell with the zinc, causing the zinc to be eaten away whether the cell is delivering current to an external circuit or not. This is called *local action.* This may be reduced or prevented by using pure zinc (which is expensive) or by amalgamating the surface of the zinc with mercury. The mercury covers over the impurities.

60. The dry cell: There are many types of wet cells, and various electrolytes, plates and arrangements are used in them. In many applications, they are rather inconvenient to use as sources of e. m. f. because they are not readily portable and are rather messy due to the liquid. The so-called *dry cell* is a more convenient form of primary battery in many cases. With the perfection of the new low-filament-current vacuum tubes, the use of dry cells, and the new Air Cell battery to be described later, should increase greatly. They may be used as sources of filament current in the battery operated receivers used in the nine million or more homes in the rural districts where ordinary electric lighting circuits are not available for operating radio receivers.

The dry cell is not entirely dry, for it contains the electrolyte soaked up into a porous mass in the cell. Its elements are similar to the wet cell just described. However, the cell may be used in any position without spilling its contents. The dry cell consists of a zinc can which acts both as a container for the various parts inside and also as one plate of the cell. The sectional view of Fig. 37 shows both the internal construction and the outside view of a standard 6 inch (6 inches high) dry cell. The zinc container is lined with absorbent paper (like blotting paper) which serves to insulate the zinc from actual contact with the interior elements, to prevent a short circuit. The electrolyte soaks into, and thus filters through, this blotting paper lining. In the center of the can is the carbon rod which does not extend quite all the way to the bottom. Binding posts are fastened to the tops of the carbon rod and the zinc can for convenience in connecting wires to them. The carbon rod is the *positive electrode* of the cell while the zinc can is the *negative electrode.* Surrounding the rod is a quantity of powdered manganese dioxide sometimes mixed with granulated carbon. This acts as the depolarizer. The granulated carbon, manganese dioxide and the blotting paper are saturated with a solution of ammonium chloride (sal ammoniac) and water. This is the electrolyte.

Upon the top of the mixture is placed a piece of corrugated paper and then a layer of sand. Over this is poured melted pitch or sealing wax, which acts as a seal to prevent evaporation of the liquid from the cell. Caution should be exercised to prevent this sealing compound from becoming cracked, and the cell should not be placed in a very warm place for it would then soon become dry and inactive. The entire cell is placed in a cardboard container which acts as a sort of insulator to the outside of the zinc can.

The chemical reaction taking place during operation of this type of cell is: $Zn+2MnO_2+2NH_4\,Cl=Mn_2\,O_3+H_2\,O+2NH_3+ZnCl_2$.

Thus Zinc chloride ($ZnCl_2$), and water (H_2O) and ammonia gas (NH_3) are formed by the chemical reactions.

In this type of cell the chemical action causes a slow eating away of the zinc, and the life of the battery is theoretically until this zinc is entirely gone. This is not quite true actually, because before this happens, the internal resistance of the cell rises due to the failure of the depolarizing agent to fully neutralize the hydrogen. This continues until the electromotive force is insufficient to overcome the resistance. So we see that the larger the cell, the greater its useful life is.

The voltage is about 1.5 volts per cell when new, and this is true whether the dry cell be a very small one such as is used in small "B" batteries, or a large 6″ dry cell. The e. m. f. of a cell depends only on the materials used in its construction and not on the size.

Such batteries are rated at a definite maximum current discharge rate, so that the depolarizing effect will have a chance to keep step with the hydrogen liberation. This rating should never be exceeded for any appreciable length of time, lest the cell be ruined. The normal discharge rate for a 6 inch dry cell used as an "A" battery is between 1/8 and 1/4 of an ampere. Dry cells are adapted only to intermittent service conditions where they will be given a chance to recuperate by the action of the depolarizer on the hydrogen film.

Dry cells deteriorate when not in use, the smaller sizes having a shorter "shelf life" than the larger sizes. A dry cell becomes exhausted as soon as the electrolyte has been consumed and the inner surface of the zinc container has changed to zinc chloride.

61. Connecting dry cells: The e. m. f. of a dry cell in good condition is about 1.5 volts on open circuit. Due to its internal resistance, the terminal voltage drops when the cell starts to deliver current.

Testing a cell with a voltmeter is of no value when the cell is not delivering current, for even a cell that is almost entirely discharged will test close to 1.5 volts on open circuit. When delivering maximum current the voltage of a new cell should remain as high as one volt.

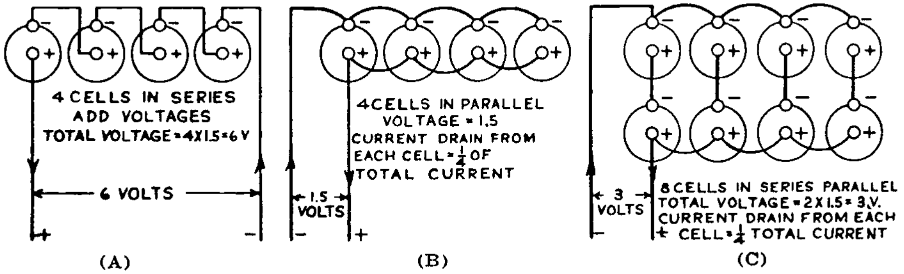


Fig. 38.—How battery cells may be connected for high total voltage, high current drain, or both.

The method of testing dry cells in practice is to connect an ammeter of low resistance (less than .01 ohm) directly across the terminals of the cell. On short-circuit through the low resistance of the ammeter (having a scale reading up to about 50 amperes) a 6 inch dry cell will generally send a current of 25 to 30 amperes. Cheap pocket ammeters are sold for testing dry cells this way. The ammeter should be left across the terminals only long enough to take the reading. As a dry cell becomes old, its internal resistance increases, so that the amount of current flowing during the short-circuit test through the ammeter decreases. A 6 inch cell should be thrown away if it reads less than 5 amperes. Dry cells cannot be recharged, so they are called *primary* cells.

In all radio diagrams a single cell is represented by a pair of parallel lines. One is long and thin, representing the positive terminal, and the other is short and thick, representing the negative terminal. The symbol is shown in Fig. 37.

If a higher voltage than 1.5 volts is required, a number of cells must be connected in *series*. The number of cells to connect in series in any case is found by dividing the total voltage required, by 1.5 (the voltage of 1 cell). Thus if six volts are required, connect $6 \div 1.5 = 4$

dry cells in series. "B" batteries used in radio receivers consist of many small dry cells connected in series to obtain the high voltages required. When connecting cells in series, the outer (negative) terminal of one cell should be connected to the inner (positive) terminal of the next, and so on. The two remaining posts are a positive and a negative, one on each of the two end cells, as shown in (A) of Fig. 38. The total voltage of the combination equals 1.5 times the number of cells.

As mentioned above, the normal discharge rate of the standard 6 inch dry cell is from 1/8 to 1/4 ampere. Smaller size cells have the same voltage but are not able to provide this much current. If more current than this is to be supplied at 1.5 volts, a number of cells should be connected in parallel as shown in (B) of Fig. 38 so as to divide the total current drain among them. All of the outer, or negative terminals, are connected together, and all of the inner, or positive terminals, are connected together. The total current drawn from the combination is divided equally among the cells but the total voltage available is equal to 1.5 volts (that of a single cell).

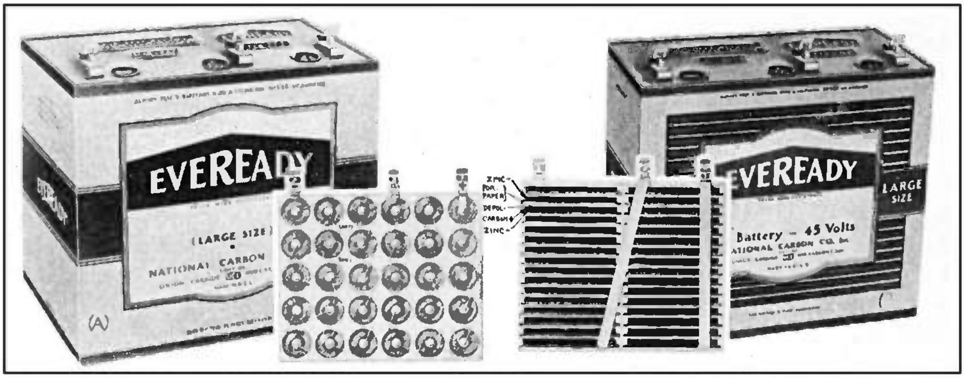
If voltages above 1.5 volts, and currents greater than 1/4 ampere are needed, the proper number of cells to furnish the necessary voltage should be connected up in series, and a sufficient number of these series combinations should be connected in parallel (as in C of Fig. 38) so as to reduce the current drain per cell to a value within the normal discharge rate for the size of cells employed. This is called *series-parallel* connection of cells. In (C) of Fig. 38, eight cells are shown, connected two series—four parallel. This arrangement will provide $1.5 \times 2 = 3$ volts, and a total of one ampere may be drawn from it. At this current drain, each cell is supplying 1/4 ampere.

A combination of two or more cells connected together is called a *battery*. Batteries are represented in radio diagrams by a series of long and short lines as shown in the radio symbol chart in Appendix A. Usually the number of *pairs* of long and short lines in the battery symbol indicates the number of cells connected together, but this is not always the case.

62. "B" batteries: Although the modern a-c electric radio receivers have eliminated the use of B and C batteries for plate and grid voltage supply, the use of dry batteries is still widespread for many other radio uses. The development of satisfactory automobile, motorboat, airplane and farm home receivers has created new fields in which batteries are the only convenient sources of filament, plate and grid voltages.

"B" batteries are dry-cell batteries used in battery-operated receivers to furnish voltages of 22½ volts or more for the plate circuits of the vacuum tubes. (B batteries are also available in storage cell form as shown in Fig. 42.) As the total current drawn from the B batteries by the tubes in the receiver rarely exceeds about 50 or 75 milliamperes (.050 to .075 amps.) the individual dry cells used in B batteries are much smaller than the standard 6 inch dry cell already described, but they are constructed exactly like the larger cell.

Dry cell "B" batteries are made in two standard sizes, considered from the voltage standpoint. One size contains 15 cells connected in series, and delivers a total voltage of 1.5×15, or $22\frac{1}{2}$ volts. The other size contains 30 cells connected in series and delivers a total voltage of 1.5×30, or 45 volts. The cells are assembled into cardboard encased blocks with suitable terminals provided. The $22\frac{1}{2}$ volt units may have taps brought out to provide intermediate values of voltages. The 45 volt units are usually provided with a tap at $+22\frac{1}{2}$ volts, in order to provide proper plate voltage for some types of detector tubes, or to allow variations in plate voltage on radio frequency amplifier tubes.



Courtesy National Carbon Co.

Fig. 39—Dry B-battery construction. Left: (A) B-battery with cylindrical cell construction. Right. (B) Layerbilt construction showing reduction of wasted space in the battery.

The units are made both in vertical and flat shape. Part (A) of Fig. 39 shows a vertical large size 45 volt "B" battery of this type. The insert in this illustration is an inside view showing the 30 cylindrical cells which compose this battery. Some of the series connection wires between the cells can be seen in this illustration.

Notice that in this type of construction the empty space between the cylindrical cells is wasted. These units are made up in various sizes to meet the various conditions of current drain encountered. Generally speaking, the larger the cells used, the greater is the economy in their use, so long as the physical dimensions of the battery are held within reason. The internal resistance of a 45 volt B battery is quite high (200 or 300 ohms) due to the fact that the internal resistances of the individual cells are all in series with each other because of the series connection of the cells.

63. Layerbilt "B" battery: In order to very materially reduce the amount of waste space in B batteries, another type known as the "Layerbilt" has been developed. This is shown in (B) of Fig. 39.

Instead of using the usual cylindrical cells, this particular type of B battery has its elements arranged in tiers forming two cubes, which, when housed within a cardboard container, form a battery of standard size. See Fig. 39. The elements are of practically the same materials used in the ordinary battery, but are of different shape. The carbon element, for example, is painted in a thick layer upon the zinc. Next below comes a porous separator containing the electrolyte, and then the mixing block which comprises the manganese dioxide and other materials usually used at this point. Below this, continues a series of similar carbon and zinc elements, until the entire assembly of the required number of plates is in place. This method of construction does away with all internal connections except three—that between the two piles and the connections of the binding-post terminals on the outside. This reduces the possibility of broken or poorly made connections, and simplifies the construction.

The difficulty, of course, lies in the possibility of leakage from one cell to the next and of a resulting internal short circuit; but this has been taken care of satisfactorily by the adoption of a dam along the edges of the plates. This is also treated to prevent seepage.

In this type of cell, it is apparent that every particle of space is used and, since the zinc no longer acts as a *container*, the battery will continue to render service even after the zinc is eaten to the appearance of old lace.

This results in longer useful life for a battery of given outside dimensions. The two 45 volt B batteries shown in Fig. 39 are approximately the same in external appearance, but the Layerbilt battery will give longer service. The Layerbilt battery also has a much lower internal resistance than the cylindrical type due to the greater surface area of the layers between zinc sheets.

It is interesting to note that the Layerbilt battery is constructed along the lines of the famous "Volta Pile" which was the world's first electric battery, developed shortly after 1800.

64. "B" battery rating: Dry cell B batteries are rated according to their capacity in *milliampere-hours*, that is, their ability to deliver a certain number of milliamperes for a given number of hours. The rating for the heavy duty cylindrical cell battery is 4500 milliampere-hours, that of the medium size is 1200, and that of the small size is 450. It is more economical to use the large size.

Small dry cell batteries for providing 4½, 9, or 22½ volts to the grid circuits of vacuum tubes are also manufactured. They are called "C" batteries.

Batteries used for "C" supply, or "negative bias" on the grids of vacuum tubes, have a service life practically equal to their shelf life;

for the reason that they are called upon to deliver but a very small amount of current, if any at all.

"B" batteries should be tested while normal current drain is being taken from them, that is, with the radio receiver turned on. When the voltage of a 22½ volt block drops to 17 or when the voltage of a 45 volt block drops to 35 volts, the battery should be replaced with a new one. Beyond this point, the voltage of the battery drops very rapidly as it is used. This results either in poor operation, or failure of the set to operate at all.

"B" batteries may be connected in series to obtain higher voltage than a single battery provides. Thus two 45 volt B batteries connected in series gives a total voltage of $45 \times 2 = 90$ volts, three in series gives $45 \times 3 = 135$ volts, four in series gives 180 volts, etc. Special single high-voltage battery blocks delivering. 108 volts, or 144 volts have been developed for automobile and airplane radio equipment (see Chap. 29).

65. Air Cell battery: Recently a new form of primary battery has been developed especially for supplying constant voltage to the filaments of the 2 volt type tubes employed in battery operated receivers. In this battery the oxygen used as a depolarizer is absorbed directly from the surrounding atmosphere instead of being supplied in the cell in the form of manganese dioxide (MnO2) as in the case of the dry cell just described.

The Eveready Air Cell "A" battery is shown in Fig. 40. It consists of 2 cells, assembled in a molded hard rubber container and permanently connected in series. Like the regular dry-cell, the "Air Cell" uses zinc and carbon electrodes. Unlike the "dry" cell, which uses a depolarizer in the form of a paste to prevent hydrogen (an insulator) from forming on the carbon electrode, (and from increasing the internal resistance of the cell and reducing the voltage actually available at its terminals), the new Air cell uses an electrolyte solution in conjunction with a plate formed of a newly invented special grade of carbon which is highly porous to oxygen. This has the peculiar property of extracting oxygen from the unlimited supply of surrounding air which we breathe, and making it available inside the cell for its function as a depolarizer to combine with the hydrogen on the carbon electrode to form water.

The electrolyte used in the Air cell "A" battery is a solution of sodium hydroxide (caustic soda), and the active ingredient is zinc. As the zinc dissolves in the electrolyte, a reaction takes place which produces, as a waste product, sodium zincate. In addition to these elementary materials the battery also contains a certain amount of calcium hydroxide, the purpose of which is to rejuvenate the spent electrolyte. The sodium zincate which results when the zinc goes into solution reacts on the calcium hydroxide to produce calcium zincate, plus sodium hydroxide. Inasmuch as sodium hydroxide is the required electrolyte, this material evolved from the above reaction is available for further dissolution of zinc.

These reactions expressed in the form of chemical equations are as follows:

Air Cell reaction $Zn+NaOH+H_2O=HNaZnO_2+2H$

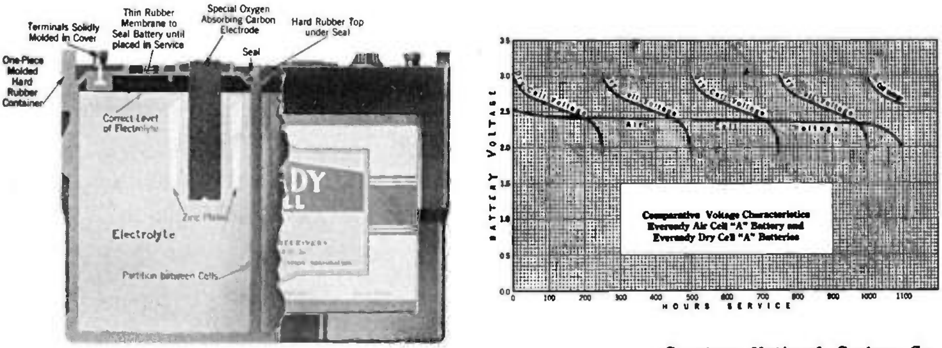
$2H+O \text{ (from air)}=H_2O$

(or, combined) $Zn+NaOH+H_2O+O \text{ (from air)}=NaHZnO_2+H_2O$

The calcium hydroxide reaction is as follows:

$$2NaHZnO_2+Ca(OH)_2=Ca(HZnO_2)_2+2NaOH$$

The passage of current through the cell dissociates the water in the electrolyte into its principal constituents, oxygen and hydrogen. The hydrogen ions migrate toward the carbon electrode, where they discharge themselves against the oxygen which the special carbon electrode draws in from the surrounding air, and by this combination produce water. Inasmuch as the oxygen in the electrode is freely available all over the surface of the electrode, there can be no accumulation of the voltage-reducing hydrogen at current drains below the overload point; and, as a consequence, the internal resistance remains constant and the working voltage of the Air cell "A" battery remains practically at its full initial strength throughout the life of the battery.



Courtesy National Carbon Co.

Fig 40—Left (A) Partial cross-section view of the Eveready Air Cell "A" Battery. Right: (B) Voltage characteristic and life curves of an Air cell "A" Battery compared to 5 banks of No. 6 Dry cells connected in series-parallel.

The electrolyte-forming chemicals, in solid form, are placed in the battery at the time of manufacture. To prevent them from losing some of their strength by possible contact with moist air, while waiting to be placed in service, the battery is hermetically sealed at the time of manufacture by thin rubber membranes under the filler holes, and by a transparent sheet of Cellophane placed over the tops of the special "breather" carbon electrodes. Thus sealed, no change can take place in the chemicals; the battery can be placed in service at any time after manufacture, and still be as "fresh" as the day it was made.

To place the battery in service, all that need be done is to remove the covers from the electrodes so they can "breathe" oxygen, punch out the membranes in the bottom of the filler holes, and fill the two compartments with cold drinking water; a total of about six quarts being required.

This battery has a definite discharge current rate beyond which it is unsafe to go. This overload point is determined by the maximum rate at which the carbon electrodes can extract oxygen from the surrounding air, and amounts to approximately 0.75 ampere.

At current drains below this figure, the porous carbon is able to replenish the oxygen as rapidly as it is consumed within the battery; and as long as the carbon contains oxygen it repels water and remains dry. As the chemist would say, there is a "meniscus" or capillary effect downward, instead of upward. Once the oxygen content is exhausted however, the water in the electrolyte rushes into the pores of the carbon and clogs them up so that oxygen can no longer be drawn through. Under such conditions the battery dies of "suffocation". Any load on the battery, therefore, amounting to more than 0.75-ampere will bring about the premature death of the battery; and, once it has been subjected to this treatment it never recovers. This should be remembered when using this battery for filament current supply in battery operated radio receivers.

The current capacity rating of this battery is 600 ampere-hours, that is, the current drain in amperes multiplied by the total number of hours of useful service at this rate is about 600. Thus it will supply 0.25 ampere for 2400 hours, 0.5 ampere for 1200 hours, etc. The ampere-hour rating of a battery is really a measure of the total amount of useful electrical energy the battery can supply. (This term is also used for rating storage batteries as we shall see later.)

The Air cell is a "primary" battery and therefore is not rechargeable. When exhausted, it is worthless and must be discarded. As the internal resistance of the battery increases only slightly with use, the terminal voltage remains practically constant, dropping from 2.5 volts when new to 2.0 volts at the end of its useful life. On account of this practically constant voltage characteristic, it is ideally suited as a source of steady filament voltage to supply current to the filaments of the two-volt filament type tubes (230, 231, 232 types) used in battery operated receivers. (Receivers of this type will be studied in detail later in the chapter on battery operated receivers). In B of Fig. 40, two interesting sets of performance curves of "dry cell" A batteries and "Air cell" "A" batteries are shown. A seven tube receiver using two-volt type tubes and drawing a total filament current of 0.55 ampere was operated first by an Air cell battery and then by banks of 8 dry cells (2 groups of 4 cells each; cells in each group connected in parallel, with the two groups connected in series as shown at the right of Fig. 38). It required 4½ complete dry battery renewals (total 36 dry cells) to operate the receiver satisfactorily for a total of 1100 hours at three hours per day. In each case the bank of dry cells was discarded when its total voltage dropped to two volts (the rating of the tube filaments). Each bank of dry cells was only good for about 250 hours of operation. Notice from these curves, how the voltage of each bank of dry cells used, dropped from three volts to two volts within about 250 hours of use. A *single* air cell battery operated the same receiver for the entire 1100 hour period during which time its voltage only dropped from 2.5 volts to 2 volts. As the cost of 36 dry cells is about double the cost of an Air cell "A" battery and the latter provides almost correct filament voltage (fixed filament resistor may be used to get exact voltage required) throughout its entire useful life, its advantages are apparent.

66. Primary and secondary batteries: We have seen how a difference of electric potential or e. m. f. can be produced by arranging two dissimilar materials so they can be acted upon chemically by an acid or alkaline solution. The e. m. f. produced will cause a flow of electrons (current flow) if a complete closed circuit is provided. Such a battery will furnish e. m. f. until the chemical action has changed all of the electrolyte or electrodes into some other chemical form. It is then said to be "dead". In a "*primary cell*" it is not possible to reverse the chemical actions which have occurred in it so as to attempt to change the materials back to their original form and composition after the cell has become dead. Therefore the cell could only be renewed by renewing both the electrolyte and the electrodes. This is not practical or worth while in the usual commercial forms of cells, so they are discarded and replaced with entire new cells when they have reached the end of their useful lives.

In a "storage" or "*secondary cell*" the chemical reactions which take place between its electrolyte and electrodes on *discharge* can be completely reversed by sending a current through the cell in the opposite direction, from some external source of e. m. f. This is called "*charging*". When a cell has been fully charged in this way its interior ingredients have been completely re-converted to their original composition and are all ready to enter into chemical action to produce e. m. f. again on discharge. Thus the difference between a primary and secondary cell is that the former cannot be "re-charged" after use, while the latter can.

67. The lead-acid storage cell: Usually two or more storage cells are connected in series to form a battery commonly called a "storage battery". It should be remembered that a storage battery does not act as a storage reservoir for electricity as its name would seem to imply. The only true storage reservoir of electrons or electrical charge is the "electrical condenser," shown in Fig. 83. In a storage battery, electric current is sent in during charging. This is stored up in the cell in the form of *chemical energy* in the active material of the electrodes or "plates" and the electrolyte. The chemical energy is converted back into electrical energy during discharge of the battery. There are two main types of storage cells; the lead-acid type most commonly used, and the Edison Nickel-iron alkaline type. The former will be studied first. Storage batteries are used extensively in all kinds of electrical work where a source of steady e. m. f. is essential. They find a wide use as a source of e. m. f. for the starting, lighting and ignition systems of automobiles, and for supplying filament current for the vacuum tubes in automobile and aircraft radio receivers. They were used more extensively in the early days of radio than at present, as a source of filament current supply for the 5-volt tubes of the 201-A type used in battery operated home receivers. The development of the new more efficient 2-volt type tubes and the Air cell A battery will undoubtedly supplant the old type tubes and storage battery in many places, such as farms, etc., where battery-operated receivers must be employed and a source of current is not conveniently available for re-charging storage batteries. Storage batteries are still used extensively in automobile receivers, talking moving pictures and television transmitting equipment.

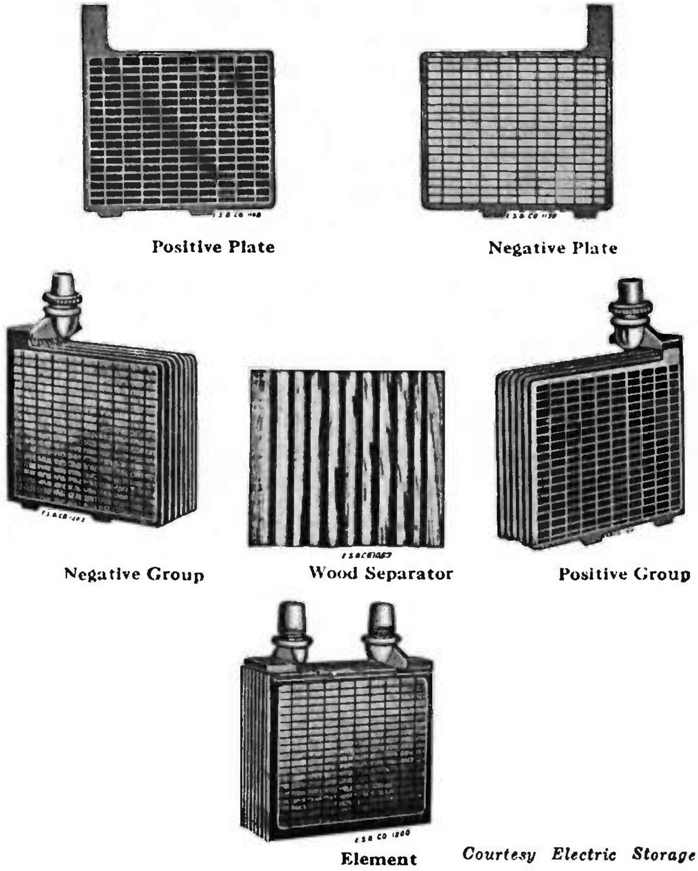
The storage cell has two electrodes, one of spongy lead and one of lead peroxide immersed in a dilute solution of sulphuric acid and water. These elements are usually contained in a hard rubber case (Fig. 42) which will not be attacked by the chemicals. The usual storage battery is made up of three cells connected in series by heavy lead-alloy *straps* as shown in Fig. 42. As the voltage of each cell is about 2.2 volts when fully charged, one of these batteries delivers 3×2.2 or 6.6 volts when fully charged. This is commonly called a "six volt storage battery".

Each storage cell contains several positive electrodes and several negative electrodes. These are commonly called *plates* since they are wide and flat as shown in Fig. 41. Each plate has for its backbone a cast *grid* made of a stiff alloy of lead and antimony for strength. There are many styles of plates in use but in radio batteries they are usually pierced to form an open framework or grid. This construction forms little "grooves," "channels" or "pockets" which are used to hold the softer active material in place. This framework of the plates does not take part in the chemical actions going on in the cell to any great extent. The pockets on one face of the grid are staggered from those in back.

The active material is a paste of litharge, or red oxide of lead, mixed with dilute sulphuric acid. This is forced into the little pockets in the grids, under great pressure. Upon drying, it "sets" like cement, and the pockets in the grids are filled with the hardened active material.

After the paste has hardened the plates are placed in a solution of sulphuric acid and water, and a current of electricity is sent from one group through the electrolyte to the others. This is known as the "forming charge". It changes the active material on one group of plates to spongy lead, (grayish in color), and that on the other plates to lead peroxide (redish brown in color). In Fig. 41 a positive plate with its brown peroxide of lead and a negative plate with its grayish spongy lead are shown.

All plates are provided with an extension or *lug* for connection to a common strap. A certain number of the negative plates (usually 6 or 7) are "lead burned" to an alloy *strap* forming a single negative group as shown in Fig. 41. In the same way a number of the positive plates (usually 5 or 6) are connected in parallel into a positive group, as shown. In



Courtesy Electric Storage Batt. Co.

Fig. 41—Individual and assembled plates and wood separators of a lead-acid storage battery.

this way a large surface area of active material is exposed to the electrolyte so as to store a large amount of chemical energy.

The negative group usually has one more plate than the positive so that when all the plates are assembled together to form an *element*, each outside plate is a negative. In this way all of the positive plates are worked as nearly equally as possible from both sides, equalizing expansions and contractions of the active material when it is changed from lead sulphate to lead peroxide, and minimizing the tendency to buckle. The negative plates are not subject to this tendency since their active material does not greatly change in volume when transformed from spongy lead to lead sulphate.

Thin separators of wood with a grooved surface (grooved on the side which goes against the positive plate, see Fig. 41) are inserted between each positive and negative plate in order to keep them from touching—thus preventing short-circuits between them. In some makes of batteries, a perforated rubber sheet is also inserted between each wood separator and positive plate. A completely assembled cell is shown in Fig. 42.

The elements and electrolyte are either contained in a single molded hard rubber case with three separate compartments, or else in three separate hard rubber jars placed in a wooden case. The former type is most popular. Projecting ribs stick up from the bottoms of the jars, (Fig 42) and support the plates. The spaces between the ribs act as sediment chambers to allow all active material shedded from the plates, etc. to collect without bridging across or short-circuiting the plates.

A hard rubber cover is sealed on to each compartment with a pitch sealing compound. Each cover has a filling tube and vent plug. An alloy collar supports the jar cover, a soft rubber gasket being placed between. A threaded seal nut on the post clamps the cover tight with a soft-rubber gasket underneath to give a very effective seal. The three cells are connected together in series by the cell connectors as shown in Fig. 42. The positive terminal, is usually marked either with a red terminal, or large cross, or in some other way.

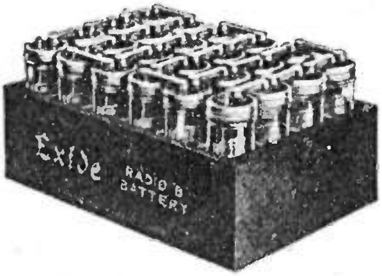
The electrolyte is a dilute solution of sulphuric acid and water. When e. m. f. is supplied by a lead storage battery to a complete electrical circuit so as to produce a flow of current, it is produced by the acid of the electrolyte soaking into and combining with the porous active material of the plates. In the positive plates it is lead peroxide (PbO_2) and in the negative plates it is metallic lead in spongy form (Pb). When the sulphuric acid, (H_2SO_4) combines with the lead (Pb) in the active material of both positive and negative plates, a new compound lead sulphate ($PbSO_4$) is formed.

As discharging continues, the active material in both the positive and negative plates is being converted into lead sulphate. The electrolyte becomes "weaker" (more dilute) because acid is being taken out of it and is used up in the plates—also because additional water is formed by the chemical combination of the hydrogen (H) and oxygen (O) in the cell. The chemical reaction taking place is as follows:

Pb	+	PbO_2	+	$2H_2SO_4$	=	$2PbSO_4$	+	$2H_2O$	
Negative Plate		Positive Plate		Electrolyte		Both Plates		Water	("Discharge")

Lead + lead peroxide + sulphuric acid *becomes* lead sulfate + water.

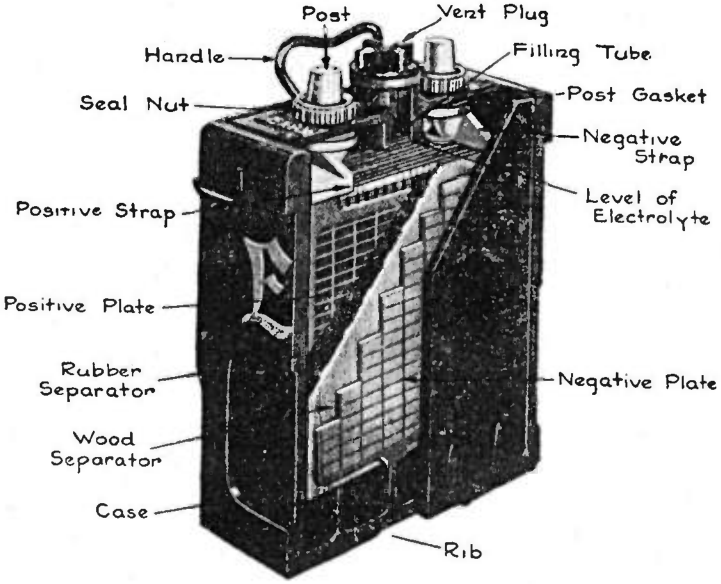
As the formation of sulphate continues on the plates, it fills the pores and retards the free circulation of the acid into the active material and then since the acid cannot get into the plates fast enough to maintain the nor-



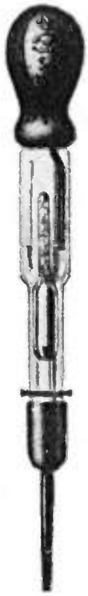
Type LR. 48-Volt Battery

Solid Cell Connector

Complete Battery, XCR Type



Sectional View of Battery XCR Type, Showing Construction Details



Courtesy Electric Storage Batt. Co.

Fig. 42—Storage "B" battery, sectional and outside view of storage "A" battery and Hydrometer with syringe at right.

mal action, the battery becomes less active as indicated by a rapid drop in voltage when it reaches a certain "critical" point in its discharge.

Also as the electrolyte becomes a weaker acid and therefore a poorer conductor, and the lead sulphate on the plates is also a poor conductor the internal resistance of the battery increases as it discharges, especially after the critical point mentioned above is reached.

In order to re-charge a storage battery *direct* current must be passed through the cells in the direction *opposite* to that of discharge. This current reverses the chemical changes which took place in the cells during discharge. The lead sulphate on the plates now combines with the water. The positive plates are re-converted into lead peroxide (PbO_2) and the negative plates are re-converted into spongy lead (Pb). Sulphuric acid (H_2SO_4) is returned to the electrolyte solution. The chemical equation which expresses this change during charging is as follows:

("Charge")

$2PbSO_4$	+	$2H_2O$	=	Pb	+	PbO_2	+	$2H_2SO_4$
Both Plates		Water		Negative Plate		Positive Plate		Electrolyte

Lead sulphate + water *becomes* "spongy" lead + lead peroxide + sulphuric acid.

As this equation is exactly the reverse of the one representing the reactions on discharge, the materials in the cells will all be converted back to their original composition and be ready to combine again to produce electrical energy.

Small storage cells are available for use as B batteries for radio receivers. These consist of 12 or 24 cells connected up in series to form B battery units of 24 or 48 volts respectively. A 48 volt B battery of this type is shown in Fig. 42. Glass jars are used for the cells. This battery has a capacity of 600 milliampere-hours. It is evident that the storage cell really stores chemical energy, which makes itself available as electrical energy or discharge.

68. **Testing storage batteries:** Sulphuric acid is heavier than water. From our study of the chemical reactions taking place during "charge" and "discharge" of the lead-acid storage battery, we found that during charge, acid is returned to the electrolyte (making the electrolyte heavier or denser) and during discharge acid is taken from the electrolyte to form lead sulphate on the plates, (making the electrolyte lighter in weight). The specific gravity of a material is its comparitive weight with respect to an equal volume of water. For example, a cubic foot of water weighs 62.5 lbs. A material weighing twice as much (125 pounds) has a specific gravity of 2. When a lead storage battery is in a fully charged condition, the specific gravity of its electrolyte ranges from about 1.275 to 1.300. This is usually read twelve seventy-five (1275) to thirteen hundred (1300). Since acid is taken from the electrolyte during discharge, the specific gravity of the electrolyte decreases. Therefore the specific gravity is a valuable indicator of the condition of charge of a battery (provided extra acid has not been purposely put into an old battery by a dishonest

battery dealer simply to bolster up the specific gravity to make it appear fully charged).

To find the condition of charge of a battery by testing the electrolyte, a *hydrometer* is used. This is shown at the lower right of Fig. 42. It consists of a rubber bulb arranged to draw up the electrolyte from the filler cap on each battery cell, through a rubber nozzle, into a glass tube. Inside of this, floats a small hydrometer consisting of a small glass tube having a hollow bulb with a weight (usually lead shot) at one end, and a thin tube with a numbered scale at the other end. The more dense the electrolyte the higher the bulb floats in it. If the cell is completely discharged, the hydrometer will sink almost to the bottom. The hydrometer float should not be allowed to stick to the sides of the glass tube. The scale marked on the hydrometer stem indicates the specific gravity of the solution (the decimal point is left off). If the cell is fully charged, the line marked 1280 or 1300 will be at the surface of the liquid as shown in Fig. 43. When the reading drops below 1185, the battery should be recharged. At 1120 the battery is fully discharged. If by chance a battery should become fully discharged, it should not be allowed to stand around for any length of time in that condition, for the lead sulphate on both the positive and negative plates will crystallize and harden. It is almost impossible to break this up into lead peroxide and spongy lead later when charging, so the battery becomes practically useless.

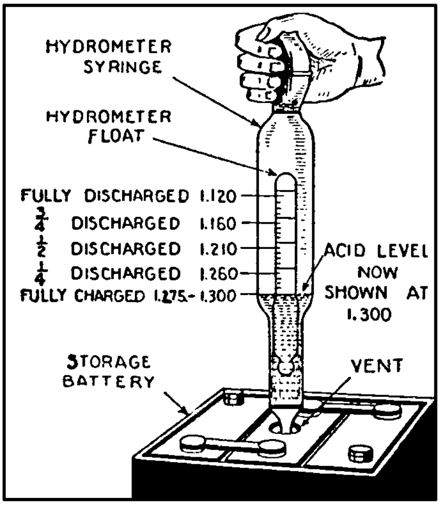
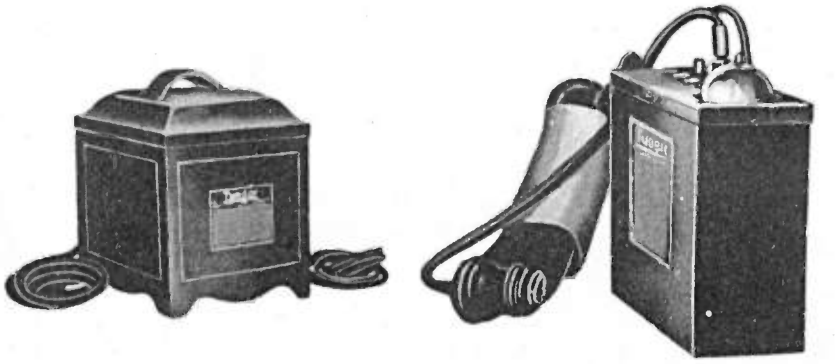


Fig 43—How to test the specific gravity of the electrolyte in a storage battery. The float in the hydrometer rises or falls according to the condition of charge.

69. Charging storage batteries: The voltage of each cell of a fully charged storage battery on open circuit is about 2.2 volts. This voltage is approximately the same for a partly discharged cell as for one fully charged, so that the condition of charge of a battery cannot be determined accurately by an open-circuit voltage test. Since a lead cell has a very low internal resistance it will give a current of from 200 to 500 amperes on direct short circuit. Therefore it cannot be tested with a simple pocket ammeter of the type used for testing dry cells, because this current is too large for such an instrument. Where it is suspected that acid has been added to the cells in a battery simply to bolster up the hydrometer readings to make the battery appear fully charged, it is usual to test the battery by measuring its output voltage while it is delivering current, for in this case a hydrometer test would be worthless.

All storage batteries must be charged by sending *direct* current through them in the direction *opposite* to their normal current flow on discharge. That is, the positive terminal of the charging source of e. m. f. must be connected to the positive terminal of the battery, and the negative terminal of the source is connected to the negative terminal of the battery.

Care should be taken in charging the battery to make certain that its positive terminal is connected to the positive terminal of the source being used for charging purposes. If the battery is charged in the opposite direction, the plates will be reversed in chemical character, and if the charging is continued for any great length of time, the battery will be destroyed. If a battery has only been charged in the wrong direction for a short length of time it can generally be brought back to normal by



Courtesy General Electric Co.

Fig. 44—Left: 5 ampere Tungar storage battery charger.
Right: Trickle charger. Four taps on top of case permit different charging rates, from 0.5 amp. to 2 amp.

charging in the right direction for a very long time at a low charging rate.

Batteries are usually charged from the electric light current line. Where alternating current only is available, it must first be changed to direct current by means of a suitable rectifier, since alternating current changes rapidly in direction and would discharge the battery just as much as it would charge it. Several types of rectifiers are used for battery charging, but the Tungar bulb type is perhaps the most popular. Fig. 44 shows two sizes of Tungar chargers designed for home charging of storage batteries from the 110 volt a-c electric light circuit. One charges at the rate of 5 amperes while the other is a "Trickle Charger", designed to charge the battery continuously at the low adjustable rate of from 0.5 ampere to 2 amperes while the battery is supplying current to the radio receiver. The top of the glass bulb of the Tungar rectifier is visible in the trickle charger. In the 5 ampere charger it is completely enclosed with the necessary transformer in the sheet steel case.

Fig. 45 shows the internal connections of a charger of this type, together with a suggested layout of charger, charging switch, and A and B batteries, for a battery-operated radio receiver installation. Chargers of this type are also adapted for charging the lead-acid type of storage "B" batteries used in some places. The three pole double throw switch in Fig. 45 enables one to charge either the A battery or storage B battery at will.

Charging should be continued until the specific gravity ceases to rise any further on continual charging for an additional one-hour period. Usually the hydrometer reading will show about 1275 to 1300 at this time, but this is only true provided extra acid has not been added to the battery at some previous time.

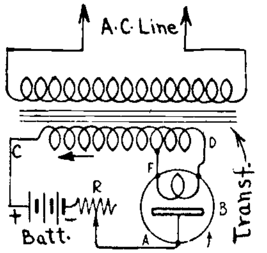
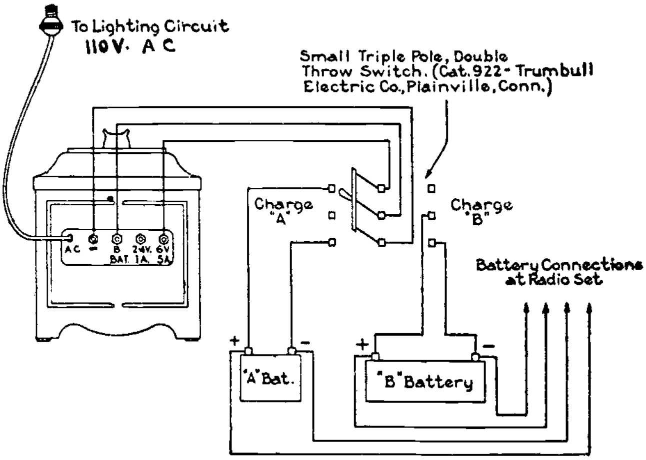


Fig. 45—Left: Internal connections of Tungar Battery Charger.

Right: Suggested layout of charger and "A" and "B" batteries so arranged that either the "A" or the "B" batteries may be charged.



Courtesy General Electric Co.

Ventilate the battery compartment when charging, in order to dispose of gas generated by battery. Never bring a flame or spark, such as candle, lantern or lighted cigar or pipe, near the battery when charging or shortly after. Keep the vent plugs in the cells. Do not remove them except to take specific gravity or temperature readings or to add water. If the cells flood or sputter electrolyte, the level is too high and should be lowered by withdrawing electrolyte.

When a direct-current charging circuit is available, as in the case where a 110 volt direct-current lighting circuit is at hand, no rectifier is needed and the charging of storage batteries is an easy matter. We cannot connect a 6 volt storage battery directly across a 110 volt charging source because a very large current would flow through the battery due to its very low internal resistance. This would damage the plates by overheating and buckling them and would blow the fuse in the electric light circuit. In order to limit and regulate the charging rate, a bank of lamps or other resistance unit should be connected in series with the line, as shown in Fig. 46. Ordinary 100 watt 110 volt incandescent lamps used in homes for lighting make very convenient and cheap forms of current limiting resistances, since each lamp will pass roughly about 1 ampere through the charging circuit. If a higher charging rate than this is required, 2 or more 100 watt lamps should be connected in parallel as shown. The total charging current is then equal to one ampere multiplied by the number of 100 watt lamps connected in parallel. It is usual practice to charge radio storage "A" batteries at a rate of 10 amperes. Thus, to charge a simple 6 volt battery at about a 6-ampere rate, connect a parallel bank of six 100-watt 110-volt lamps in series with the battery and charging circuit as shown in Fig. 46. The lamps will light up during the charging process.

Before connecting the battery to the charging circuit it is important to determine which side of the line is positive, by means of a voltmeter. If no voltmeter is available, dip the separated ends of the two line wires into a glass full of water containing a very small amount of battery electrolyte, or common table salt. A larger number of bubbles will rise from the negative wire than from the positive wire.

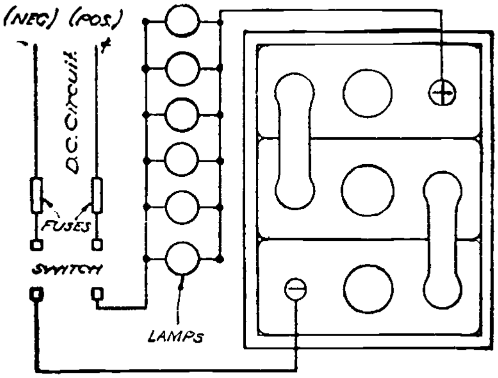


Fig. 46—Connections for Charging Battery from d-c Elect. light circuit through lamp Resistance.

Where two or more batteries are all to be charged at once at the same rate from a 110 volt d-c line, they may be connected with the positive terminal of one to the negative of the next, etc. When more than 3 or 4 batteries are thus connected the charging current passing through each 100 watt lamp is a bit less than 1 ampere due to the counter voltage of the batteries in series.

70. Care of lead storage batteries: It is very important to keep the battery clean and dry, for dampness or dirt permits the electric current to leak away over the surface between the positive and negative terminals, and in time accumulates sufficiently to corrode the terminals, and rot the case if it is made of wood. See that the battery, its connections and surrounding parts are kept clean, and the vent caps are in place and tight. It is considerably easier to prevent corrosion, especially when starting with a new battery, than it is to get rid of it afterward.

If corrosion has started, the only way to eliminate it is to scrape the corroded surfaces clean and then remove all traces of acid film from contact with the metal connections or terminals by the use of cloth or waste wet with ammonia or soda solution. Then (1) cover the metal surfaces which are connected together, with a film of pure vaseline to keep acid from creeping in afterwards, and (2) keep the top of the battery dry and clean.

It will be noted that pure vaseline is specified. This is because only a pure mineral grease with no filler or other material should be used. Ordinary grease generally contains an animal or vegetable fat, which, under usual operating conditions, is more corrosive than the battery electrolyte, and instead of preventing corrosion actually increases it.

The solution (electrolyte) is a mixture of pure water and pure sulphuric acid. Ordinarily the only loss in volume of electrolyte is from the loss of its water. Some water is lost by evaporation, but most of the loss is due to the action of the charging current which decomposes the water forming gases which are given off through the vent holes. Acid is never lost from the battery by evaporation or decomposition. It will, therefore, *never be necessary to add new electrolyte* unless some should get outside the cell through carelessness by leaving the vent plugs out or loose, or by bringing the level too high when adding water.

During the operation water must be added regularly to each cell. *Do not allow the surface of the electrolyte to get below the top of the separators;* keep it above by removing the vent plugs at intervals from all the cells and adding sufficient approved water to each cell as often as necessary. Do not fill higher than about 3/8 inch above the separators, otherwise electrolyte will be lost through the vent plugs. Less harm will result by allowing the level to get a little low than by adding too much water. After filling, be sure the plugs are replaced and tightened.

Only water free from impurities such as iron, lime, etc. should be used in storage batteries, for if impurities get into the battery they will either neutralize some of the acid or else cause local action inside the battery with resultant eating away of the active material. If in doubt as to the suitability of the water, clear rain water or distilled water should be used. Distilled water is now sold in quart bottles especially for the purpose.

If a battery is to be left idle for a few weeks, it should be stored away fully charged, for if it is left uncharged, crystals of hard lead sulphate will form on the plates. These will materially reduce the output and life of the battery because they are not readily converted back into lead peroxide and spongy lead during re-charging.

If a battery is not to be used for a long period of time, say a few months, it should be put into *wet storage.* The battery is first charged, then placed on wooden strips on a dry bench or shelf, so that air can circulate freely around it. Vaseline should be applied to all exposed metal parts. If possible the battery should be placed on a low-rate trickle charge of about half an ampere. The level of the electrolyte should be kept above the plates by adding distilled water. If continuous trickle charging is not possible, the battery should be charged until all of the cells are gassing freely, about every month or two.

71. Battery rating and life: The capacity of a storage battery is rated in *ampere hours,* that is, amperes × hours. The capacity decreases as the discharge rate is increased, due to the increased losses caused by internal heating of the battery and the inability of the acid to properly and quickly combine with the active material of the plates at the more rapid rate of discharge. Therefore it is usual to base the *normal discharge rate* for most batteries upon an 8 hour rate of discharge. For example, suppose a battery is rated at 100 ampere-hours. The normal rate of discharge is found by dividing 100 by 8, giving 12.5 amperes. This means that when the battery is fully charged, 12.5 amperes can be drawn from it for 8 hours. According to rules adapted by the National Electrical Manufacturers Association the *ampere-hour rating* of a radio "A" battery is based on the rate (amperes) at which the battery will discharge in 100 hours down to a cut-off voltage of 1.75 volts per cell, the cell temperature being 80 degrees Fahrenheit. The rating of a storage B battery is based on the same conditions, except than the time is 200 hours. The battery must deliver current at its rated capacity until it is charged and discharged three times. As storage batteries used on automobiles are called upon to deliver heavy currents when starting the engine, the Society of Automotive Engineer's ratings for storage batteries are based on a 20 minute discharge to an end voltage of 1.5 volts per cell.

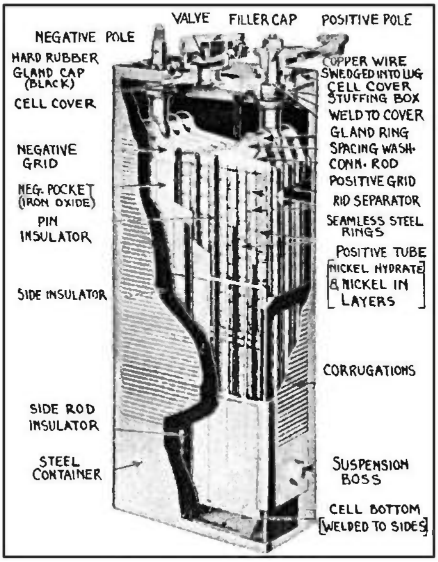
The life of a lead-storage battery varies from one or two to four or five years depending on the charge and discharge rates and the general care accorded it. Rapid charging or discharging tends to buckle the plates and causes the active material to *shed* from the pockets in the plates and fall to the bottom of the jar where it is useless. This of course decreases the amount of energy which the battery can store and deliver. Allowing the battery to stand idle when in a discharged condition causes the formation of hard sulphate crystals. When a battery approaches the condition where it must be replaced, it is generally unable to deliver current for anywhere near the usual length of time after being charged. This means that it must be charged very much more often than usual.

72. Edison nickel-iron-alkaline battery: Another type of storage battery in use is known as the "Edison nickel-iron-alkaline battery." The positive or nickel plate consists of a number of perforated steel tubes heavily nickel plated and filled with alternate layers of nickel hydroxide and pure metallic nickel in thin flakes. The tubes are drawn from a perforated ribbon of steel, nickel plated and reinforced with eight steel bands. These prevent the tube from expanding away from, and breaking contact with, its contents. The construction is shown in Fig. 47.

The negative or iron plate consists of a grid of nickel plated cold-rolled steel that holds a number of rectangular pockets filled with powdered iron oxide. These pockets are made up of finely perforated steel, nickel plated. After the pockets are filled, they are inserted in the grid and subjected to great pressure between dies which corrugate the surface of the pockets and force them into intimate contact with the grid. The (non-acid) electrolyte consists of a 21 per cent solution (mixed one part in five) of caustic potash (KOH) and distilled water with a small percentage of lithium hydroxide added.

The density of the electrolyte does not change materially on charge or discharge, so that the state of charge of an Edison cell cannot be determined with a hydrometer as in the case of the lead-acid cell. Each Edison cell has a voltage when fully charged of 1.2 volts and a voltage when discharged of 0.9 volts. Its state of charge should be tested by a voltmeter connected across its terminals. It may be overcharged or discharged, or even short-circuited without injury to the plates. It will retain its charge for a long time and is not damaged by being left in a discharged condition. Edison batteries may be charged by the same methods specified for lead-acid storage batteries. Distilled water should be added from time to time to make up for evaporation of the electrolyte.

Each cell container is made of heavily nickel plated sheet steel, making a very rugged assembly. The individual cells are mounted in wooden trays and are connected to one another by copper connections provided with tapered steel lugs. The positive terminals have bright red bushings on them while the negative terminals have black bushings for identification.



Courtesy Edison Stor. Batt. Co.

Fig 47—Interior construction of single cell of an Edison alkaline storage battery.

While Edison batteries require less attention, are lighter in weight, and have a much longer life than lead-acid batteries, their rather high internal resistance and high first cost have made their use and general application rather limited. The individual positive tubes and negative pockets of Edison storage batteries have been used for making B batteries. They are usually mounted in glass test tubes for this purpose, a number of them being arranged in a rack and connected up in series. A thin layer of white mineral oil should be placed on top of the electrolyte in each tube to reduce the evaporation. B-batteries of this kind should be charged at a rate below 0.5 amperes.

(Review Questions on Following Page)

REVIEW QUESTIONS

1. Four vacuum tube filaments having the following resistances are all connected in series; 20, 4, 5, 10 ohms.
   (a) Draw the circuit diagram showing the connection.
   (b) What is the total resistance of the combination?
   (c) How much current will flow if the entire group is connected to a source of e. m. f. of 50 volts?
2. The resistances in question (1) are all connected in parallel.
   (a) Draw the circuit diagram for this connection.
   (b) What is the joint resistance of the combination?
   (c) What current will flow through each filament if the source of e. m. f. is 6 volts?
   (d) What is the total current taken from the battery?
3. The filaments of two 201-A vacuum tubes having a resistance of 20 ohms each are connected in parallel. In series with this group is another filament having a resistance of 10 ohms. The entire group is supplied with current from a 6 volt storage battery. What is the combined resistance of all the tube filaments, and the total current flowing?
4. A resistance of 950 ohms is required. Resistances of 1,000, 1,000, 450 and 650 ohms are available. Show how these may be connected up to make the resistance required.
5. Explain three ways in which e. m. f. may be produced. Which is used most in practice?
6. What is the internal resistance of a 6 volt storage battery which delivers 300 amperes on short-circuit through a cable of negligible resistance?
7. How does an ion differ from an electron? What is a positive ion?
8. Describe the internal construction of a dry cell and state why a dry cell must be discarded when it is used up.
9. Why is a dry cell not adapted to service where it must supply a current steadily for some length of time?
10. Explain the construction of the Eveready Air Cell A battery. What is the depolarizer in this battery? What advantage does the Air Cell possess over dry cells?
11. The filaments of four 201-A tubes are connected in parallel. Each filament takes 0.25 ampere at a voltage of 5 volts. How many dry cells would be necessary to supply the current for these filaments and how should they be connected? What value of single resistance must be connected in series with the filaments to reduce the voltage to exactly 5 volts at the filaments? Draw a complete diagram of connections.
12. Describe the internal construction of (a) the ordinary round cell "B" battery, (b) the Layerbilt B battery. What advantages does the latter construction possess?

13. What is the difference between a primary cell and a secondary or "storage cell"; between a cell and a battery?
14. Describe the internal construction of a lead-acid storage battery.
15. Explain the chemical reactions which take place in a lead-acid storage battery, (a) on charge, (b) on discharge.
16. Why can the state of charge of a lead-acid storage battery be determined by a hydrometer? What should the hydrometer reading be for a fully charged cell; a discharged cell?
17. What is the objection to allowing a lead battery to stand around completely discharged?
18. How may storage batteries be charged from 110 volt alternating current electric light lines; from 110 volt direct current lines?
19. Why must the positive terminal of the charging source always be connected to the positive terminal of the battery?
20. A 6 volt lead battery is to be charged at about a 5 ampere rate from a 110 volt D. C. line with 100 watt incandescent lamps to act as current adjusters. Draw the circuit diagram of connections, showing exactly how many lamps must be used.
21. Why should the top of a storage battery be kept clean and dry and the exposed metal parts coated with vaseline?
22. Why cannot the state of charge of an Edison battery be determined with a hydrometer? How should it be measured? What would be the reading for a fully charged cell?
23. What is the effect on a lead storage battery of (a) continued overcharging, (b) charging at very high rate, (c) allowing water level to get very low, (d) allowing battery to stand idle in discharged condition?
24. What proceedure must be followed when a battery is to be out of service for several months?
25. Why should pure water only, be used for keeping the electrolyte in batteries up to the proper level? Why is acid not added for this purpose?
26. What is meant by the ampere-hour capacity of a storage battery?
27. What are the active materials used in lead storage battery plates? What is the electrolyte?
28. If you did not have a voltmeter handy how could you determine which wire of a direct current battery charging source was positive and which was negative?
29. The internal resistance of a dry cell is 0.05 ohm. The e.m.f. of the cell, due to chemical action is 1.5 v. What current will flow in a wire having negligible resistance if it is connected across the dry cell terminals?
30 What current would flow in the above problem if the wire had a resistance of 10 ohms?

CHAPTER 6.

MAGNETISM

MAGNETISM IN RADIO — NATURAL MAGNETS — ARTIFICIAL MAGNETS — LAWS OF ATTRACTION AND REPULSION — MAGNETIC CLASSIFICATION OF SUBSTANCES — MAGNETIC LINES OF FORCE — TEMPORARY AND PERMANENT MAGNETS — MOLECULAR THEORY OF MAGNETISM — AGEING PERMANENT MAGNETS — PERMANENT MAGNET STEELS — MAGNETIC SCREENS — REVIEW QUESTIONS.

73. Magnetism in radio: Magnetic fields, permanent magnets and electromagnets perform very important functions in radio and television transmitting and receiving apparatus. Radio and audio transformers, magnetic types of loud speakers, phonograph pickups, B eliminators and power packs, battery chargers, etc., all depend for their operation on the proper use of magnetism and magnets. In fact, the transmission of radio signals themselves is partly due to the actions of the electromagnetic fields sent out through space by the transmitting aerials of the broadcasting stations.

The proper use of magnetism also plays a very important part in our everyday lives. There could be no dynamos for generating e. m. f. commercially on a large scale, and no electric motors to turn the wheels of industry, if it were not for the action of magnets. The telegraph, telephone, and thousands of other common necessities of life depend upon magnetic action. Like electricity, we cannot actually see magnetism, but that does not prevent us from learning a great deal about it by studying its many effects which can be seen and measured.

74. Natural magnets: We probably all first come in contact with magnetism during our childhood days when we "discover" that the common small steel horseshoe magnet, (painted bright red) will pick up nails, needles and other iron objects. Some of us also find that a straight bar magnet consisting of a magnetized piece of hard steel will point north and south when suspended in a horizontal plane by a piece of thread.

Magnetism first became known to our world many years ago, (probably independently in different places and at different times) when it was discovered that lumps of a certain kind of iron ore found in the ground would always point approximately to the north star (direction of the north pole) when suspended so that they could move freely. This ore was used as a compass by the early Norse navigators and for land navigation by the Chinese as early as 218 A. D. This ore (iron oxide, Fe_3O_4) was called *lodestone* or *leading stone.* It is now called *magnetite.* Not all magnetite is found already magnetized. The word "magnet" originated from the fact that the best specimens of lodestone were originally found mostly in the city of *Magnesia* in Asia minor. A knowledge of these stones reached Greece as early as 585 B. C. Magnets of lodestone are called natural magnets, because they are found in the earth already magnetized.

75. Artificial magnets: If a piece of hard steel be stroked continuously in the same direction with a piece of lodestone it will be found that the steel also becomes magnetized. If it is suspended by a piece of thread it will always point in a north and south direction. If it is dipped into a quantity of iron filings, small iron tacks or nails, and withdrawn, the filings or nails will adhere to it, particularly at two well defined points as shown in (A) of Fig. 48. These points are called the *poles* of the magnet. They are the places on the magnet where lines of magnetic force either enter or leave it. The pole which always points to the north magnetic pole of the earth when the magnet is suspended freely, is called the *north seeking*, or simply the *north* (N) pole of the magnet. The other is called the *south* pole (S).

The earth itself is a great big magnet, with its magnetic poles lying within short distances of the true north and south geographical poles of the earth.

This property of attracting iron and steel is called *magnetism*, and the body possessing it is called a magnet. Natural magnets are not used commercially now, because many alloys of iron have been developed which make stronger and more satisfactory magnets than these. Also, artificial magnets are no longer magnetized by stroking them with lodestone, but, as we shall see later, they are now magnetized very powerfully by inserting them in coils of insulated wire through which electric currents are sent.

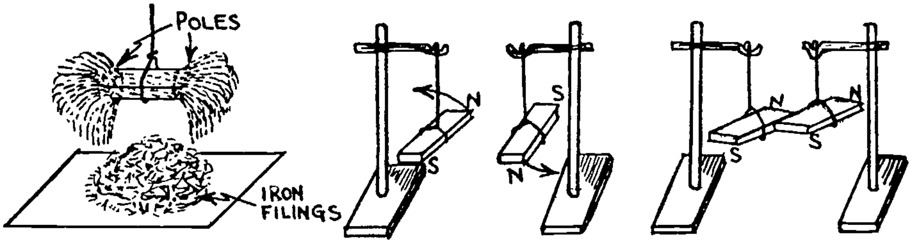
76. Laws of attraction and repulsion: If two bar magnets made of hard steel are freely suspended by a string, one at a time, their north and south poles can be determined by noticing which end points toward the north pole of the earth in each case. These poles can then be marked on the magnets. Now if the north pole of one magnet is brought near the north pole of the other, as shown in B of Fig. 48, they will be found to exert a force of repulsion between each other. If the south pole of one is brought near the south pole of the other, repulsion will take place again. If the south pole of one is brought near the north pole of the other, a force of attraction will draw them together as shown in C of Fig. 48. The same action will take place if north pole of the first is brought near the south pole of the other. These results may be summed up in the first two laws of magnetic attraction and repulsion:

(1) *Unlike magnetic poles attract each other.*

(2) *Like magnetic poles repel each other.*

It has become common practice to call that pole of a magnet which is attracted toward the earth's north geographical pole, the *North* magnetic pole. Therefore, it is evident that since unlike poles attract, the earth's magnetic pole in the northern hemisphere must really be a *south* magnetic pole. Likewise, the earth's magnetic pole in the southern hemisphere is really a *north* magnetic pole.

The force of magnetic attraction and repulsion between two magnets decreases very rapidly as the distance between them is increased, and of course increases greatly as they are brought nearer together. This can be proved experimentally by placing the unlike poles of two bar magnets about one half inch apart and noticing the strength of the attraction, and then placing them about four times as far apart and again noticing the attraction. If a delicate spring balance were used to measure the force in each case, it would be found that when the distance is



(A) (B) (C)

Fig. 48. (A) Bar magnet attracts iron filings mostly at its ends (poles).
(B) Like poles repel each other.
(C) Unlike poles attract each other.

increased four times, the force of attraction or repulsion is only *1/16 as* much. That is:

(3) *The force of attraction or repulsion between two magnetic poles is inversely proportional to the square of the distance between them.*

Representing the pole strengths by *m* and *m'* respectively and the distance between them by *d*, the force *F* is found from the equation:

$$F = \frac{m\,m^1}{d^2} \qquad (11)$$

This relation is a very important one to remember. We shall see later that the distances between the stationary magnet poles and the poles on the moving parts of loud speakers are kept as short as is practical, in order to develop strong forces to move the loudspeaker cone or diaphragm. If the air gap is made large the speaker will sound weak. The reader will note the similarity between the laws of attraction and repulsion between magnets and the laws of attraction and repulsion between electric charges already stated in Art. 13.

When a magnetic substance is stroked by a magnet, the induced pole is opposite to the inducing pole. That is, if a N pole is used, it will induce a S pole at the end of the magnetic substance it strokes.

77. Magnetic classification of substances: Any substance capable of being magnetized or attracted by a magnet is commonly termed a *magnetic substance.* Those that are not noticeably attracted are usually called *non-magnetic.* In recent years it has been found that some substances also become weakly magnetized in a direction opposite to that of the magnetizing field. Therefore a more detailed classification of magnetic substances than the above has been formulated.

When certain substances such as bismuth, antimony, copper, silver, zinc, sulphur, mercury, gold, water and quartz are placed in an intense magnetic field, they become very weakly magnetized in a direction *opposite* to that of the magnetizing field. They are called *diamagnetic substances.*

When certain substances such as air, oxygen, manganese, chromium, platinum, aluminum, etc., are placed in an intense magnetic field they become very weakly magnetized in the same direction as the magnetizing field. They are called *paramagnetic substances.*

When iron, steel, nickel or cobalt are placed in a magnetic field they become very strongly magnetized in the same direction as the field. These substances are characterised by the fact that a weak field produces a strong magnetization in them. They are called *ferromagnetic substances.*

The paramagnetic and the diamagnetic substances become so weakly magnetized under the action of even comparatively strong fields that for practical purposes they are considered as being non-magnetic. In practical work, the *magnetic substances* are considered to be steel, iron, nickel, and cobalt; soft iron being the best magnetic substance of the four and cobalt the weakest.

In the practical applications of magnetism, steel and iron are used mostly as the magnetic substances. Small percentages of nickel, chromium, cobalt or tungsten are added to steel for making commercial permanent magnets having great magnetic strength and certain other desirable properties as we shall see later. All other substances, such as air, brass, copper, aluminum, zinc, glass, etc., are practically non-magnetic. These substances allow magnetism to go through them however, without themselves becoming magnetized to any noticeable extent.

Experiment: This can be proved by bringing samples of all of these materials up to the poles of a powerful permanent or electro-magnet. It will be found that only the samples of iron, steel, nickel, cobalt and chromium will be attracted, and the latter three only very weakly. Now a thin sheet of brass or copper is placed against the poles of the magnet. A piece of iron placed on top of this will be attracted to the magnet, showing that the magnetic force penetrates right through the non-magnetic copper or brass. If the copper or brass is now dipped in iron filings, it will not attract them, showing it is not magnetized.

78. Magnetic lines of force: When we dipped the magnet in iron filings (A of Fig. 48) we saw that the attractive force of the magnet was greatest in the vicinity of the places we call the *poles.* As will be shown presently, magnetic effects are noticeable for a considerable distance in the space surrounding a magnet. This space around a magnet in which a magnetic substance would be subject to mechanical forces of attraction or repulsion if placed in it, is called the *magnetic field.* It is convenient to speak of the *direction* along which the magnetic force is acting at any point in the magnetic field, as a *line of force.* The student should not fall into the habit of looking upon magnetic lines of force as actual lines having physical existance, for this idea will be found misleading. There are no lines around a magnet. What we call lines of force are merely the imaginary lines along which the magnetic forces act. The total number of lines of magnetic force crossing a given space or field is called the *magnetic flux.*

If fine iron filings are sprinkled over a piece of thin paper placed on

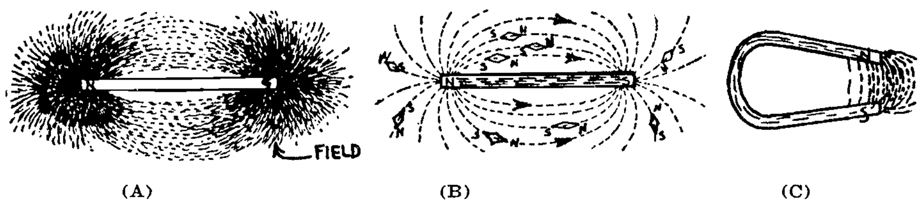


Fig. 49—(A) Poles at the ends of a simple bar magnet as shown by the concentration of iron filings there. (B) Compass needle positions around a bar magnet. (C) Concentration of field by horseshoe magnet shape.

a magnet, they will arrange themselves in definite lines around the magnet as shown in (A) of Fig. 49. These lines mark out the general direction of the magnetic force around the magnet. If a short magnetic compass needle is moved around in the field of the magnet, it will set itself in the direction of the magnetic force acting at any point in the field at which it is placed, as shown at (B) of Fig. 49. Thus the complete field around a magnet may be plotted either by means of iron filings or a short compass needle, even though the magnetic forces are themselves invisible. The magnetic maps or figures obtained in this way are often of great service in showing the actual distribution of the magnetic field in a magnetic device. Thus the intensity and directions of the fields around power transformers and choke coils in electric radio receivers may be easily studied by these methods. The strength of the magnetic field at any point is expressed in terms of lines of force per square inch at the point considered. This is called the *flux density.*

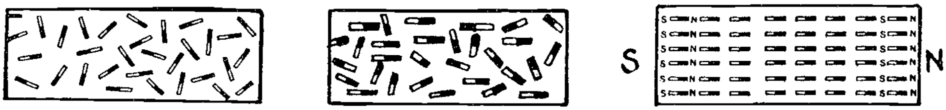
For the convenient description of some electrical facts it has become common to assign direction as well as position to lines of force. By agreement, lines of force are said to come out of the N pole of a magnet and enter the S pole. They then continue through the magnet to the N pole, always forming closed curves or loops as shown in (B) of Fig. 49. The lines of force really show the paths a tiny north pole would take if it were placed in the magnetic field and were free to move under the influence of the magnetic field. It would be repelled out by the north pole and be attracted around to the south pole.

Examination of (A) of Fig. 49 shows that the lines of force of a bar magnet must traverse quite a long path through the surrounding air—which is a very poor magnetic material. If the bar magnet is bent around in the form of a horseshoe, as shown in (C) of Fig. 49, the path of the lines of force is mostly through iron, which is a good magnetic material, and there is only a short path through the air between the poles. In this form most of the magnetic force would be concentrated in the short space between the poles, making it a much stronger magnet than the bar magnet. Permanent magnets used in practice are usually of the horseshoe shape. In radio equipment, horseshoe permanent magnets are used in earphones, magnetic type loudspeakers and electric phonograph pickup units. The pieces of steel are first bent into shape and any holes required are drilled while they are soft. Then they are hardened by heating to a red heat and quickly dipping into water or oil. They are then magnetized by powerful horseshoe electromagnets. Special alloys of steel are used for permanent magnets because soft iron would not retain its magnetism. While soft iron possesses a greater attractive force than hard steel while the magnetizing force is present, the steel possesses far superior attractive properties to the iron, after the magnetizing force is removed.

79. Temporary and permanent magnets: If a strong horseshoe magnet is dipped in soft iron filings or soft iron nails they will be attracted to it and themselves become magnetized and attract each other. If they are removed from the magnet they lose their magnetism entirely. Their magnetism is only *temporary*, that is, they are *temporary magnets*. The horseshoe magnet used, retained the greater part of its magnetism after it was magnetized. Therefore it is a *permanent* magnet. Most magnetic substances such as wrought iron, soft steel, nickel, etc., will lose practically all of their magnetism as soon as the magnetizing force is removed. Hardened steel and its alloys retain the magnetic property for a long time. The permanent magnets used in electrical measuring instruments, earphones, loudspeakers, phonograph pickups, etc. are made of hardened steel alloys.

The power of a specimen to retain its magnetism when the magnetizing force is removed is known as the *retentivity*. Steels used for good permanent magnets have great retentivity. The harder the substance, the greater its retentivity. Soft iron has very little retentivity. The magnetism which a piece of iron or steel retains after it has been subjected to a magnetizing force of some kind is called the residue or "*residual*" magnetism.

80. Molecular theory of magnetism: Many theories have been developed to attempt to explain the various magnetic actions. One popular explanation called the "molecular theory of magnetism" assumes that each molecule in a magnetic substance is itself a tiny magnet with a north and south pole. When the substance is not magnetized, all of the molecules are supposed to be arranged in rather haphazard positions as shown in (A) of Fig. 50, with the poles neutralizing each other so that no manifestations of magnetism are observed outside of the body. The process of partly magnetizing the magnetic substance consists in bringing it under the influence of a magnetic force so that some of the molecules are turned around to one direction as shown at (B) of Fig. 50. At (C) all



(A) (B) (C)

Fig. 50—The molecules are represented like tiny bar magnets in (A) unmagnetized iron; (B) partly magnetized, (C) completely magnetized (saturated) iron.

of the molecules have been turned around and the bar is completely magnetized. They then work together as one magnet, since the combined forces of the separate molecules all act in the same direction.

It must be admitted that this theory of magnetism is supported by many facts which can easily be proved experimentally. For instance, heating or jarring a magnet weakens it greatly since both of these processes make it easier for the molecules to move back to the haphazard positions of (A) in Fig. 50. When a magnet is rapidly magnetized and demagnetized it becomes heated, thus indicating that friction exists due to the motion of the molecules. If a magnet is broken in the middle, opposite poles are found on either side of the break. Careful measurements indicate that substances undergo a series of changes in length when being magnetized. In general, the substance first expands and later contracts. This latter phenomenon of contraction is known as "*magneto-striction*". The difference between permanent magnets and temporary magnets, is due to the fact that in the hard steel used for permanent magnets there is greater friction between the molecules. After the molecules are turned around during magnetizing, this friction prevents them from turning back easily. If a piece of iron be placed in a magnetic field, the amount of magnetization increases as the strength of the inducing field increases. At last a condition is reached where all of the molecules have been turned around as shown at (C) of Fig. 50. The iron is then said to be magnetically *saturated*, because all of its molecules have been completely turned around and its magnetism cannot be further increased. The ease with which a magnetic steel saturates is in many cases a determining factor as to whether it will be used for a particular device. As we shall see later, the electron theory of magnetism goes a bit further in explaining the nature of the causes of magnetism in terms of the molecular currents and structure of the atom.

81. Ageing permanent magnets: In many practical applications, it is essential that the flux density of a permanent magnet shall remain as constant as possible for a long period of time. Examples of such cases are, the permanent magnets in moving-coil ammeters and voltmeters, the brake magnets of electric watt-hour meters, and the magnets in earphones, loud speakers and phonograph pickup units. A permanent magnet becomes gradually weaker with age. The strength falls off sharply soon after it is magnetized and then decreases at a very much slower rate. The loss of strength is hastened by excessive jarring or heating of the magnet. The loss of magnetic strength is caused by a structural rearrangement of the molecules of the steel, some of them going back to their haphazard positions. It is possible to artifically "age" permanent magnets by heating them to suitable moderate temperatures below the point where the steel would be softened. This is called "ageing" because it is an artificial and quick method of bringing the magnetic strength down to the nearly steady value which a long period of years would naturally accomplish. The ageing process is used extensively in the manufacture of permanent magnets for electrical measuring instruments, etc. Magnets may be aged by heating them to 100° C. for about 12 hours.

82. Permanent magnet steels: Originally, permanent magnets were made of tempered high-carbon steel. The demand for permanent magnets having a greater permanency and constancy than these magnets provided, led to the use of alloyed steels. (An alloy is a simple mixture of the two or more metals. The metals do not enter into chemical combinations with each other.) It was found that certain alloys of iron and tungsten, and iron and chromium, had these desirable properties. Tungsten magnet steel is now used almost exclusively for the permanent magnets in high grade electrical indicating instruments.

Recently it was found that alloys of iron and cobalt could be made having greater permanency or higher coercive force than the tungsten alloys. The *coercive force* of a magnetic material is a measure of the amount of applied opposing magnetizing force required to completely demagnetize the sample and completely remove any residual magnetism. It is therefore a measure of the permanence and the merit of a steel intended for permanent magnets. Tungsten magnet steel usually contains about 6 per cent tungsten and 0.55 to 0.80 per cent carbon, the remainder being iron. A loud speaker unit employing a large tungsten steel permanent magnet is shown in Fig. 51.

Chromium magnet steel contains about 2 per cent of chromium, 1 per cent carbon and 97 per cent iron. An alloy of cobalt and iron must be added to chromium steel to make it useful for permanent magnets.

Cobalt magnet steel is of two types. Low cobalt steel has about 9 per cent chromium, 0.8 to 1.0 per cent carbon and 9 to 20 per cent cobalt. High cobalt or "Japanese Steel" contains 35 per cent cobalt, 3 to 4 per cent tungsten, 1 to 2 per cent chromium and 0.8 per cent carbon. Cobalt steel has come into general use in electro-magnetic phonograph pickups because of the large air gaps which have been employed in these devices. The size and weight of a suitable tungsten magnet to furnish adequate intensity of magnetism under these conditions would be too great.

Cobalt steel magnets are superior (bulk for bulk) to tungsten steel magnets. Since cobalt is an expensive metal, a 35 per cent cobalt steel must be used in moderation where economy is concerned. The object to be attained is to produce permanent magnets of suitable strength and

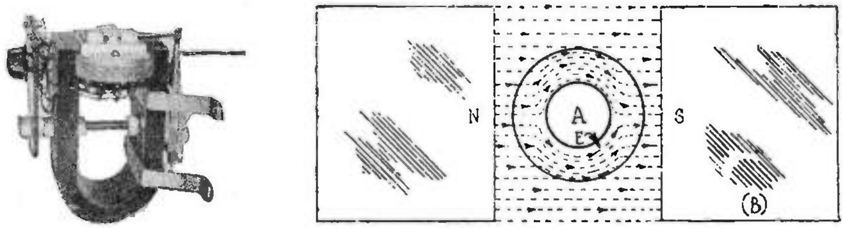


Fig. 51—Left: A cone-type loud speaker unit employing a tungsten steel magnet. Right: Magnetic "shielding" effect of an iron enclosing case.

dimensions at a reasonable price. With this end in view it is usual to employ magnet steel containing 9 to 15 per cent of cobalt, although 35 per cent is used in some cases.

In pickups having short air gaps, tungsten steel with its lower reluctance or resistance to magnetism, and its higher flux density, is used on account of its relative cheapness.

A special alloy steel has been developed for making permanent magnets of low cost, having a magnetic flux density of 20,000 lines per square inch in the air gap. This is used in loud speakers. The magnetization and re-magnetization of permanent magnets will be studied in connection with electro-magnets. The reader is referred to the sections on electrical measuring instruments, ear-phones, loudspeakers and phonograph pickups for illustrations of actual application of permanent magnets in radio equipment. Permanent magnets used in electrical apparatus are usually cadmium plated to prevent rusting. This gives them a dull silvery appearance.

82A. Magnetic screens: There is no material which will insulate magnetism, that is, entirely stop the lines of magnetic force. Magnetism will go through air, wood, brass or any other non-magnetic substance, but of course not as easily as it goes through iron or steel. The method of *shielding* or *screening* any device from the effects of a *steady* magnetic field is to use a soft iron enclosure that completely encircles the device as shown in (B) of Fig. 51. The iron enclosure E offers a good path for the lines of force to go through it, thus leaving the inner region A free from the field. This principle is used for enclosing certain measuring instruments to shield them from the effects of external stray magnetic fields. The enclosure must be made thick, so as to offer a very good path for the lines of force. A thin sheet iron enclosure is worthless as a shield for strong magnetic fields.

Experiment: The shielding action of a magnetic ring or enclosure can be illustrated by placing an *iron* ring between the poles of two bar magnets as shown in (B) of Fig. 51. Iron filings sprinkled over a thin sheet of paper placed over the magnets and ring will show by their position that the region inside the ring is free of magnetism. If a *brass* ring is substituted and the experiment is repeated, the lines of force will be found to go directly through the brass and the empty part inside as though it were not there at all, for it is a non-magnetic substance.

When the field is *rapidly changing* in strength or direction, it is common to magnetically shield an object located in it by enclosing the object in a non-magnetic shield of copper or some other good electrical conductor. In this case the energy of the field is absorbed by making it induce electric currents in the shield. This type of shielding is used around the coils in radio frequency amplifiers, etc. and will be discussed more in detail later.

Choke coils and transformers used in radio equipment are usually enclosed in soft iron cases but in most instances these cases are so thin that they do not act as magnetic shields to any great extent. This can be proved by connecting a pair of earphones to the secondary winding of an audio transformer and moving the transformer around in the vicinity of a power transformer operating from the 110 volt 60 cycle a-c-line. Any stray field around the power transformer will induce a voltage in the audio transformer winding and will be heard in the earphones as a low-pitched hum. The more stray field there is around the power transformer, the louder the hum will be.

REVIEW QUESTIONS

1. What is meant by magnetic lines of force? By a magnetic field?
2. What is a natural magnet; temporary magnet; permanent magnet? Is magnetite a permanent magnet or a temporary magnet? Why?
3. Name two devices used in radio receivers which depend for their operation on the use of permanent magnets.
4. Of what metals are permanent magnets made? Why?
5. How would you permanently magnetize a piece of hard steel by means of another magnet?
6. Upon what two factors does the force of attraction or repulsion between two magnets depend?

7. When the poles of two magnets are one inch apart, a force of attraction of 2 pounds exists between them. What force will exist if they are separated so they are 6 inches apart?
8. What is a diamagnetic substance? Name three.
9. What is a paramagnetic substance? Name three.
10. What is a ferromagnetic substance? Name four.
11. Explain how you would proceed to map the magnetic field existing around the horseshoe magnet in a magnetic loud speaker unit.
12. Explain what you mean by the molecular theory of magnetism. Give sketches.
13. Explain 4 observed facts regarding magnets which tend to support the molecular theory of magnetism.
14. What is magneto-striction?
15. What do you understand retentivity to mean?
16. What is coercive force? Of what use is it in expressing the suitability of a material for use in permanent magnets?
17. Why should permanent magnets used in electrical measuring instruments be "aged"? How is this accomplished?
18. How would you determine the N and S poles of a bar magnet which was not marked, if you had no other instruments to aid you?
19. How could you protect the delicate steel hairspring in your watch from becoming magnetized when you are in the vicinity of powerful electromagnets?
20. Why are permanent magnets usually made in horseshoe or U-shape? Explain the reasons for your answer.
21. What are the advantages of cobalt steel for use in permanent magnets? Name one disadvantage.
22. According to the molecular theory of magnetism would you expect a piece of steel to get warm or cold if its magnetism was rapidly reversed in direction over and over again? Explain!

CHAPTER 7.

ELECTROMAGNETISM

USE OF ELECTROMAGNETS — MAGNETIC FIELD AROUND A STRAIGHT CURRENT CARRYING CONDUCTOR — MAGNETIC FIELD OF A SOLENOID — POLES OF A SOLENOID — EFFECT OF NUMBER OF TURNS — CAUSE OF MAGNETIC FIELD AROUND A WIRE — THE ELECTRON THEORY OF MAGNETISM — MAGNETOMOTIVE FORCE — ELECTROMAGNETS — KINDS OF ELECTROMAGNETS — MAGNETIZING PERMANENT MAGNETS — PERMEABILITY — MAGNETIZATION CURVE — MAGNETIC SATURATION — MAGNETIC CALCULATIONS — AMPERE TURNS TO PRODUCE A GIVEN FLUX — HYSTERESIS LOSS — REVIEW QUESTIONS.

83. Use of electromagnets: While permanent magnets have definite uses in radio and electrical work, magnetism produced by electric currents flowing through electrical conductors is employed far more in practical electric devices because it is possible by this means to create much stronger magnetic fields. Also, many of these devices, for example the transformer, depend for their operation on a changing or varying field which cannot be obtained practically with a permanent magnet. Almost every part and wire in a radio transmitter and receiver has around it an associated magnetic field produced by the current flowing through it. Electromagnetic fields, more intense than could be obtained by the permanent magnets made of the alloys available at the present time, are in daily use in the fields of electro-dynamic speakers, in transformer cores and in the field frames of electric motors and dynamos.

Most of the facts concerning magnetism and permanent magnets explained in the previous chapter were set forth by Gilbert as early as 1600. Of course the development of the various special steel and nickel alloys which have made possible the manufacture of very small permanent magnets having remarkably high strength, came only recently. Many of the early electrical experimenters suspected that there was a relation of some kind between magnetism and electricity, but it was not until 1819 that Oersted, a Danish physicist, discovered a definite relation between the two, namely, that a flow of electric current is *always* accompanied by surrounding lines of magnetic force which have exactly the same properties as those which surround permanent magnets. This quickly led to a tie-up of the studies of magnetism and electricity, which, up to that time had been considered separately.

84. Magnetic field around a straight current-carrying conductor: Oersted found that an electric current, which represents charges of electricity in motion, produced a magnetic field. This was easily demonstrated by placing a small compass needle (a small permanent magnet pivoted on a bearing having very little friction) in the vicinity of the wire. The fact that the needle would always turn around to a position at right angles to the length of the wire, indicated that it was being acted upon by some force. Since the only thing which will act upon a magnet not in contact with anything other than the air is a magnetic field, it was evident that the electric current produced a magnetic field in the space around the wire.

Experiment: Oersted's experiments can be repeated with the aid of a 6 volt storage battery (or two or three dry cells connected in series); a piece of rather large size wire (about No. 10 or 12 B. & S.) about 4 or 5 feet long, and either with or without insulation; some fine iron filings (obtainable from the local machine shop); a piece of cardboard, and a small compass needle.

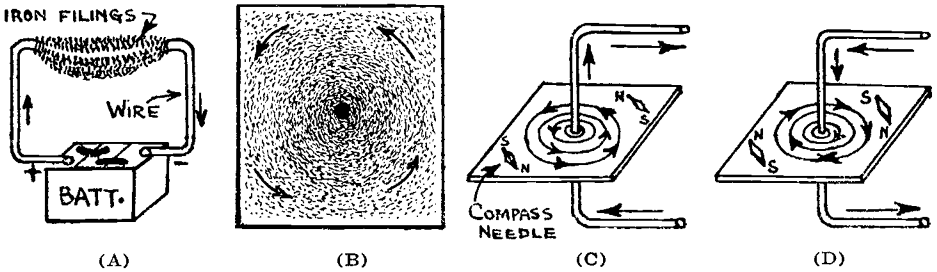


Fig. 52—Iron filings attracted to a current-carrying wire. Magnetic field surrounding a conductor.

Connect the wire across the source of e. m. f. so current flows through it. Now dip the wire into the iron filings. They will arrange themselves in circular form around it as shown in (A) of Fig. 52 proving that a magnetic field exists around the wire. Now disconnect the wire from the battery. The iron filings will immediately fall from the wire, proving that the magnetic field exists only while the current flows, that is, the magnetic field is caused by the current.

Now connect the wire across only one cell of the battery. Dip it into the filings and notice how many cling to it. Connect the wire across two cells of the battery (sending twice as much current through it). Notice that more filings now cling to it. This indicates that the intensity or strength of the magnetic field around the wire is very strong near the wire and diminishes in strength as the distance from the wire increases. The strength of the magnetic field is inversely proportional to the *square of the distance* from the conductor.

Experiment: Now pass the same wire up through a small hole in a horizontal piece of cardboard as shown in (C) of Fig. 52. Send the current through it and sprinkle iron filings lightly on the cardboard around the wire. Tap the cardboard lightly with a pencil and the filings will arrange themselves in concentric circles around the wire and at right angles to it, as shown at (D) (by using paraffin-paper instead of cardboard, the picture of the magnetic field may be made permanent by applying heat). The filings being small magnetic bodies free to move, arrange themselves in the direction of the magnetic forces (lines of force) surrounding the wire. A small compass needle held near the wire as shown at (C) of Fig. 52, will take up a position tangent to the circular field at any point, whether the current be sent up the wire or down the wire. This field exists at all points along the wire as can be proved by sliding the cardboard along it.

Experiment: Mark on the cardboard the position of the poles of the compass needle when it is placed at various places on the cardboard as shown in (C) of Fig. 52. Now reverse the connection of the wire to the battery, so as to reverse the direction of the current through it. Notice that the compass needle now reverses in direction as shown in (D) of Fig. 52, proving that the direction of the magnetic field produced depends on the direction of the flow of current. The direction of the magnetic field around a current-carrying wire can be determined by the Right Hand Rule for wires (Fig. 53) which states: "*Grasp the wire in the right hand with the thumb in the direction in which the current is flowing; then the fingers will be pointing in the direction in which the magnetic lines of force encircle the wire.*" Prove this rule by noticing which way the compass needle points when placed on the cardboard, remembering that the *current* flows from the positive terminal through the wire to the negative terminal of the battery; also that the lines of force in the magnetic compass needle go from its S pole, through the needle, and out of the N pole, and the needle will set itself so its lines of force are going in the same direction as those of the field around the wire, that is the N pole of the compass needle will point in the direction of the lines of force around the wire as shown in (C) of Fig. 52.

These simple experiments show clearly that when a current flows through a conducting path, magnetic lines of force surround it in concentric circles. (These are sometimes called *magnetic whirls* because of their circular form.) The direction of these lines of force depends upon the direction of the current. The greater the strength of the current (number of amperes) the stronger is the magnetic field. The magnetic lines of force are distributed uniformly along the entire length of the conductor. No *magnetic poles* exist around a *straight* current-carrying wire because the lines do not enter or leave the wire at any points. The direction of the lines of force around a wire may be determined by using the following Right Hand Rule For Wires:

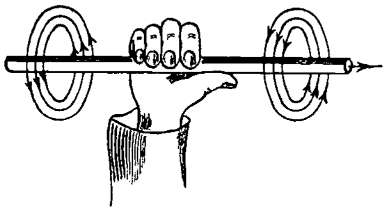


Fig. 53—Right-hand Rule for finding the direction of the current through or the direction of the magnetic field around a conductor.

"*Grasp the wire with the right hand with the thumb extended in the direction in which the current is flowing, then the fingers will be pointing in the direction in which the magnetic lines of force encircle the wire.*" (Fig. 53.)

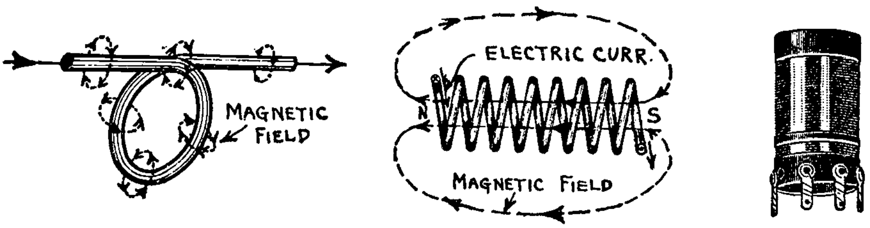
If it is desired to determine the direction in which a current is flowing through a wire, a compass needle can be placed near the wire, and by noting the position it takes and applying this rule the direction of the current can be determined. The student should check this in (C) and (D) of Fig. 52.

85. Magnetic field of solenoid: A solenoid is a coil of wire of more than one turn wound like a coiled spring as shown in (B) and (C) of Fig. 54, and having a non-magnetic core. A solenoid having but one turn (A of Fig. 54) is called a *loop* or *helix*. In electrical work the term *solenoid* is used extensively but in radio work the terms coil, and *inductor* have come into rather popular use. The student must remember these names, and remember that they are all used rather loosely to refer to the same thing although each really has a definite meaning as will be pointed out later.

If a wire or conductor is made into a single-turn loop, as shown at (A) of Fig. 54, all the circular magnetic lines of force which surround the wire will pass through the center of the loop as shown. The magnetic field within the loop is *more dense* than on the outside, since all the lines of force are concentrated into a smaller area here than on the outside where they spread out. However the *total number* of lines of force is the same inside the loop as it is outside.

By winding a number of these loops together as shown at B, a solenoid is formed having properties similar to a bar magnet. The magnetic fields or forces surrounding the individual turns of wire unite to form a resultant magnetic field or force around the entire coil. In C of Fig. 54 is shown a type of solenoid tuning coil used in radio receivers. This contains many turns of fine silk covered copper wire wound on a thin form of Bakelite.

We must remember that magnetic fields are really magnetic *forces.* "Forces" acting in the same direction combine to form a stronger resultant force equal to the sum of the individual forces. "Forces" acting in opposite directions oppose each other and their resultant force is equal to the difference between them. When a wire is wound into the form of a solenoid the magnetic forces around the individual turns act on each other. In Fig. 55 is shown a cross section view of a solenoid cut along its center axis, with the top half removed. The direction of current flow is down the back ends of the turns and up the front. A cross mark on the end of a

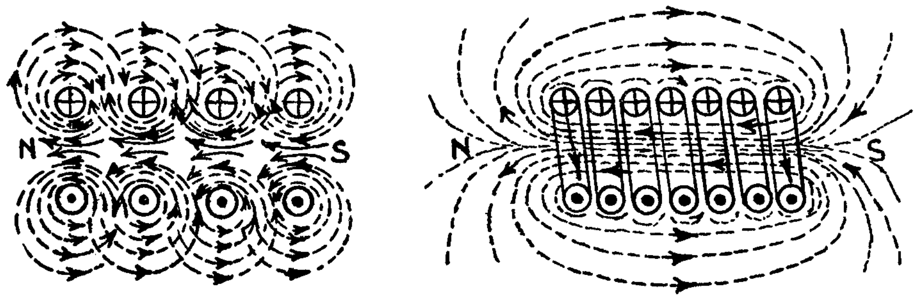


(A) (B) (C)

Fig. 54—Magnetic fields around (A) a single turn coil; (B) a solenoid. (C) A form of solenoid tuning coil used in radio receivers.

wire indicates that the current is flowing down from that point, (the tail of the arrow used for showing current direction). A dot on a wire indicates that the current is flowing up to that point (head of the arrow coming up).

At (A) of Fig. 55 are shown the lines of force actually existing around a few turns of the solenoid. The turns are shown spaced to make the illustration clear. Remember that the circular magnetic field exists all along the length of the wire of the solenoid. The direction of these lines of force is determined by the right hand rule. It will be noticed that inside the solenoid all the lines of force are in the same direction, therefore combining to produce a strong field through it as shown in (B). In the space between each two adjacent turns, the lines of force are equal in



(A) (B)

Fig. 55—How the magnetic fields or forces around the individual turns of wire in a solenoid coil as shown at (A), combine to form the resultant field shown at (B).

strength and opposite in direction as shown, so they cancel each other (the magnetic *forces* really neutralize each other) that is, there is no field between the turns. On the outside of the coil the lines of force of adjacent turns are all in the same direction, so they add or combine to produce a resultant field around the outside of the solenoid in the direction shown in (B).

86. Poles of a solenoid: Examination of (B) shows that the lines of force go through the center of the solenoid, out at one end, around the outside, and back into the other end. Thus a magnetic pole is formed at each end—one where the lines of force come out of the coil (N pole), and one where they enter the coil (S Pole), just as in the permanent steel magnet. It is evident that the direction of the *current* determines the direction of the lines of force and also the poles.

A simple rule for determining the polarity of a solenoid is as follows:

"Grasp the coil with the right hand so that the fingers extend in the direction in which the current is flowing around each turn of wire; the extended thumb will then point toward the north pole." (Fig. 56.)

This rule is sometimes called the Right-Hand Rule for solenoids. It should be remembered that the magnetic poles on a solenoid depend on the direction of the *current* through the coil and not on the direction in which the *coil is wound.* Attraction or repulsion exists between the poles of solenoids, just as it exists between the poles of permanent steel magnets.

87. Effect of number of turns: It is evident that since the magnetic field of force of each turn adds to that of the next turn, both in the center and around the outside of a solenoid, the more turns of wire the solenoid has, the stronger the magnetic field will be. The strength of the lines of force around each turn also depends upon the current flowing through it.

Experiment: Connect the battery to the piece of wire used in the previous experiment. Dip the wire into the iron filings and notice the quantity which cling to it. Now form a single turn loop with the wire as in A of Fig. 54 and dip it into the filings again. Note the great increase in strength as evidenced by the fact that a larger quantity of iron filings now cling to the wire. The current is still the same as in the previous tests, for the total length and resistance of the wire has not been changed and the same e. m. f. is being applied to it. The additional strength has been obtained by the concentration of all the lines of force around the entire length of wire into a small space around, and inside of, the single turn loop.

88. Cause of magnetic field around a wire: The magnetic field produced around a wire through which a current is flowing, is due simply to the electrons or negative electric charges moving through the wire. When considering static electricity (charges at rest), we found that bodies having like charges repelled each other, and bodies having unlike charges attracted each other. Electrons, being negative charges, will repel each other. Also, electrons will attract a positive atom (positive ion). When electrons are in *motion* they produce forces in the space around them. These are the forces which we have learned to call *magnetic* forces. They are the forces which are responsible for the action which current-carrying conductors exert on compass needles, iron filings, etc. The passage of one ampere across any section of a wire means that 6.28×10^{18} electrons move past that section every second. The movement of these electric charges produces a certain amount of magnetic force outside of the wire. There is no perceptible displacement of the positive or neutral copper atoms. They are comparatively heavy and do not migrate, whereas the smaller, lighter electrons thread their way between them and progress with a steady average speed which is proportional to the applied e. m. f. which drives them.

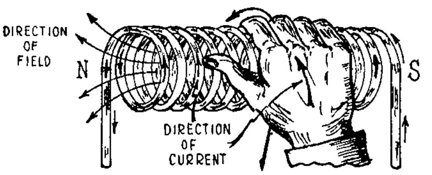


Fig. 56—Right-Hand Rule for determining the magnetic poles of a solenoid coil.

89. The electron theory of magnetism: We are now prepared to digress for a few moments from our study of electromagnetism, to find out just why some materials can be magnetized.

Shortly after Oersted discovered (1819) that exactly the same effects obtained from permanent magnets could be obtained from currents flowing in coils of wire, Ampere advanced the hypothesis that the observed actions of magnetism are to be accounted for in terms of the properties of electric currents. In the light of our modern knowledge and the electron theory, we now know that his ideas were substantially correct, and we are able to explain quite satisfactorily just what causes the mysterious magnetic forces in lodestone and iron which puzzled the ancients for hundreds of years.

The idea that a magnet is made up of innumerable smaller magnets of molecular dimensions, was put forward by Ampere over 100 years ago to explain the fact that however much a magnet is broken up into smaller pieces, each fragment is a complete magnet with a N and S pole. He even went further than this and offered an explanation in terms of molecular current orbits that is remarkably in accordance with our present theories on the subject.

Every atom of a substance is supposed to consist of one or more electrons revolving in more or less circular orbits around a center nucleus.

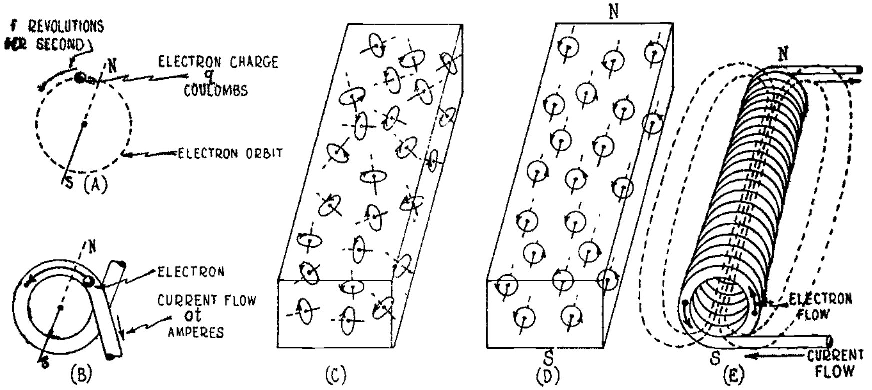


Fig. 57—Electron orbits in (A) an atom; (B) a one-turn loop of wire; (C) unmagnetized body; (D) magnetized body; (E) current-carrying solenoid.

For simplicity we will consider a single electron in an orbit. Now an electron of charge q (coulombs) revolving in a circular orbit (see (A) of Fig. 57) at a frequency of f revolutions per second, is equivalent to a current of qf amperes flowing around the same orbit or around a similar circular wire as shown at (B) of Fig. 57; (since a current of one ampere is equal to a flow of one coulomb of electric charge per second). (The atoms of higher atomic weights are thought to have many such electrons rotating in each orbit.) A magnetic force or field is thus created by each revolving electron just as a magnetic field is created by a movement of electrons (electric current) through the single-turn loop of wire shown in (A) of Fig. 54. (When applying the right-hand rule for determining magnetic poles, remember that the direction of current flow is opposite to that of electron flow.)

Magnetic substances contain one or more electron orbits, whose magnetic effect is not neutralized by oppositely directed orbits. When an external magnetizing force is applied to a magnetic substance, it acts on the magnetic force produced by each revolving electron and thus tends to turn these atoms so that the planes of their electron orbits are parallel to each other and perpendicular to the direction of the magnetizing force, the electrons all rotating in the same direction as shown in (D) of Fig. 57. The magnetic effects produced by the revolving electrons thus reinforce each other and become effective at points outside the body. (The atoms may be assumed to turn somewhat from their previous random distribution.) Thus the body as a whole exhibits the properties of magnetism. If a large number of the atoms are turned around by the magnetizing force as shown in the illustration, the resulting total magnetic force is strengthened, and we say we have a strong magnet. This is what occurs in the *ferromagnetic* substances.

In *paramagnetic* substances (see Art. 77) only comparatively few of the atoms turn around, so the magnetic effect is weak. If the magnetizing force is strong enough to turn all the available atoms or molecules around, the magnetic strength cannot be increased, and the body is said to be magnetically *saturated.* Thus, a magnet is really a highly complex system of spinning electrons and the external magnetic forces which magnets can exert is due to these electrons. A permanent bar magnet would look like (D) of Fig. 57 if we could see this structure. Comparison of (D) and (E) of Fig. 57 will show how similar a magnetized bar really is to a solenoid winding carrying a current. In both, the external magnetic field is due to the movement of electrons in circular paths.

In *diamagnetic* substances, the atoms and electron orbits are normally arranged as shown in (C) of Fig. 57 so that the resultant magnetic effect of each atom at points outside the body is zero. If an external magnetizing force is applied to such a substance, it exercises no directive effect upon the atoms, but the substance is not magnetically inert. Let us suppose that the external magnetizing force is produced by a current flowing through a coil of wire. During the building up of the current in the magnetizing winding, the electrons in the substance are subject to forces which tend to speed up those circling in the opposite direction to the electrons in the winding, and retard those circling in the same direction. The frequency of revolution of the electrons circling on one direction is raised, and that of those circling in the opposite direction is decreased. The result is that the atoms are no longer neutral, but they exert a resultant magnetic force in a direction opposite to that of the current in the magnetizing winding, since stronger magnetic forces are produced by the electrons revolving fastest. The flux density inside the magnetizing coil in the space occupied by the diamagnetic substance is therefore less than unity, i. e., less than it would be if the substance were not there and the space were filled with air instead. When the external field through the electronic orbits is removed, the electrons resume their normal frequencies of rotation.

It will be seen that the "electron theory of magnetism" is merely an extension of the "molecular theory of magnetism" explained in article 80. In the former, we get down to the fundamental structure of the atom for our explanation of the magnetic effects, whereas in the latter we consider the action of the molecules each consisting of a number of atoms.

90. Magnetomotive force: From the experiment described in Art. 87, it is evident that the total magnetic flux (lines of force) depends upon the number of turns of wire as well as the current strength. In exactly the same way that we looked upon electromotive force (flow of electrons) through the electrical circuit, a force called *magnetomotive force* (M. M. F.) is looked upon as that which is responsible for the production of external magnetic effects in bodies. The magnetomotive force which produces the magnetic flux in a solenoid is created by means of the current flowing through the turns of wire in the coil. This quantity is really not a *force*, in any sense of the word. The name is not a good descriptive name and has no justification, except for the fact that the *magnetomotive* force bears the same relation to the magnetic intensities along the path of the magnetism that *electromotive* force bears to the electromotive intensities at the various points along an electrical conductor.

The m. m. f. is directly proportional to the product of the current strength and the number of turns in a solenoid. If the current is expressed in amperes, the m.m.f. may be expressed by a unit called the *ampere-turn*. To find the magnetomotive force of a coil (air core) in ampere-turns:

Multiply the current in amperes by the number of turns on the coil, or

$$\text{Magnetomotive force} = \text{ampere-turns} = I \times T.$$

For example, 6 amperes flowing through 25 turns of a coil (25 turn coil) produces an m. m. f. of $6 \times 25 = 150$ ampere-turns. Exactly the same m. m. f. would be produced by one ampere flowing through 150 turns, or 150 amperes flowing through one turn, or 15 amperes flowing through 10 turns, etc.; the product of the turns and current in each case being 150.

It is evident from the above, that when a magnet winding is to be designed to produce a certain value of m.m.f. there is a certain latitude of choice possible for the number of turns and current to be used. It must be remembered that if the current is made large the wire must also be of large cross-section in order to carry the current satisfactorily without undue heating. If the current is small, a smaller size wire can be employed and more turns can be wound into a given space. (See Copper Magnet Wire Table for magnet wire turns-per-square-inch). However, the arrangement used in any case, is determined by the voltage and the current available for energizing the coil. For instance, a small magnet designed to operate directly from a 110 volt circuit would be wound with fine wire, so that its resistance would be high and the current requirement small, making it inexpensive to operate. Even though the current is small, considerable magnetizing force may be obtained due to the use of a large number of turns of wire. The same magnetic force could be obtained with fewer turns of coarse wire, but the resistance would be lower and more current would be taken from the source.

When only small values of current are available, a large number of turns of fine wire must be employed to obtain an appreciable amount of magnetism. In the magnet windings on a pair of high grade earphones for instance, the operating current is so weak that several thousand turns of very fine No. 40 or 50 enameled covered wire are employed. In the two electro-dynamic speaker field magnet windings shown in Fig. 58, we have a very good illustration of the choice of proper wire size and number of turns to meet the operating conditions. At (A), is a representation of the winding for a certain make of speaker designed to obtain its field current from a source delivering about 1.5 amperes at 12 volts. This winding contains 1600 turns of No. 21 enamel covered copper wire. The m. m. f. of the winding is $1.5 \times 1600 = 2400$ ampere-turns. The winding at (B) is for a similar speaker designed to obtain its field current from a vacuum tube rectifier circuit which is able to deliver 60 milliamperes (.06 amps.) at 300 volts to it. To produce the same m. m. f. as the winding (A), this one contains 40,000 turns of No. 36 enamel covered wire. The m. m. f. is $.06 \times 40{,}000 = 2400$ ampere-turns. Thus, the 1600 turn coil having 1.5 amperes flowing through it produces a magnetic field of the same strength as does the coil of 40,000 turns with .06 amperes flowing through it.

91. Electromagnets: If a bar of iron or some other magnetic substance is placed in a coil of wire when a current is flowing, as shown at (A) of Fig. 59, the iron becomes magnetized for the reason set forth in Art. 89. This forms what is called an *electromagnet.* When the iron is magnetized, the orbits of the rotating electrons are turned around (see (D) of Fig. 57) until their own magnetic fields are in the same direction as the field produced by the current in the winding. Needless to say, the addition of all of these fields of the atoms to the external field produced by the current in the coil alone, greatly strengthens the total field. We are really calling in the aid of the atomic currents—ready made currents which only require turning around—to obtain the powerful magnetic fields which electromagnets can be designed to produce. Thus, the magnetic core greatly strengthens the magnetic field.

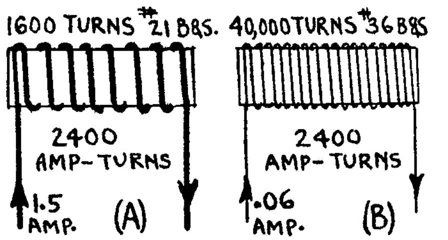
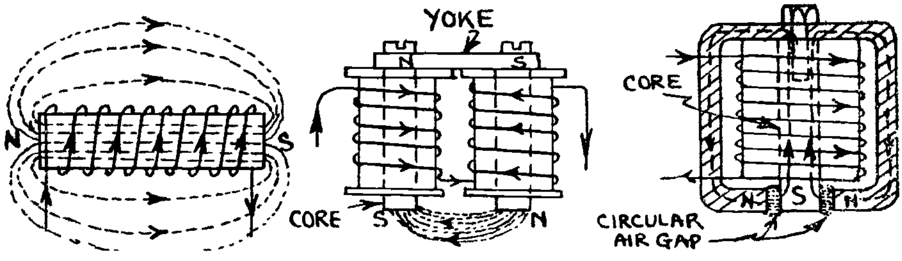


Fig. 58—Electro-dynamic speaker field windings both designed to produce same field strength with different values of field current.

Experiment: Dip the solenoid used in the experiment of Art. 87 into the iron filings and notice the quantity attracted. Now insert a bar of iron, or a bundle of iron nails or wires, inside of the solenoid so as to form a magnetic core. This will produce a great increase in the strength of the field as evidenced by the larger quantity of iron filings picked up. As soon as the circuit is opened, the current stops flowing and the iron loses most of its magnetism, but retains some residual magnetism. Thus an electromagnet with a soft iron core may be classed as a "temporary" magnet.

This may be explained as follows: When the magnetizing force is removed, most of the electron orbits remain in their new positions, being held there by their mutual attractions. In this case, we have "residual magnetism". If the iron is struck a sharp blow, the mechanical disturbance makes the electron orbits swing back to their haphazard arrangement as shown at (C) of Fig. 57. In hard steel, tungsten steel, cobalt steel, etc., considerable residual magnetism remains, even when the external magnetizing force is reversed, until the reversing field acquires considerable strength (coercive force). This indicates that in hard steel, the electron orbits are so large, or so close together, that when they are once in line a considerable force is required to turn them back to their former haphazard arrangement.

92. Kinds of electromagnets: Electromagnets are made in different shapes according to the uses for which they are designed. A straight *bar electromagnet* is shown in (A) of Fig. 59. At (B), a simple *horseshoe electromagnet* is shown. This is the form usually employed in earphones and other sensitive electromagnetic devices, due to the fact that the magnetizing force is applied mostly to iron, thus turning many electron orbits around and obtaining the additional strength created by the many electronic fields. Only a small air gap is in the magnetic circuit. It would be mechanically inconvenient to wind coils of wire on the ends of a U-shaped core. Therefore the two coils of horseshoe electromagnets are usually wound separately on spools which are slipped over the cores. The coils are both wound in the same direction for manufacturing convenience, and are then connected together as shown, so that the current will flow through them in opposite directions and produce the proper



(A) (B) (C)

Fig. 59—Three different forms of electromagnets

(A) A straight bar electromagnet.
(B) A form of horseshoe electromagnet.
(C) An iron-clad electromagnet, (coil completely enclosed by iron.)

sequence of magnetic poles shown. The cores are then attached to the ends of a bar of soft iron called the *yoke* to present a good magnetic path.

Where a very strong field is desired, the special *ironclad* form of horseshoe electromagnet is used. This is the type employed in lifting-electromagnets used to pick up scrap iron and steel, steel rails, etc. It also is used in telephone switchboard apparatus and for the field magnets of electro-dynamic loud speakers in radio receivers, where a very intense magnetic field is required in the air gap in which the voice-coil moves.

An electro-dynamic speaker field is shown at (C) of Fig. 59 and in Fig. 343. The coil is wound on a short, straight, round, silicon steel core, and this is bolted to the center of a round enclosing shell-shaped casting of steel. When the current is sent through the coil, lines of force from the inner end of the core extend through around the steel to the edges of this housing, then through the short circular air-gap to the core again. The outside shell of the core also forms a protective housing for the winding. Notice that this construction provides a very good magnetic path of large cross-section area. As we shall now see, the strength of an electromagnet depends not only on the number of ampere-turns, but also on the magnetic qualities (permeability) of the material used for the core, and on the length and cross-section area of the magnetic path.

The magnetic polarity of electromagnets is found by the same right-hand rule as used for solenoids (see Art. 86).

93. Magnetizing permanent magnets: Electromagnets of the horseshoe type are used extensively for strongly magnetizing horseshoe permanent magnets. The permanent magnet is placed in an inverted position with its poles resting on the poles of the electromagnet. Then the current is turned on and the permanent magnet is struck sharply with a hammer to aid the electron orbits to turn around so they all face in the same direction. Within a few seconds the current is shut off, and the magnetized permanent magnet is removed. The magnetizing force should be great enough to *saturate* the steel of the permanent magnet. Only direct current should be sent through the coil. Electromagnets for this purpose are usually designed for operation directly from the 110 volt direct current lighting socket. In order to preserve permanent horseshoe magnets from loss of strength, a piece of soft iron called the "keeper" is usually kept across its poles when it is not in use. The keeper furnishes a short closed path for the lines of force of the magnet and thus retains the atoms and molecules in their regular arrangements. Permanent magnets may be "aged" after being magnetized, by keeping them at a temperature of about 100° C (in boiling water) for several hours.

94. Permeability: If the m. m. f. (amperes $\times$ turns) of a solenoid with air core is kept constant, magnetic flux of a constant strength will be produced. If a soft iron core is slipped into the solenoid, thus forming an electromagnet, the magnetic flux will be increased about 300-fold without any increase in m. m. f. If a core of "permalloy" (alloy of nickel and iron containing from 45% to 80% of nickel), is inserted, the magnetic flux will be increased another 300-fold (provided the magnetizing force is low enough to prevent saturation). If a cast iron core were inserted, the magnetic flux would be weaker.

It is evident then that the "multiplying power" or the *strength* of an electromagnet depends upon the material used for the core. The ratio of the strength of the magnetic field with a given substance forming the entire core, to the strength of the field if air is used as the core, is known as the *permeability* (μ). The reciprocal of permeability, that is, 1 divided by permeability $\frac{1}{\mu}$, is called the *reluctance* of the substance. Non-magnetic substances all have a permeability of 1. All magnetic materials have permeabilities much greater than 1 (see Fig. 61). Substances of high permeability are of course preferable for use as cores of electromagnets, but the elements of cost and saturation characteristics must also be considered when selecting a magnetic material.

95. Magnetization curve: Fig. 60 shows the comparative increase in magnetism for five common magnetic materials, for a given increase in magnetizing force in ampere-turns per inch length of mag-

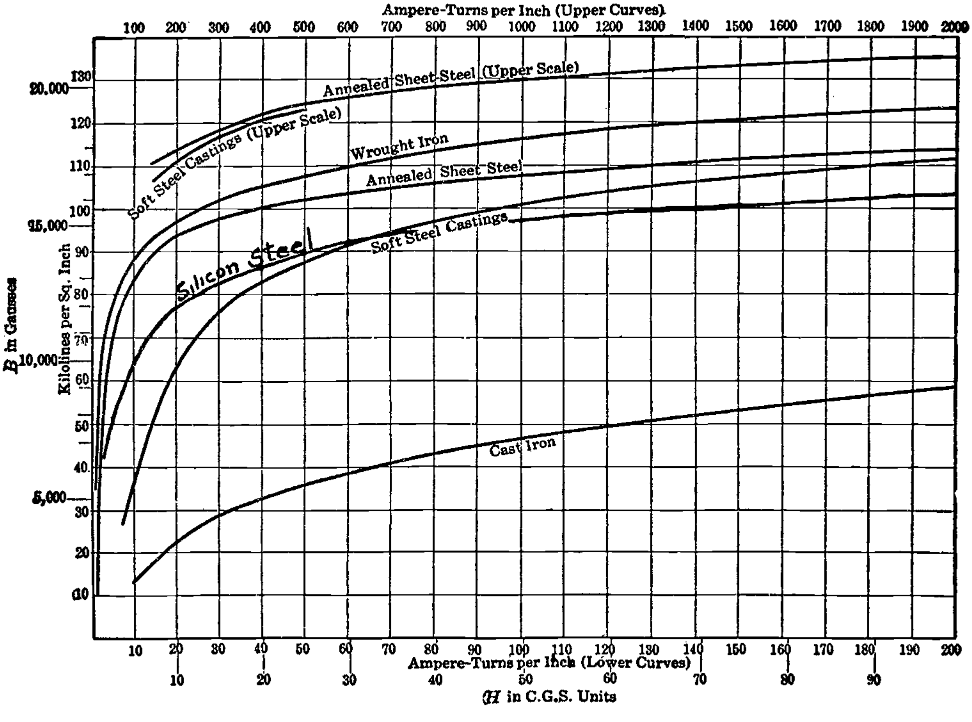


Fig. 60—"B-H" curves showing the relation between the magnetizing force H and the corresponding flux density B produced in various kinds of iron and steel.

netic circuit. This is called the *characteristic curve of magnetization*, or the *B-H curve*. The horizontal scale represents the increase in magnetizing force produced by the number of ampere-turns per inch. The vertical scale represents the increase in magnetic lines of force or magnetic flux in kilolines (1000 lines) per square inch of cross-section area. To use this *B-H* curve, follow the lower horizontal line to any of the numbers representing the magnetomotive force in ampere-turns per inch; then follow up the vertical line from this point until it intersects the curve of the material considered, from which point follow the horizontal line to the left side where the number of lines of force produced in the material, per square inch of cross-section, is recorded.

Thus, a m.m.f. of 100 ampere-turns per inch will produce about 47,000 lines (47 kilolines) of force per square inch in cast iron, 100,000 lines in soft steel castings and 116,000 lines in wrought iron. Wrought iron, which is very soft (annealed) will accommodate more lines of force than any similar material and hence is said to have high permeability. Mild steel is second and cast iron is third in this respect. Of course different grades of these materials vary in their permeability.

96. Magnetic saturation: When all the electron orbits of a magnetic material have been turned around by the magnetizing force, the material is *saturated*, and an increase of applied magnetizing force does not result in noticeable increase of magnetism. Examination of the curve for annealed sheet steel for instance, shows that for magnetizing forces up to about 10 ampere-turns per inch a large number of lines of force are produced per ampere-turn. Increasing the m. m. f. from 10 to 20 ampere-turns per inch only increases the flux from 83,000 lines per square inch to 93,000 lines; increasing the m. m. f. to 40 ampere-turns per inch only increases the flux to 100,000 lines and increasing the m. m. f. to 200 ampere-turns per inch only increases the flux to 114,000 lines. The nearer the B-H curve approaches to being a vertical line, the greater is the number of lines of force produced by a given number of ampere-turns. The point where it begins to flatten out is called the "knee" of the magnetization curve. Good design dictates that the cross-sectional area of the magnetic circuit should be made ample, so that the density of the flux in the magnetic material is not very much above the knee of the curve.

The peculiar shape of the magnetization curves may be explained by the electronic theory of magnetism. At magnetizing intensities which are insufficient to break up the permanent atomic groupings, the permeability is low; at intermediate intensities under which the groupings become unstable and start to break up, the maximum permeability occurs. An almost steady value of permeability is found as saturation occurs. The permeability decreases as the magnetizing force is increased after saturation has been reached; and a "residual" flux due to stable atomic grouping is formed while the atoms are aligned.

97. Magnetic calculations: The number of lines of force per unit area is called the *flux density*. When there is one line per square centimeter of cross-section area, the field strength is one *gauss*, or one *maxwell*. When one line goes through one square inch, the field strength is *one line per square inch*. The total number of lines through any given area is called the flux (Φ). To find the flux multiply the flux density B by the area A using the proper units. Thus:

$$\text{flux } \Phi = B \times A.$$

The total flux produced in a magnetic circuit is proportional to the m. m. f. applied, and inversely proportional to the reluctance of the circuit.

This is analogous to Ohm's law for the electric circuit. The reluctance is proportional to the length of the magnetic circuit and inversely proportional to its cross-section area. The *permeability* of the magnetic circuit is analogous to the *conductivity* of the electric circuit. The permeability of a given material is the reciprocal of the reluctance of a unit cube of this material.

For the magnetic circuit:

$$\text{Flux } \Phi = \frac{\text{magnetomotive force}}{\text{reluctance.}}$$

where Φ = flux in maxwells.
the magnetomotive force is in gilberts.

The magnetomotive force in gilberts is:

$$M.\ M.\ F. = 1.257 \times N \times I$$

where N = No. of turns of wire
I = current flowing through it (amperes)

The reluctance may be found from:

$$\text{Reluctance} = \frac{L}{\mu A}$$

where L = the length of the magnetic path in centimeters.
μ = the permeability of the material at the particular flux density used.
A = the cross-section area of the magnetic circuit. (sq. cm.)

Therefore the total flux is found from:

$$\text{Total Flux } (\Phi) = \frac{1.257 \times N \times I \times \mu A}{L} \text{ (maxwells)}$$

and the:

$$\text{Flux Density } (B) = \frac{\text{total flux}}{A} = \frac{1.257 \times N \times I \times \mu}{L} \text{ (gausses)}$$

The permeability of iron is not a fixed quantity but depends upon the flux density at which the iron is operated. Fig. 61, shows a set of curves which give the relation between the permeability and flux density of several magnetic materials. Notice that at low flux densities the permeability of the iron is fairly low, that there is a certain density at which maximum permeability is reached, and above this flux density, the permeability decreases.

The curves in Fig. 60 give the values of the flux density in kilolines per sq. inch produced by various magnetizing forces expressed in ampere-turns per inch length of magnetic path. On the same curves will be found corresponding values of flux density in gausses produced by the magnetizing forces H in C.G.S. units (gilberts per centimeter). The flux density in lines per square inch is equal to 6.45 times the density in gausses (since 6.45 sq. cm.=1 sq. inch). The magnetizing force in gilberts per *centimeter* is 1.257 times the ampere-turns per *centimeter*.

98. Ampere-turns to produce a given flux: If a magnetic circuit is not uniform, its total reluctance is obtained by considering the reluctance

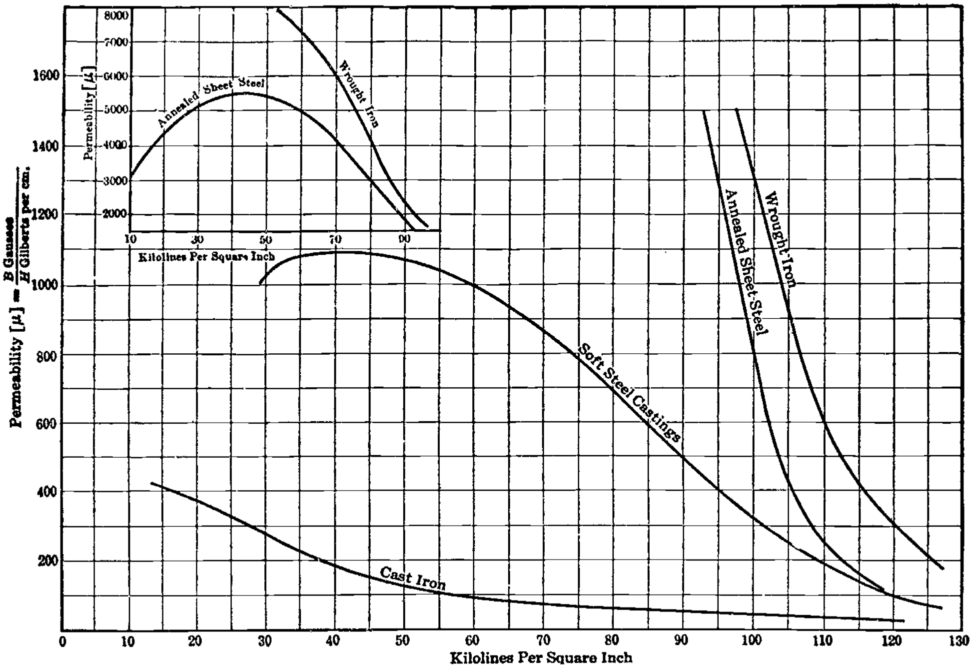


Fig. 61—Curves showing how the permeability of iron and steel varies when the magnetic flux density is varied.

of its several parts, just as in the case of resistances in electrical circuits. If two reluctances are in series, the total reluctance is the sum of the individual reluctances. For two reluctances in parallel, the total reluctance is equal similarly to the reciprocal of the sum of the reciprocals of the separate reluctances (as in the case of resistances).

Problem: Suppose it is required to find the current necessary in a magnetizing coil of one thousand turns in order to produce a total flux of 200,000 lines of force in a transformer core built up of sheet steel laminations as shown in Fig. 62. The cross-section area of this core is 2.5 square inches and the mean length of the magnetic path in the core is 20 inches.

(Solution on Next Page)

Solution: The flux density is: $\frac{200,000}{2.5} = 80,000$ lines per sq. in., or 80 kilolines per sq. in. Refering to the B-H curve for sheet steel in Fig. 60 we find that for a flux density (B) of 80 kilolines per sq. in. there are required 8 ampere-turns per inch of magnetic circuit. If the length of the magnetic path is 20 inches, the total ampere turns required is $8 \times 20 = 160$. The current is then $\frac{160}{1,000} = 0.160$ amperes. Ans.

It is evident that the use of the B-H curves makes the solution of problems of this kind very simple. Curve sheets for the various steels may be obtained from handbooks on steel, or by direct application to the steel manufacturers. The latter is probably the most accurate source of information for the magnetic characteristics of the many special steels made for use in electrical devices.

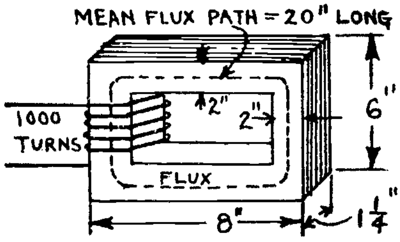


Fig. 62—Transformer Core.

99. Hysteresis loss: When a piece of iron is subjected to a varying magnetizing force (as in the case of transformer cores) the magnetism produced in it lags behind the magnetizing force. Thus let (A) of Fig. 59 represent an electromagnet having a *hard steel core,* and with current flowing as shown by the arrows, and the magnetic poles as shown, and (A) of Fig. 63 represent the changes of magnetism plotted against the applied magnetizing force. The horizontal scale (abscissa) to the right of the starting point O, represents the strength of the current or magnetizing force in one direction; that to the left of O is in the opposite direction. The vertical scale (ordinates) above O represents the total magnetic flux in the steel in the one direction; that below O represents the flux in the reverse direction.

If the current is slowly increased, the magnetic flux in the iron also increases along O—B, up to the point C where saturation is reached. If the current is now gradually decreased, the iron loses some of its magnetic lines of force, but when the current reaches zero, the iron still has some lines of force O-D left in it as residual magnetism. If the current is now reversed so that it flows in the opposite direction, when the current reaches a certain strength the magnetic flux in the iron has just come down to zero at point E. It required a magnetic force O-E in the opposite direction to completely demagnetize it. If the current is slowly increased in this opposite direction, the iron becomes slowly magnetized again along E, F, G, but in the opposite direction, that is, its poles have changed. If the current is again reduced to zero, the magnetism decreases along G-H, the iron still retains some flux, and the current must be reversed again to demagnetize it to point I. The variations in the magnetic field of the iron thus lag behind those of the current or magnetizing force. If the current is sent through again in the original direction, the magnetism will build up along I-J to the point of saturation C, and the process is repeated over again.

The atoms of the iron do not easily change their positions. It requires a certain magnetic force to change them around. Some of the energy of the applied electric current is used up in changing the magnetism of the iron. The property of a magnetic substance to maintain the magnetic state which it has once acquired, is called *hysteresis*. The electrical energy used up in changing the magnetization of the iron is known as *hysteresis loss* and is supplied by the magnetizing winding. Hysteresis loss is very important in the magnetic materials used for the cores of alternating current electrical apparatus where the flux changes from zero to maximum to zero, and also changes its direction 120 times every sec-

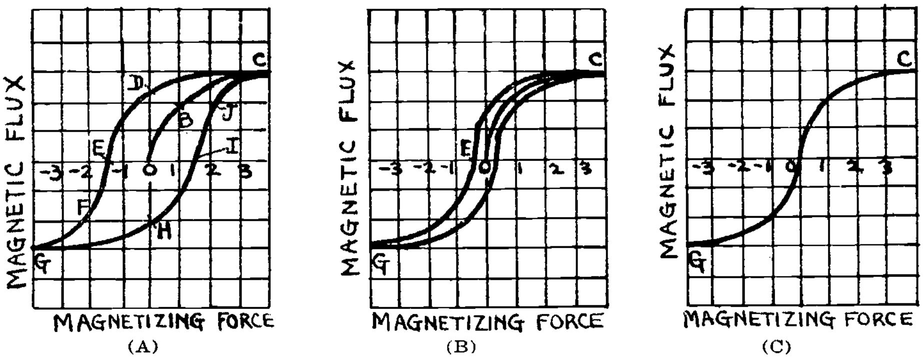


Fig. 63—Hysteresis Loops for (A) hard steel; (B) annealed silicon steel; (C) for ideal magnetic material having no hysteresis loss.

ond in ordinary electric light circuits, and at very much higher rates in audio and radio frequency apparatus. Designers of electrical apparatus usually select grades of iron which have low hysteresis losses, for a certain amount of electrical energy is wasted in reversing the magnetism during each cycle. Soft iron and annealed silicon steel offer less opposition to changing magnetism than the harder forms of iron and tempered steel. Soft iron and silicon steel therefore have less hysteresis loss than the other common forms of iron.

The reason for the hysteresis effect is, that owing to the forces between the atoms when they have all been turned around to the magnetized position, there is a constraint which prevents the magnetism of the iron from being reduced proportionally to the reduction of the magnetizing force, so that when the latter is reduced to zero, there is a considerable amount of residual magnetism still in the iron, corresponding to points D and H in Fig. 63. In other words, the changes in the magnetic induction *lag* behind the changes in the magnetizing force. It is this retentive property of steel which enables us to make permanent magnets. The energy expended by reason of the effect all appears as heat energy in the steel, because when each atomic group is separated, the individual members are set vibrating, the corresponding kinetic energy being transformed into heat.

The hysteresis curve for hard steel is shown in (A) of Fig. 63. The curve at (B) of Fig. 63 is for annealed silicon steel used extensively in the magnetic circuits of transformers, dynamos, etc., on account of its low hysteresis and eddy-current losses. (The eddy-current losses will be studied in Art 113 when considering transformer-iron losses.) Notice that in this case the loop is more slender, that is, the magnetism changes more readily hence there is much less energy loss. Note that the magnetic force OE required to bring the magnetism back to zero value is much less in this case than in the case of the hard steel in (A).

At (C) is shown the hysteresis curve for an ideal magnetic material, that is, the curve obtained for a steel having no hysteresis loss. In this case when the magnetizing force is reduced to zero, the magnetic strength of the iron also drops to zero at once and no force is required to demagnetize the iron. Of course in devices in which the magnetic flux does not change in direction or strength, no hysteresis action or loss is present, and it need not be considered when selecting the magnetic material.

The problem of selecting the proper magnetic material for any magnetic or electrical device usually results in a compromise between several conflicting factors. While a designer will always try to use the steel which he believes will meet all requirements as to permeability, low hysteresis loss, ease of machining, flux density at saturation, etc., the element of cost must always be considered. It is sometimes much cheaper to use a slightly larger magnetic circuit made of a cheaper grade of steel, than it would be to make the magnetic circuit more compact by using a more expensive but better grade of steel. In both cases the results obtained might be the same. Of course whether the device is to be used with a-c current in the magnetizing winding, or with direct current, determines whether it can be cast cheaply in a solid piece by the use of cast iron, wrought iron or a soft steel casting, or whether it must be built up of thin individual laminations to reduce the wasteful eddy currents which might be produced by the varying field as we shall see later. In the case of permanent magnets, while we know that cobalt steel makes very good magnets which are much stronger than tungsten steel magnets of equal size, in many applications where size is not an important factor it might be preferable to make the magnet of the cheaper tungsten steel even though it will be larger in size. An example of this is furnished by the use of tungsten-steel permanent magnets in those types of loud speakers in which a permanent magnet is employed. Cobalt steel magnets could be used, but they would be more expensive. Since there is ample space for the magnet, the somewhat larger, but cheaper, tungsten-steel magnet is usually employed for this purpose. On the other hand, the permanent magnets used in electrical phonograph pickup units (see Art. 542) must be strong magnetically, but light in weight, so cobalt steel is commonly used for them.

REVIEW QUESTIONS

1. Explain two ways in which you could prove that a magnetic field always exists around a current-carrying conductor.
2. Explain two methods of determining the shape of the magnetic field around (a) a straight wire, (b) a solenoid, (c) a horseshoe electromagnet, (d) the flux in the air gap of the loud speaker field in (C) of Fig. 59.
3. A similar coil of wire is wound on each leg of the horseshoe permanent magnet in an earphone. The coils are connected in series. Draw a diagram, marking the poles on the magnet, and show how the coils should be connected together and which way the signal current should be sent through them so that the magnetic field produced by the current will aid the field of the permanent magnet. State the rule used for determining this.
4. A 110 volt d-c circuit is to be used to charge a storage battery through two lamps. The polarity of the line terminals is to be determined. The lamp is first connected across the line terminals and turned on. A compass needle is held over one of the wires and the direction of deflection noted. Make a sketch showing this condition. Assuming a direction of deflection of the compass needle, determine and mark the direction in which the current is flowing through the wire, and the + and — terminals of the line.
5. Is a solenoid a permanent magnet or a temporary magnet? Why?
6. How would you make a permanent electromagnet?
7. A horseshoe electromagnet is to be used to re-magnetize the horseshoe permanent magnets in earphones and loud-speaker units. If the windings are covered up so they cannot be seen, (a) How would you determine the poles on the electromagnet? (b) On the permanent magnets? (c) How would you place the permanent magnets on the electromagnet in order to magnetize them? Make a sketch.
8. Explain by means of the electron theory of magnetism, just what happens when the core of an electromagnet is magnetized.
9. Draw sketches showing the supposed arrangement of the electron orbits in a piece of (a) unmagnetized steel, (b) partly magnetized steel, (c) magnetically saturated steel.
10. If you had to wind a magnet coil for use in a circuit in which only a small current was available, would you use many turns of fine wire, or a few turns of coarse wire? State your reason!
11. The field coil of an electro-dynamic speaker having a dry plate rectifier contains 1000 turns of No. 18 wire. The current sup-

plied to it is 2 amperes at 12 volts. The rectifier is to be changed to the vacuum tube type necessitating the re-winding of the speaker field coil. With the vacuum tube rectifier the available current will be 50 milliamperes at 300 volts. How many turns of wire will be required to produce the same magnetizing force with this arrangement? Would you use a smaller, or larger, size wire? Why?

12. What is magnetomotive force? What factors does it depend upon?
13. What is the objection to constructing an electromagnet with so many turns of wire on the winding, and so much current through it, that the iron core is saturated?
14. What is meant by permeability?
15. The following materials are available for use in making the core of a very strong direct current electromagnet: cast iron, brass, aluminum, wrought iron, sheet steel, silicon steel, copper. Which would be the most suitable? Why?
16. Two parallel wires are close together and have current flowing through them in the same direction. Draw the magnetic field around each, and state whether there will be any appreciable magnetic field in the space between them. Do the same for the condition where the current in one wire is opposite in direction to that in the other wire.
17. The magnetizing coil in Fig. 62 has 10 turns of wire, and an ammeter connected in series with it reads 20 amperes. The core is made of silicon steel of the dimensions shown. What is the total flux produced in the core? What would the total flux be if the core were made of (a) cast iron? (b) wrought iron?
18. Explain in detail what is meant by hysteresis. Is it desirable to use magnetic materials having low hysteresis loss, or those having high hysteresis? Why?
19. Is it desirable to use a hard steel for the core of radio or audio frequency transformers in which the current may vary in strength as much as 1,500,000 times a second? Why?
20. Explain the advantages and disadvantages of each of the magnetic circuit constructions shown in Fig. 59.

CHAPTER 8

ELECTROMAGNETIC INDUCTION

GENERATING E. M. F. — E. M. F. PRODUCED BY A MAGNETIC FIELD AND A CONDUCTOR — VALUE OF INDUCED E. M. F. — EXPLANATION OF ELECTROMAGNETIC INDUCTION — DIRECTION OF INDUCED CURRENTS AND LENZ'S LAW — THE ALTERNATING CURRENT GENERATOR — DIRECT CURRENT GENERATOR — WAVE FORM AND EFFECTIVE VALUES — MUTUAL INDUCTION — THE TRANSFORMER — LEAKAGE FLUX — PRACTICAL TRANSFORMER CORE ARRANGEMENTS — TRANSFORMER WINDINGS, RATIO AND DESIGN — THE AUTO-TRANSFORMER — TRANSFORMER IRON LOSSES — EDDY CURRENTS — GENERAL TRANSFORMER CONSTRUCTION AND APPLICATIONS — REVIEW QUESTIONS.

100. Generating e. m. f.: We saw in chapter 5, that the electromotive force produced by the chemical action in the cells of a battery causes free electrons to flow through the conducting circuit in one direction. The flow of electrons, and therefore the flow of current, is usually maintained at a steady rate in circuits of this kind. This is known as a *steady direct current* or *unidirectional current.* If the current flows always in one direction but the rate of flow varies, it is called a *varying* or *pulsating direct current.*

We also found in chapter 7, that a current of electricity (stream of electrons) flowing through a conductor sets up magnetic forces (a magnetic field) around the conductor. In 1831 the English physicist Michael Faraday discovered that an e. m. f. can also be set up in a conducting circuit by moving a magnet near it, or by moving the conductor across the field of the magnet. If the conducting circuit is arranged to form a closed loop, the induced e. m. f. will produce a flow of current through it. This great discovery forms the foundation of the entire science of induced e. m. f., and its practical application led to the discard of the use of primary batteries and chemical action for the commercial production of e. m. f. and currents on a large scale, in favor of the electric generator which generates e. m. f. by causing a relative motion between conducting circuits and an intense magnetic field. Without this simple, efficient means of producing electricity on a large scale, the development of present-day electrical devices and machinery, and the growth of the electrical industry, would never have come about. Radio and broadcasting as we know it today would never have been developed.

101. E. M. F. produced by a magnetic field and a conductor: The experiments of Faraday may be repeated in their essentials by means of very simple apparatus consisting of one or two permanent bar magnets, a 100 foot roll of ordinary No. 18 cotton covered copper wire (commonly called *bell wire*) ; one or two No. 6 dry cells; and a galvanometer, low reading milliameter, or other sensitive current or voltage indicating instrument. The instrument used should have the + and − terminals plainly marked on it. The (+) plus terminal of such a device is that terminal, which when current is sent into it (or is connected to the positive side of a circuit), will make the pointer deflect to the right on the scale. If the terminals are known, we can quickly tell which way the current is flowing through such an instrument, by simply noticing the direction of deflection of the pointer.

Experiment: If the bar magnet is a very strong one and the current indicating device is very sensitive, it will be possible to induce a voltage of sufficient strength to

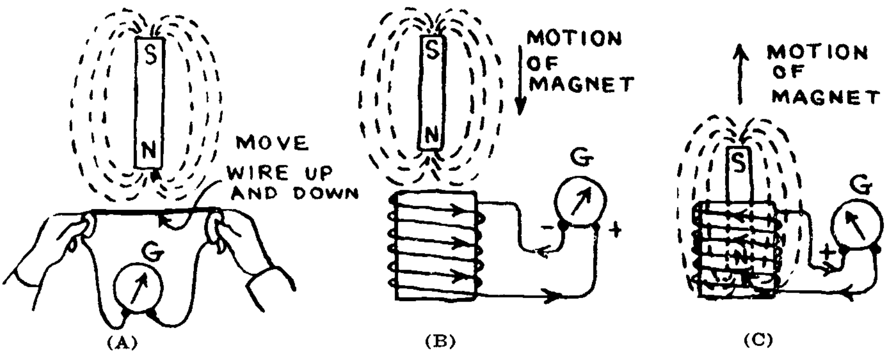


Fig. 64—Inducing E.M.F. and Current in a conductor by means of a magnetic field.

be indicated on the galvanometer, by connecting the ends of a straight piece of the wire about two feet long to the terminals of the instrument and then quickly moving the wire up and down *across* the magnetic field of the bar magnet (close to the pole where the field is strongest), as shown in (A) of Fig. 64 (If a horseshoe permanent magnet is used instead, the field will be stronger and a larger deflection will be obtained on the meter.) Since nothing but an electric voltage or current could cause the galvanometer to register, it is evident that during *motion* of the wire an e. m. f. and current was produced. It will be noticed that the induced voltage and current reverse in direction when the direction of motion of the wire is reversed (as indicated by the deflection of the meter needle in the opposite direction.) If the wire is held stationary in the field, no e. m. f. or current is produced. If the wire is moved from left to right in a direction across this page, no e. m. f. will be generated because its motion is parallel to the lines of force.

Now wind about 50 feet of the bell wire into the form of a solenoid coil having a hole just large enough to admit two bar magnets together. This may be wound on a wooden spool or a cardboard tube, or may simply be taped up to hold the turns together. Connect the ends of the coil to the indicating instrument as shown at (B) of Fig. 64.

If the N pole of the bar magnet is suddenly thrust into the solenoid, the galvanometer needle will be temporarily deflected. Notice that the deflection now is much greater than in the case when the single straight wire was used, indicating that a stronger e. m. f. is now being induced in the wire. If the galvanometer is watched carefully, it will be seen that the needle moves as soon as the pole of the magnet begins to approach the end of the solenoid. When the bar magnet comes to rest inside the solenoid, the galvanometer needle returns to the zero position.

When the magnet is rapidly pulled out of the solenoid as shown at (C) of Fig. 64, the pointer deflects in the opposite direction, showing that the induced e. m. f. and current are now in the opposite direction.

If the magnet is plunged into the solenoid first quickly, and then very slowly, it will be found that the quicker it is moved in and out, the stronger will be the e. m. f. and current produced. If the motion is too rapid, the needle does not have the time to take up the alternate positions due to the opposite currents traversing the instrument, and will remain at zero with only a slight vibration.

Now quickly plunge the S pole of the magnet into the coil and notice that the galvanometer needle deflects in a direction opposite to that when the N pole was plunged in. The same thing happens when the S pole is pulled out, showing that the direction of the induced e. m. f. and current depends on the direction of motion of the magnet or conductor.

Place the two bar magnets with both N poles together so as to make a strong N pole. Plunge them into the solenoid together and notice that the e. m. f. is stronger than when a single magnet was used.

Now leave the magnet stationary and quickly slide the solenoid over it. Notice that the galvanometer deflects just as before. If more turns of wire are added to the solenoid it will be found that the more turns of wire employed, the stronger will be the e. m. f. and current produced.

It must be remembered that the linking and unlinking of the lines of force of the magnet with the turns of wire on the solenoid really induces an e. m. f. in the wire. If the two ends of the wire were left open, the e. m. f. would be present but no current could flow. If the circuit is closed, this e. m. f. causes a flow of electrons around through the wire. in a direction opposite to that conventionally ascribed to the current. The phenomenon observed in the experiments described above is termed *electromagnetic induction.* Hereafter, we shall designate the e. m. f. or difference in electrical potential thus produced, as an *induced e. m. f.* The current produced by this induced *e. m. f.* is an *induced current.* Each individual conducting element which cuts the lines of force is called an *inductor.* A *complete turn* or *loop* of wire in a generator contains two *inductors.*

102. Value of induced e. m. f.: These experiments prove that an e. m. f. can be induced by the motion of an inductor in a magnetic field. The results may be summarized by saying that the magnitude of the induced e. m. f. depends upon the following factors:

(a) The flux or total number of lines of magnetic force sweeping across the inductors.

(b) The number of inductors being swept across by the field.

(c) The rate of speed of unlinking or linking of the lines of force with the inductors.

These statements may all be summed up and written in a simple equation of the form:

$$\text{E.M.F.} = \frac{\Phi \times N}{T \times 10^{8}} = \frac{\Phi \times N}{T} \times 10^{-8}$$

Φ=total number of lines of force linked, or unlinked, *by each inductor,* during time T seconds.

N=number of inductors.

Example: Ten inductors cut across a magnetic field of 50,000 lines of force 50 times every second. What is the value of the total induced e. m. f.?

Solution: $$\text{E. M. F.} = \frac{\Phi N}{T} \times 10^{-8} = \frac{50{,}000 \times 50 \times 10}{1} \times 10^{-8} = 0.25 \text{ volts.}$$

This example illustrates the fact that an inductor must cut across a very large number of lines of force every second (100,000,000 to be exact) in order to generate one volt of e. m. f. In commercial dynamos, high voltages are generated by rotating a large number of conductors at high rates of speed in intense magnetic fields produced by the strong field electromagnets. The field electromagnets obtain their exciting current from the generator itself in most cases, since the exciting current required is only a small fraction of the total output of the machine.

103. Explanation of electromagnetic induction: It will be remembered from Article 89 in Chapter 7, that each atom of a magnet has one or more negative electrons revolving about a circular orbit acting as a current-carrying loop, and is lined up so the plane of its electron orbit is parallel to those of the other atoms as shown in (D) of Fig. 57. All so-called magnetic phenomena are merely interactions of the forces produced by these moving electrons.

When the bar magnet of (A) Fig. 65, full of these electrons moving in the direction shown, is plunged into the solenoid, an equal and opposite reaction is set up in the wire of the solenoid, that is, a displacement of electrons takes place around through the turns of wire in the direction shown by the dotted arrows—just opposite to the direction of the electron flow in the atoms of the magnet. If the circuit of the solenoid were open, only a slight electron displacement would take place, crowding some of them to the end C of the wire, thus electrified negatively—that is—an e. m. f. would be induced. If the circuit is closed as shown, this e. m. f. causes a continuous flow of electrons around the circuit just so long as the magnet is in motion. The direction of current flow as shown by the solid arrows is opposite to that of the electron flow. The current is induced in the wire at the expense of the muscular or mechanical power used in plunging the magnet into the coil. Likewise mechanical power must be expended in pulling the magnet out of the coil, the total amount of mechanical power required in each case being exactly equivalent to the total amount of electrical energy produced. Since there is always some I^2R loss due to the resistance of the wires, less than this total amount of electrical power generated is available for useful purposes outside the circuit. Thus, in commercial electric generators in which current is induced by electromagnetic induction, a steam engine or turbine, waterwheel, gas engine or some other device is used to furnish the mechanical power used to rotate the electrical conductors in the intense magnetic field.

It is interesting to note that electrons in motion (electric current) set up a magnetic field around a conductor. A change in the magnetic field around a conductor tends to set the electrons in motion (electric current).

104. Direction of the induced current and Lenz's Law: It will be seen from (A) of Fig. 65 that the induced current flowing around the solenoid produces a N magnetic pole at the top end, and a S magnetic pole at the bottom end when the magnet is pushed in. The magnet pole repels the N pole of the solenoid, tending to stop the motion. This can be checked by using the right hand rule for solenoids (studied in Article 86). While the magnet is being pulled out, a S pole is formed at the top of the coil and a N pole at the bottom, as shown in (B) of Fig. 65. The S pole of the solenoid attracts the N pole of the magnet tending to stop this motion of the magnet.

In every case of electromagnetic induction, the induced current will flow in such a direction that the magnetic field produced by it tends to oppose the "motion" (or "cause") producing the current.

This is known as "Lenz's law of electromagnetic induction." Stated

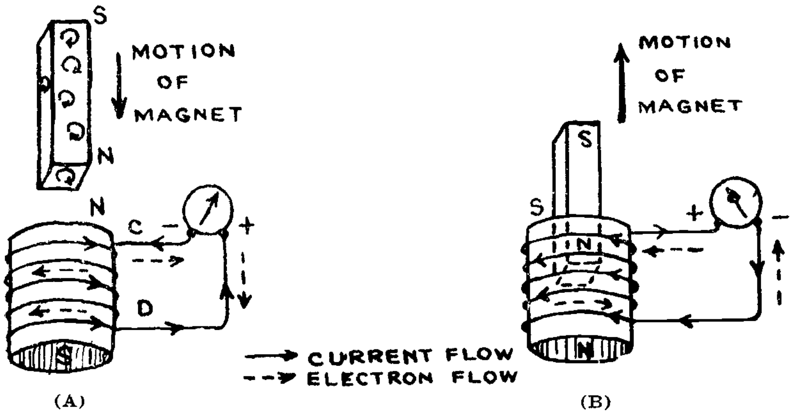


Fig. 65—Direction of the induced e.m.f., current and magnetic poles in a coil of wire which has a magnet plunged in and out.

simply, it means that if we produce electricity by electromagnetic induction we must use up an equivalent amount of mechanical power to overcome the opposition set up by the induced current. It is this *mechanical* power that is converted into the *electrical* power by the process.

The direction of the induced current can be found by first applying Lenz's law to find the induced magnetic poles. Then the "right-hand rule" is applied to find the direction of the current required to produce this pole arrangement. A simple rule for finding this directly is known as Fleming's rule and may be stated as follows:

"Imagine the right hand held in the magnetic field with the thumb, forefinger and middle finger extended at right angles to each other, the forefinger pointing in the direction of the lines force, and the thumb in the direction of motion of the wire, then the middle finger points in the direction of the induced e. m. f. (Positive to negative)."

105. The alternating current generator: We have seen that when a coil is moved in a magnetic field—or the field is moved in the coil—an e. m. f. is induced in the coil, and that the direction of the induced e. m. f. and current depends upon the direction of the motion; the direction of the induced current always being such that it tends to stop the motion or cause producing it. This principle is used in the electric generator shown in simple form in Fig. 66. Here, a simple loop of wire A-B-C-D is arranged to be mechanically rotated on a shaft between the poles N and S of two powerful electromagnets. We will assume that the magnetic field between the poles is uniform, as shown, that is, of the same strength throughout. The two ends of the coil are connected to two collector rings (of brass or copper), F and G respectively (sometimes called slip-rings), insulated from each other and from the shaft. They are arranged to rotate with it. The two stationary copper or carbon brushes H and J make a wiping contact with these rotating collector rings to lead the current to the external circuit, consisting in this case of a lamp K. This arrangement of parts not including the external circuit, constitutes the simplest form of alternating current generator.

Let us assume the coil to start from the vertical position (A) of Fig. 66 and to rotate at a uniform speed in a clockwise direction as shown. At this position the induced e. m. f. is zero because the coil sides A-B and C-D are moving parallel to the lines of force. Therefore in a given small angular movement at this position there will be very few lines of force unlinking with the loop A-B-C-D and hence very little e. m. f. is induced.

It should be noted that at this position all of the lines of force of the field are passing through the loop but this does not mean that an e. m. f. is induced. The induced e. m. f. is proportional to the *rate of change* of the lines of force linking and unlinking, and not to the total number of lines of force through the loop. For instance, when we held the bar magnet stationery inside the solenoid in the experiment in article 101, no e. m. f. was induced in the coil even though all the lines of force of the magnet went through the solenoid in this position. When the magnet was moved, so as to link or unlink lines of force with the coil, an e. m. f. was induced.

After passing the vertical position, lines of force begin to unlink with the loop at an increasing rate and the induced e. m. f. gets stronger and stronger. The direction of the current is shown by the arrows in (B). This is found by using the right-hand rule and remembering from Lenz's law that the magnetic poles produced by the current in the coil are such as to tend to stop the rotation, that is, a S pole is produced at the top of the coil and a N pole at the bottom. This south pole is forcibly rotated toward the south pole of the field by the applied mechanical power, and the N pole of the coil is also rotated toward the N pole of the field against the force of repulsion. At the horizontal position (B) the coil has maximum e. m. f. induced in it, because during a small angular movement from this position the maximum number of lines of force are unlinked, since coil sides A-B and C-D are moving at right angles to the lines of force.

As the coil continues on to the vertical position of (C) the e. m. f. is still in the same direction but diminishes in value again. At the vertical position the e. m. f. is zero.

As it continues past this, the induced e. m. f. and current change in direction, as shown by the arrows in (D), since the poles of the coil must now reverse in order to keep opposing the motion of rotation. The

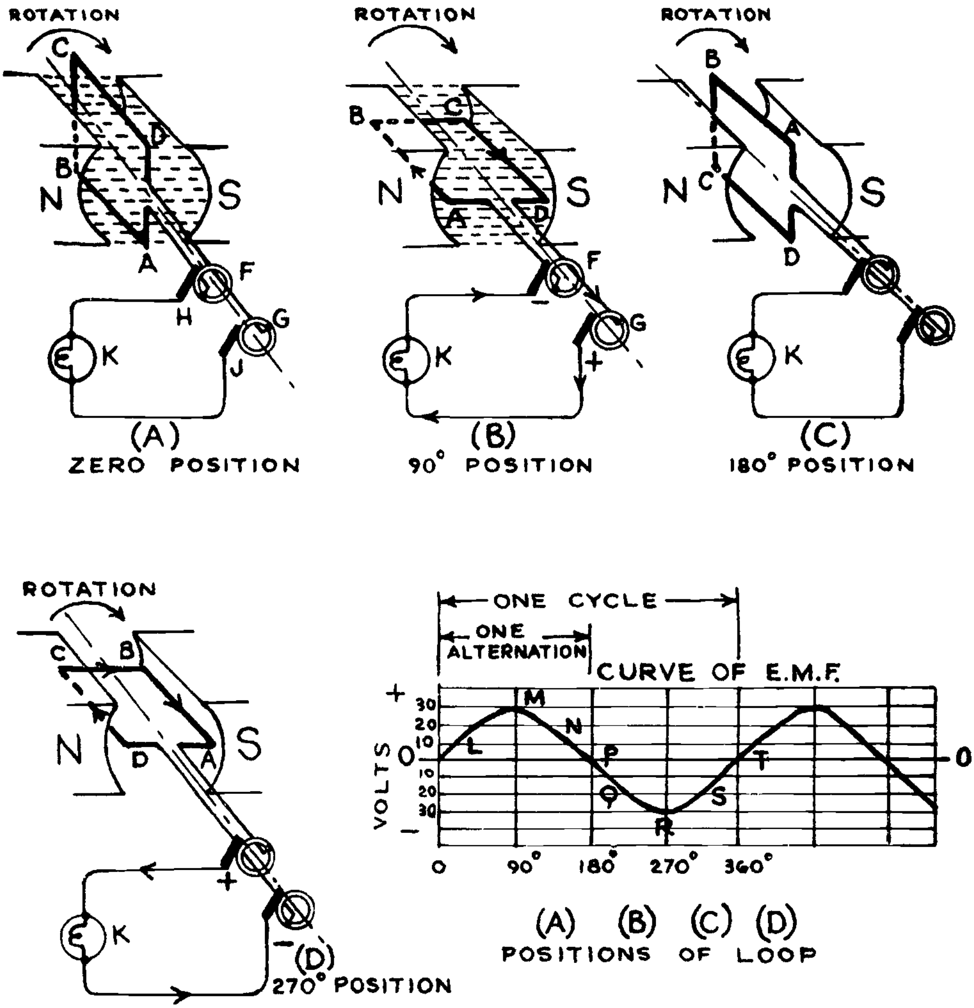


Fig. 66—Generating an Alternating E.M.F. in a loop of wire rotated in a magnetic field.

e. m. f. increases in strength, and becomes maximum when the coil is horizontal as shown.

Continuing the rotation another 90 degrees brings the coil back to its original starting position and condition of (A). The e. m. f. decreases to zero again. As the rotation is continued, the above conditions repeat themselves over and over.

In one complete revolution of the coil there are two positions (A) and (C) at which there is no induced voltage and hence no current in the external circuit and two (B) and (D) in which the voltage is at maximum value, although in opposite directions. At intermediate positions, the voltage has intermediate values. A complete revolution of the coil takes in 360 degrees of the rotation. Since the rotating coil moves in a circle, we can mark the positions of the coil as so many degrees from the starting point (A) which is considered as 0 degrees. Thus (B) is the 90° position, (C) is the 180° position, etc.

We may plot the voltage induced in the coil at every instant, against the degrees through which the coil has rotated from the zero position (A). This is shown in Fig. 66. When the current is flowing in one direction we call it *positive*, and lay off the voltage values vertically *above* the zero line O-O. When it is flowing in the opposite direction, we call it *negative* and lay off the voltage values vertically *below* the zero line O-O. If the conductor moves at a uniform rate, the induced voltage can be plotted against the "time in seconds" instead.

The curve thus obtained, is called a "sine-curve", because the induced voltage at any instant, in the ideal generator just described, is proportional to the trigonometric natural sine function of the angle of rotation of the coil from the zero position. In an actual generator, the curve is not a true sine curve because the field flux is not exactly uniform. Also, in an actual generator the armature coils are wound on a circular iron core to reduce the magnetic reluctance of the space between the field poles. This makes the magnetic field and the induced voltage very much stronger.

The curve shows that at first the e. m. f. increases rapidly (O to L), then less rapidly until it reaches its maximum value M when the coil reaches the 90-degree position. At the maximum value, the rate of change is least. Then it decreases slowly at first to N, and then more rapidly to zero at P. Then the e. m. f. reverses in direction and begins to increase in value in that direction to Q, and to maximum at R. Then it decreases to S, and completes one cycle at T. The e. m. f.'s in the negative direction are represented by drawing them below the O-O axis line.

A complete wave of changes of the e. m. f. or current from zero to maximum in one direction, then down to zero and to maximum in the opposite direction and back to zero again is called one *cycle*. At the end of a cycle the coil is at the same electrical position or condition as at the beginning. It then starts to repeat the same thing all over again. If it continues to rotate, it repeats the cycle once for each rotation (for a 2 pole generator). The time required for a complete cycle is called a *period*. One-half cycle is called an alternation—see Fig. 66. The number of cycles produced each second is called the *frequency*. It is evident that for a 2 pole generator as shown, the frequency is equal simply to the number of revolutions per second. In order to produce the ordinary commercial lighting frequency of 60 cycles per second without rotating the armature at excessive speeds, commercial a-c generators (commonly called alternators) as a rule have a larger number of poles than two. One cycle is produced when an inductor passes each *pair* of poles. Therefore, in one complete rotation as many cycles will be produced as there are *pairs* of poles. The *frequency* (cycles per second) is:

$$f = \frac{\text{No. of poles}}{2} \times \frac{\text{Speed in R. P. M.}}{60} = \frac{\text{No. of poles} \times \text{R. P. M.}}{120}$$

In the ordinary commercial lighting circuit the frequency is usually 60 cycles per second, although in some localities the frequency is 25 cycles and in others still different frequencies are employed. In a 60 cycle current there are 60×2 or 120 alternations per second. Special alternators for generating a-c voltages at frequencies up to 20,000 cycles per second are used in long-wave radio transmitting stations. As it is not practical to generate e. m. f.'s of frequencies much higher than this with alternators of the type described, vacuum tube oscillators or generators are used for generating the e.m.f.'s of the higher frequencies required in radio work. These will be described later, (see Art. 635).

Commercial a-c generators have a stationary armature consisting of many coils in series in order to make the individual e. m. f.'s generated in each coil additive so as to produce a large total e. m. f. The field poles are usually rotated. They consist of heavy iron cores covered with wire through which a *direct* current is sent to maintain a strong unidirectional magnetic field. The direct field current is furnished by a separate small d-c generator called an *exciter*, or by a separate small d-c winding, commutator, and brushes built right on the main armature.

It is seen that an alternating current is really a current that flows first in one direction, through the circuit and then reverses and flows in the opposite direction. The e. m. f. forces the free electrons through the circuit first in one direction, and then they all reverse and flow in the opposite direction usually many times a second. Not only are the electrons reversing in direction but the rate at which they are flowing also varies throughout each cycle. As we shall see later, this gives rise to many effects in a-c circuits and apparatus which are not encountered in direct current circuits.

106. Direct current generator: If current flowing only in one direction is desired, the machine producing it is called a *direct current generator*. In d-c generators, the collector rings shown in (A) of Fig 67 are not used. An automatic switching device called the commutator is employed instead, (see B of Fig. 67). The commutator is a switch which keeps the current in the external circuit flowing in the same direction continuously, even though the current in the armature coils is reversing. The simple commutator shown, consists of a split ring having two segments insulated from each other and from the armature shaft. The commutator rotates with the shaft, and the stationary contact brushes rest against it.

At the instant that the direction of the induced e. m. f. in the rotating coil reverses in direction (position C of Fig. 66), the commutator segments are just ready to slide around and reverse their positions under the brushes. Thus in (B) of Fig. 67, segment D touches brush E and segment F touches brush G. The direction of the current in the moving coil and in the external circuit, is as shown. At the instant that the e. m. f. in the coil reverses, segment D is just ready to slide around to brush G and segment F slides around to brush E, thus maintaining the current in the same direction in the external circuit as shown. (C) of Fig. 67 shows the positions just after this has taken place. Commercial d-c generators have a large number of coils on their rotating armatures. Their commutators thus have a large number of copper commutator segments, each one in-

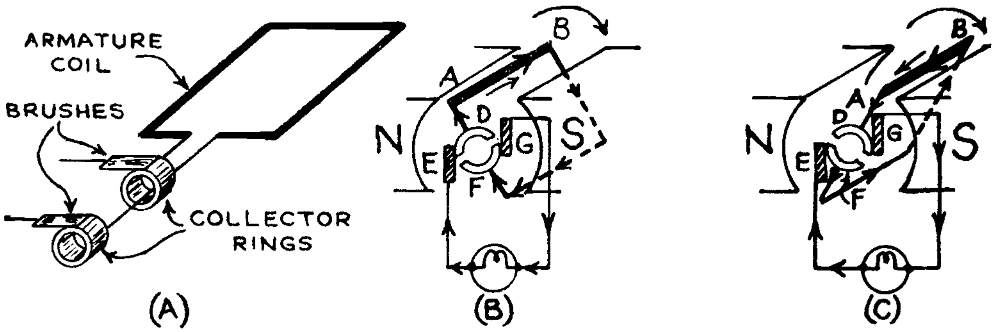


Fig. 67—Action of the Commutator in a D. C. Generator.

sulated from the next and from the clamping rings and armature shaft, by means of mica insulation. A pair of commutator segments connects to each coil. There are usually as many brushes as there are poles in the field magnet. The commutator must be kept clean. This is done by holding a piece of 00 sandpaper (never emery cloth) against its surface for a few seconds while running. The brushes should be fitted properly so they make good contact with the armature surface, to reduce any sparking.

By winding a large number of *coils* of wire, each having only a few *turns*, on the armature of a d-c generator, instead of a fewer number of *coils* each having more *turns* of wire, a more constant e. m. f. is made available at the terminals of the machine. There will always be at least one coil producing its maximum e. m. f. while the others are going through zero or some intermediate value. The sum of the e. m. f.'s of all the conductors gives a fairly smooth resultant voltage, as shown at (B) of Fig. 68. Only a slight ripple remains in it. We shall see later, when studying the operation and construction of electric radio receivers designed to operate directly from 110 volt direct current electric light lines, that this ripple in the e. m. f. or current is objectionable in that it causes hum in the output. Hence the ripples must be smoothed out. (A) of Fig. 68 represents a smooth unvarying direct current voltage such as might be produced during the discharge of a storage battery. (C) represents direct current voltage with rather strong pulsations in strength, such as might be produced by a d-c generator having only a few coils on its armature. An alternating current wave is shown at (D).

The strength of the induced voltage depends on the number of turns of wire on the armature, the field strength, and the speed of rotation of the armature. This voltage may be varied either by changing the speed of the armature (this would also change the frequency in an a. c. generator), or by varying the current that energizes the field magnets. This is done by means of a variable resistance (field rheostat) inserted in series with the field coils for this purpose.

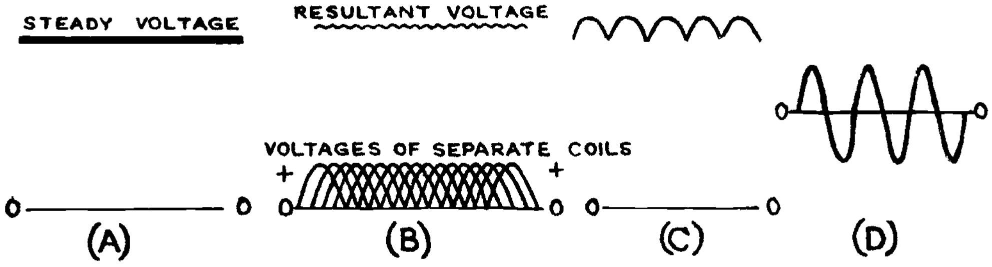


Fig. 68—Various Types of e.m.f. waves; (A) Steady d-c, (B) Slightly rippled d-c, (C) Pulsating d-c, (D) Alternating.

It should be remembered that the electrical power produced in the electric generator, is developed at the expense of the mechanical power used to rotate the armature conductors in the magnetic field against the forces of repulsion existing between the magnetic poles of the field and the magnetic poles produced in the armature by the induced current flowing through the coils. The more electrical power taken out of the generator the greater is the mechanical power which must be supplied to it by the steam engine, turbine, water wheel, or gas engine which drives it. When a generator is run on open-circuit no power other than that required to make up for its magnetic losses, friction losses in the bearings, windage, etc., need be supplied to keep it running.

107. Wave-form and effective values: The rapid variation of voltage in a well designed alternator can be closely represented by a sine curve as shown at the lower right of Fig. 66. Expressed in the form of an equation this becomes, $e = E_m \sin 2\pi ft$.

where e=the value of the voltage at any instant of time.

E_m=the maximum (peak) value of the voltage generated.

f=the frequency of the voltage in cycles per sec.

t=elapsed time (sec.) since voltage last went through zero value.

π=3.1416, (a constant.) The quantity $2\pi ft$ is in circular measure (radians). Before its sine function can be taken, it must be converted into *angular* measure (degrees). 1 radian equals 57.3 degrees (approx).

The same units (volt and ampere) are used for measuring and expressing alternating voltage and current as are used for direct voltage and current. At some instants the voltage and current are maximum, at others they are zero, and at others they have intermediate values, as shown in (A) of Fig. 69. Since the voltage and current of an a-c circuit are continually varying in value and reversing in direction, it is evident that the equivalent to an equal unit of steady direct current is really some value intermediate between the maximum and minimum value of the a-c. In order to establish the units of a-c voltage and current on a common basis with those of direct current, an *ampere* of alternating current is defined as that rate of alternating current flow

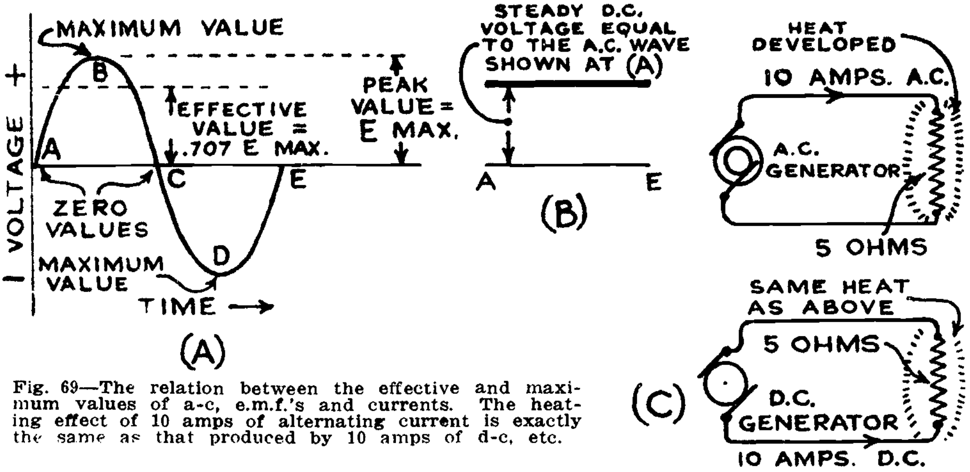


Fig. 69—The relation between the effective and maximum values of a-c, e.m.f.'s and currents. The heating effect of 10 amps of alternating current is exactly the same as that produced by 10 amps of d-c, etc.

which will produce heat at exactly the same rate as one ampere of steady direct current, as shown at (C) of Fig. 69. This is known as the *effective value* of the alternating current, and is equal to the maximum or peak value multiplied by 0.707 (for a sine wave voltage) as shown at (A) and (B). Also, the effective voltage is equal to 0.707 times the maximum voltage (for a sine wave).

The effective value is also known as the *root-mean-square* or *r. m. s. value*, for the following reasons. The heating effect of a direct current is proportional to the square of the current (I^2R). If we consider the instantaneous values of current flowing at various intervals during a cycle of alternating current, then square them (heating effect), then find the average of these values (average heating effect) and then extract the square root of this average value, it will be equal to the direct current that will produce an identical heating effect. The effective value of the current obtained in this manner is 0.707 times the maximum value. Since it is the "square root of the average or mean squares" of several current values during one cycle, it is abbreviated to "root mean square" or r. m s.

This may be summarized as follows:

The *r. m. s.* or *effective value* of a sine-wave voltage or current is equal to 0.707 multiplied by the maximum value of that voltage or current. Conversely, the *maximum value* of a sine voltage or current is equal to 1/0.707 or 1.41, multiplied by the effective value of that voltage or current.

Alternating current voltmeters and ammeters read the "effective values" of alternating voltage and current respectively, as will be shown later in the chapter on electrical instruments. Voltage or current values are always considered as effective values unless otherwise stated or indicated.

Example: What is the effective value of an alternating voltage whose maximum or peak value is 155 volts?

Solution: E(eff)=E(max)x0.707=155x0.707=109.6 volts. Ans.

Example: The value of an alternating e.m.f. as read by a voltmeter is 300 volts. What is the maximum or peak value of voltage which the dielectric in a condenser connected across this line must withstand?

Solution: E(max)=E(eff)x1.41=300x1.41=423 volts. Ans.

Example: The maximum value of an alternating current is 100 amperes. What is its effective value?

Solution: I(eff)=I(max)x0.707=100x0.707=70.7 amps. Ans.

It should be kept clearly in mind that the insulation in a-c circuits must be able to safely withstand the "peak" value of the voltage, since the peak value is impressed across it during two instants in each cycle. In high voltage circuits this is very important, for the actual difference in volts between the effective value as read on an a-c voltmeter, and the peak value may be quite large. Thus in a power pack for a public address sound amplifier, the pulsating rectified a-c voltage may be as high as 1000 volts. The filter condensers in this pack really have to stand the $1000 \times 1.41 = 1{,}410$ volts peak value twice every cycle.

The "*average*" value of an alternating e. m. f. or current is simply the average value over one cycle. The average value of a sine-wave voltage or current is equal to the effective value divided by 1.11. Average values are not dealt with often in practical problems.

It must be remembered that the above relations hold only for alternating voltages and currents of true "sine-wave" variation. The errors produced when these constants are applied to distorted wave shapes, depends not only on the magnitude of the distortion, but on the maximum values. Wave-forms of this kind are usually difficult to study. They are usually analyzed by using the known fact that any wave-form can be expressed as the sum of a series of pure sine-waves of various amplitudes, consisting of a fundamental and of harmonics, each harmonic having frequencies of 2, 3, 4, 5 etc. times the fundamental frequency. Pure sine waves can consist of the odd harmonics 3, 5, 7, etc. only. The effective or r. m. s. value of any distorted wave is equal to the square root of the sum of the squares of the r. m. s. values of the fundamental and each harmonic, divided by their number, that is, $E = \sqrt{e_1^2 + e_3^2 + e_5^2 + \text{etc.}/N}$.

108. Mutual inductance—the transformer: We found by the experiments in Art. 101 that it is possible to induce a voltage in a conducting circuit by means of a permanent magnet. It is also possible to induce a voltage in one conducting circuit by means of the magnetism produced by current flowing in another *separate* circuit. This will now be shown by a simple experiment.

Experiment: Take the 50 ft. of bell wire not yet used in the experiment in Art. 101 and wind it up to form another solenoid similar to the one you already have. Connect the ends of one of these to the galvanometer, and connect the ends of the other through a small single pole switch to one or two dry cells connected in series—or a single cell will do—as shown in (A) of Fig. 70. Place coil No. 1 near No. 2 as shown. Now quickly close the switch and notice the deflection of the galvanometer needle, indicating that a momentary voltage and accompanying current is being set up in coil No. 2. Now open the switch and notice that another momentary current is set up in coil No. 2 in the opposite direction.

From our previous considerations of electromagnetic induction, we know that when a current is sent through coil No. 1, a magnetic field is produced within and outside of this solenoid. Because coil 2 is placed near it, at least part of the field of coil No. 1 will link with the wire of coil No. 2 as shown at (A) of Fig. 70. When the field of coil No. 1 varies due to a change in current, this induces voltage in coil No. 2 just as a bar magnet plunged in and out of it would do.

Now close the switch. Notice that even though a steady current is flowing through coil No. 1 (possibly the wire will get hot), no voltage is induced in coil No. 2. The magnetic field around coil No. 1 is now steady and since no lines of force are either linking or unlinking with coil No. 2, no voltage is being induced in it. We could send 1000 amperes steadily through coil No. 1 without producing the slightest voltage in coil No. 2. Voltage is only induced in coil No. 2 when the current in coil No. 1 is varying.

Quickly open and close the switch several times. Notice that you can produce a varying current almost continuously. If you had some mechanical means (a vibrator or interrupter) for quickly opening and closing this circuit, you could induce voltage and current in coil No. 2 continuously. Also if you were to send an alternating current through coil No. 1 (the 110 volt a-c electric light line could be connected to coil No. 1 with a 100 watt incandescent lamp in series to keep the current down to about one ampere for this purpose) the magnetic field around it would be changing rapidly and would induce an alternating voltage in coil No. 2. The galvanometer will not indicate a 60 cycle alternating current, but the needle will seem to vibrate or shiver about the zero mark on the scale. This is the principle on which transformers used so very extensively in radio and electrical work of all kinds, operate.

The winding into which the current is sent is always called the *primary* (coil No. 1). The winding in which the voltage is induced by electromagnetic induction (coil No. 2), or which delivers the *energy,* is called the *secondary* coil. The primary may have the *same number* of turns, *more* turns, or *less* turns than the secondary, as we shall see later.

Now place coil 2 in various positions around coil No. 1 as shown at (B) to (G) of Fig. 70, and in each case close and open the switch quickly and notice the amount of deflection of the galvanometer needle. The deflection is a measure of the voltage induced in coil No. 2. Notice that the induced voltage depends on the distance of coil No. 2 from coil No. 1 and its relative position to it. When they are parallel and close together, as at (B) the induced voltage is high because a large part of the lines of force of coil 1 link through coil No. 2. Another way of looking at this is that the forces produced by the electron orbits in coil No. 1 are then very effective (since the distance is short) in affecting the electrons in coil No. 2, and making them flow around through the wire of coil No. 2.

When they are placed so their central axes are mutually at right angles and coincide, as at (D) and (E), no effective induced voltage is obtained, for the induced voltage set up in each half turn of coil No. 2 is exactly equal and opposite to that set up in the remaining half turn, as shown at (D), so the voltages cancel each other. This is called a *zero coupling* position. As we shall see later, when discussing radio frequency amplifiers, this fact is made use of in the mounting of radio frequency coils mutually at right angles to each other to prevent magnetic coupling between them. Notice that the coil No. 2 must be exactly centered about the axis of coil No. 1 to get zero coupling. If it is moved one way or the other, a resultant voltage will result in a direction depending on which side coil No. 2 is moved to.

In these simple experiments we have succeeded in transmitting electrical energy across space from one coil to the other by means of the magnetic field. This is really somewhat similar to the phenomena occurring between the transmitting aerial and the receiving antennas in radio reception, although several modifications must be made in practical transmission to produce electromagnetic radiations that will travel over long distances.

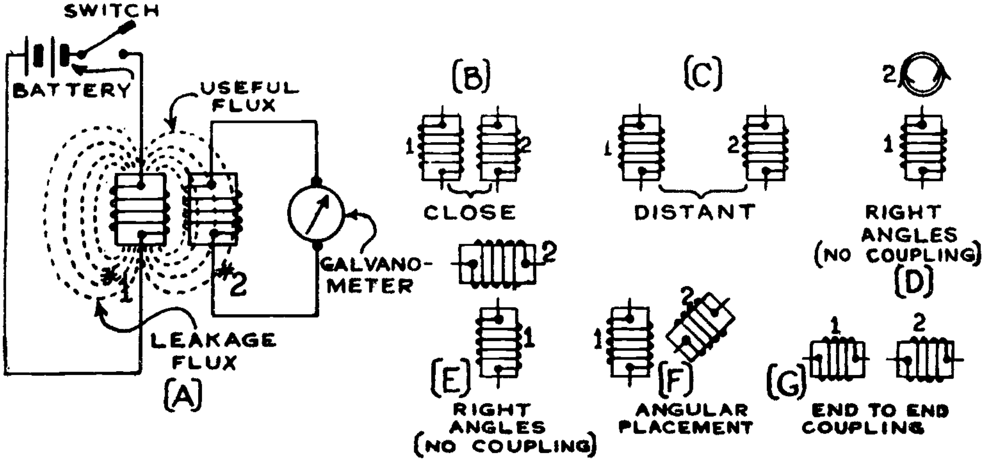


Fig. 70—Mutual Induction Between Two Coils Placed In Various Positions.

109. Leakage flux: It is evident that since only part of the lines of force set up around coil No. 1 link through coil No. 2 not as much voltage is induced in coil No. 2 as there would be if we could make all of the lines of force of coil No. 1 go through it. The lines of force of coil No. 1 which do not link with coil No. 2 but go around through the air by some other path (see (A) of Fig. 70) are called *leakage lines of force* or *leakage flux.* Since they do not contribute in producing induced e. m. f., it is important to keep the leakage flux in a transformer as low as possible. This is accomplished in the practical commercial transformers by winding the two coils on a core of some highly permeable magnetic material such as soft steel, as shown in Fig. 71. Two advantages result from this construction. First, the leakage flux is greatly reduced, since practically all of the magnetic field will now be within the core and will therefore thread through the secondary coil. Also, since the iron core is a good magnetic material, a much stronger magnetic field is now available for the same current and number of turns of wire in the primary, since the magnetic forces of the electronic orbits in the steel are now made effective and add to the effect of the electron flow or current in the primary winding. Some lines of force may leak directly across the air space in the iron core as shown, if it is made too long or too wide. This results in a lower induced e. m. f. in the secondary than there would be if there were no leakage. Also the leakage flux induces an opposing or counter-e. m. f. back into the primary. The effect is the same as though a resistance (or reactance) were placed in series with the primary winding so as to reduce

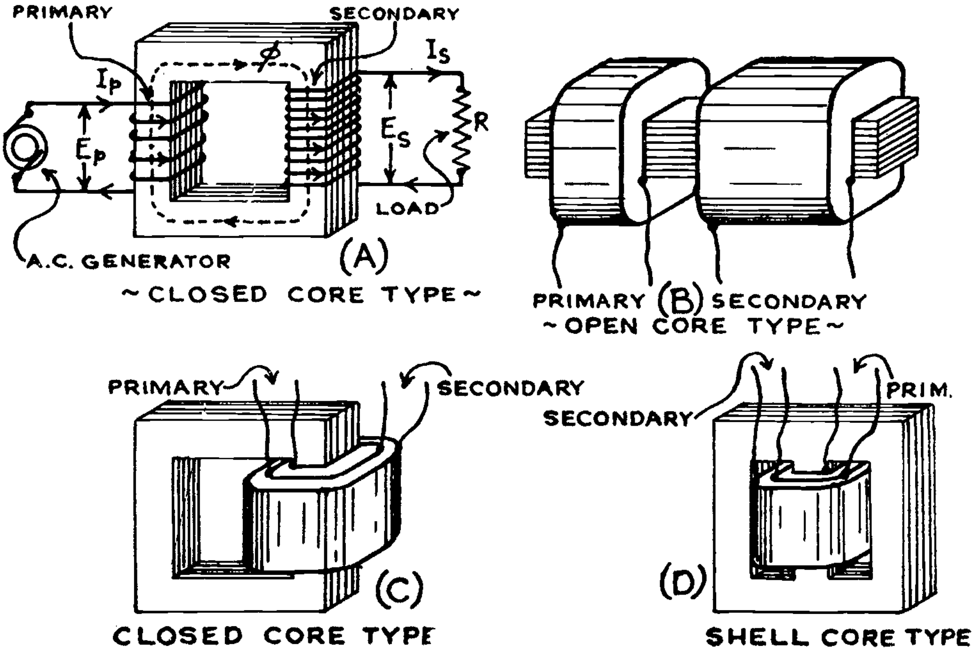


Fig. 71—Various Types of Transformer Core and Winding Arrangements. The Shell Type is used most on account of its lower Magnetic Leakage.

the available primary current and so reduce the induced voltage in the secondary. This is called *leakage reactance.* It is easier to look at the effects of magnetic leakage as a reactance reducing the primary current, because it is impractical to try to find out just how many lines of force are leaking across, whereas it is easy to measure with a voltmeter just how much lower the reduced voltage is than the calculated value, and then express this as a voltage drop due to a certain amount of "leakage reactance" in ohms connected in the primary circuit.

Transformers having air cores are used in radio receiving circuits where the frequency is so high that heavy losses due to hysteresis and eddy currents would occur in iron cores. Their use in the radio frequency amplifier will be studied in detail later. Where the frequency of the primary current is comparatively low as in the case of audio transformers, power transformers in electric receivers operated from the 60 cycle a-c lines, etc., transformers with soft steel cores are employed on account of their higher efficiency of transferring energy from the primary coil to the secondary coil by means of the magnetism in the iron-core path between the coils.

110. Practical transformer core arrangements: There are three main forms of transformer core construction used, some being more efficient but more expensive to manufacture than others. The *open-core* type is shown at (B) of Fig. 71. This is inexpensive to build, since the primary and secondary coils are wound on spools by machine, and are simply slipped over a rectangular steel core. Not much steel is used in this type, the magnetic field completing its path mainly through the surrounding air. Needless to say this type is not efficient and is used very little.

The type shown at (A) of Fig. 71 is known as the *closed core* type because its core encompasses a closed area and forms a closed magnetic field. The portions of the core on which the primary and secondary are wound are referred to as the "core legs". The primary and secondary coils are usually wound with enameled or cotton covered wire of adequate size to safely carry the currents the transformer is designed for—without too much rise in temperature. It is common practice in the design of transformer windings to allow from 1000 to 1500 circular mils of wire cross-section area per ampere of current.

In high voltage transformers, each layer of the winding is usually insulated from the next by a paper insulation so that the voltage effective between layers will not be able to break down the insulation on the wire, and the coils are insulated from the core to prevent short circuits. Best design of this type of transformer results when the entire core forms approximately a square. Then the length of the magnetic path is a minimum. Under these conditions, the distance between the primary and secondary coils should be kept as small as possible consistent with adequate insulation and cooling facilities, that is, the outside dimensions of the core are kept small. This core construction is not used as much as the shell type to be described later, because it is impossible to entirely eliminate magnetic leakage in it, and the cross-section area of the core must be made quite large if much power is to be handled, in order to keep the flux density down below the saturation value for the core. Leakage is sometimes reduced by winding half of the primary winding on each leg of the core and then winding half of the secondary winding directly over each primary half with suitable insulation between. The primary coils are then connected in series, and the secondary coils are connected likewise. This increases the cost of manufacture, but has some advantages in special applications.

At (C) another form of core-type transformer is shown. This has both the primary and the secondary winding wound one over the other on a single leg of the core, to reduce magnetic leakage. This form of core is used more for inductor or choke coils in the filter systems of radio receiver power packs than it is used for transformers. It is also used extensively for audio transformers. These will be described later in Art. 427.

At (D) the shell-type transformer is shown. This has a completely closed core with a center leg and two outside legs. This forms two outside parallel paths for the magnetic lines of force, as shown by the dotted lines drawn on the power transformer of this type, illustrated at the left of Fig. 72. This construction provides very low magnetic leakage since the primary and secondary coils are wound directly over each other on the center core leg, or are sometimes wound with the windings interleaved. Also, since the total flux divides into two equal paths, each outside leg need

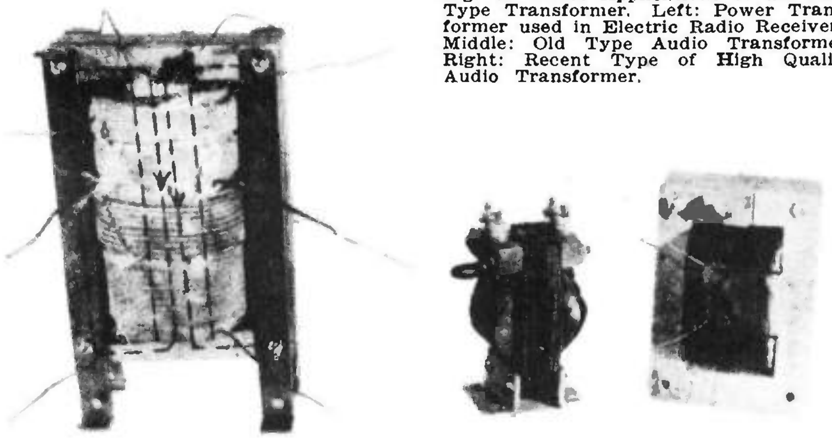


Fig. 72—Three Applications of the Shell Type Transformer. Left: Power Transformer used in Electric Radio Receivers. Middle: Old Type Audio Transformer. Right: Recent Type of High Quality Audio Transformer.

only have half of the cross-section area required for the center leg, for the same flux density. This type of transformer is the most common one used for audio transformers and power transformers in radio, and for the large power transformers used in electrical power work. Fig. 72 shows three transformers of the shell type. At the left is a power transformer from an electric radio receiver. This has a primary winding operating from the 110 volt a-c electric light line, and several secondary windings. If any one of the secondary windings is not to be used, its ends may simply be left disconnected. In the middle is a type of audio transformer (studied later in the chapter on audio amplification) popular in the early days of radio. At the right is a modern high grade audio transformer of efficient design. Notice how much more iron and copper was used in this transformer than in the old type photographed next to it.

111. Transformer windings, ratio and design: The student may wonder why transformers should be used to *transfer* electrical energy from one circuit to another in this fashion. Why not simply leave out the coils and complete the circuit without them? If we desired to use the current in its original form, the transformer would be quite unnecessary, (except in the case where it is used as an "impedance matching device"). It is when the *voltage* of a circuit is to be either *raised* or *lowered* that the transformers are used. Whether the transformer raises or lowers the voltage supplied to its primary depends entirely upon the ratio of the number of turns in the secondary to the number of turns in the primary winding.

Referring to (A) of Fig. 71, it is evident that since the coils and magnetic circuit are all stationary with respect to one another, the e. m. f. is induced in the secondary by the change in *magnitude* and direction of flux with time, caused by the flow of alternating current through the primary winding. A transformer will also operate of course if a *pulsating* or changing direct current is sent through its primary. In this case an alternating e. m. f. is induced in the secondary, for when the primary current is increasing in value (corresponding to closing the switch in our experiment of Art. 108) the e. m. f. is induced in one direction in the secondary. When the primary current decreases in value (corresponding to opening the switch in the experiment of Art. 108) the e. m. f. is induced in the secondary in the opposite direction. Radio frequency and audio frequency transformers used in radio receivers are operated this way, for the plate current flowing through their primary windings is a pulsating direct current. A corresponding alternating e. m. f. is induced in the secondary, and is applied to the grid circuit of the following vacuum tube.

An alternator supplies current to the primary winding **P** having Np turns. The voltage is induced in the secondary having Ns turns. We will assume that there is no leakage of lines of force between the primary and secondary coils. As the primary winding is wound on the iron core, its magnetomotive force produces an alternating flux Φ in the core, which links with the secondary S, inducing e. m. f. Es of the same frequency as its own. Because of this induced e. m. f., the secondary winding S is capable of delivering current and energy, the energy being transferred from P to S by the mutual magnetic flux Φ. We will assume first for our purpose, that the secondary terminals are left open so no current is flowing in the secondary winding. The mutual flux Φ in passing through the magnetic circuit formed by the iron core, links not only the turns of the secondary winding S, but also the turns of the primary winding P. Therefore an e. m. f. is really induced in both the windings S and P. That in P is really a back or counter-e. m. f. of *self induction* always opposite in direction to the applied e. m. f. If the transformer had no iron losses and no resistance losses in the copper primary winding (100 per cent efficiency) this counter-e. m. f. of self induction would equal the applied line

e. m. f., and when once the magnetic field was set up, no further current would flow in the primary. Of course this condition is impossible, since energy is used up in sending current through the resistance of the primary winding, and electrical energy must also be taken from the line to make up for the losses in the magnetic material. Consequently, in a practical transformer when the secondary is on open circuit, a small current called the *no-load magnetizing current* is taken from the line by the primary. In efficient transformers this current is very small.

Since the same magnetic flux Φ in the core links and unlinks with both windings, it must induce the *same e. m. f. per turn* in each winding. Since the e. m. f. per turn of the primary winding is $\frac{Ep}{Np}$ and the e. m. f. per turn of the secondary is $\frac{Es}{Ns}$ we have the relation that:

$$\frac{Ep}{Np}=\frac{Es}{Ns} \text{ or } \frac{Ep}{Es}=\frac{Np}{Ns} \text{ or } Es=Ep\times\frac{Ns}{Np}$$

In other words the *induced* secondary voltage is proportional to the ratio of the number of secondary turns to the number of primary turns.

Since in the ordinary transformer under load the voltage drop due to the resistance of the secondary winding is usually rather low, the secondary terminal voltage differs from the induced e. m. f. in the secondary by only a very small percentage, so that for most practical purposes it may be said that the primary and secondary voltages are proportional to the respective number of turns, or the turns ratio.

By using the proper number of turns, voltages either greater or less than the primary voltage may be obtained at the secondary terminals. The above relation is not absolutely true for a practical transformer delivering current from its secondary winding, for under these conditions there is some leakage, flux, etc., but for our purpose we may neglect this.

Example: A filament-heating transformer in a radio receiver is to reduce 110 volts a-c from the electric light line, to 2.5 volts for the filaments of a group of 224 type vacuum tubes connected in parallel. What is the turns ratio between the secondary and primary?

Solution: $\frac{Ep}{Es}=\frac{Np}{Ns}$ or $\frac{110}{2.5}=\frac{Np}{Ns}=44.$ Ans.

That is, the primary has 44 times as many turns as the secondary.

It should be noted that this does not give the actual number of turns in either the primary or secondary windings. The actual number of turns depends upon several design factors, the ratio depends simply on the voltage desired.

The induced electromotive force in a transformer winding due to the alternating flux is proportional to three factors, the flux, the frequency, and the number of turns. The complete equation for induced e. m. f. (assuming a sine wave current is as follows) :

$$E = 4.44 f N \Phi_{max} 10^{-8} \text{ volts.}$$

f=frequency in cycles per second.

N=is the number of turns.

Φ_{max} is the maximum value of flux in the core.

4.44 is a factor which takes care of the fact that in an a-c cycle, (see (A) of Fig. 69), the current varies in strength, and therefore the flux produced by it also varies, hence the *average* value of the current or flux must be considered (average value= effective value divided by 1.11); and also the fact that a complete change of flux occurs each half cycle, or 4 times in a complete cycle. This gives 4×1.11 or 4.44 for the factor. Otherwise the formula is the same as that given previously for the value of an induced e. m. f. in direct current work.

This formula can be put in a form more convenient for most transformer calculations. Remembering that the maximum flux $\Phi_{max} = B_{max} A$; where B_{max} is the maximum flux density in lines per square inch and A is the cross-section area in square inches. Substituting this for the above, we obtain. $E = 4.44 f N B_{max} A\ 10^{-8}$ volts.

Example: The core of a special 60-cycle step-down transformer has a cross-section of 10 square inches and the maximum flux density in the core is 60,000 lines per square inch. There are 300 turns in the primary and 48 turns in the secondary. What is the rated voltage of primary and secondary windings?

Solution: $Ep = 4.44 \times 60 \times 300 \times 60{,}000 \times 10 \times 10^{-8} = 479.52$ volts. Ans.
$Es = 4.44 \times 60 \times 48 \times 60{,}000 \times 10 \times 10^{-8} = 76.72$ volts. Ans.

Check: $Es = Ep \frac{Ns}{Np} = 479.52 \times \frac{48}{300} = 76.72$ volts. This checks with the value found above

The complete design of the magnetic and electric circuits of transformers is largely a matter of cut-and-try, and former experience. The usual handbooks do not help the beginner much in designing a transformer. It is not only necessary to know the magnetic characteristics of the particular core steel to be used, but the final cost of the transformer, outside dimensions, space available for the windings, etc. are all factors which must be more or less juggled, and from which a satisfactory compromise must be effected for the final design.

When the secondary terminals of a transformer are connected to a complete circuit as in (A) of Fig. 71 so that a current Is flows out of the secondary, the transformer is said to be *loaded.* In accordance with Lenz's law the direction of the secondary current at every instant is such as to always oppose the changes of flux of the primary. The relative directions of the primary and secondary current then tend to reduce the value of the flux in the core. If the flux is reduced, the counter-e. m. f. of self induction in the primary is also reduced, and hence more current will flow in the primary to supply the increase in power due to the load put on the secondary. This is the sequence of reactions which accompany the application of load to the secondary, enabling the primary to automatically take from the line the increased power demanded by the secondary. The change in the counter-e. m. f. is proportional to the mutual flux Φ; the value of Φ does not change appreciably; and so the net ampere-turns acting on the core cannot change appreciably. Since the magnetizing current is very small in comparison with the total primary current, it may be neglected, and then the primary and secondary ampere-turns are equal, and

$$N_p \times I_p = N_s \times I_s$$

$$\text{therefore } \frac{I_p}{I_s} = \frac{N_s}{N_p}.$$

That is, *the primary and secondary currents are inversely proportional to the respective turns.*

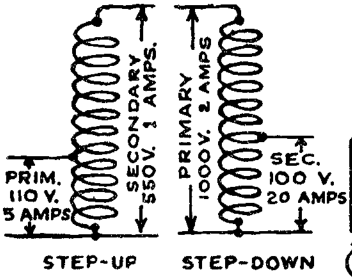
It follows then that a transformer which steps up the voltage. steps down the current an equal amount; one which steps down the voltage, steps up the current by an equal amount.

When no current is taken from the secondary, the current taken by the primary is very small. The energy associated with this current is used up in two ways. Heat is produced in the winding and in the core, due to the electrical and magnetic losses in these materials. Also, some current is used to maintain the magnetic field of the primary. The latter consumes no energy from the line, because at each reversal of the current the energy of the field is returned to the circuit.

Transformers used in audio amplifiers (see Fig. 72), are examples of transformers working practically without secondary load in actual operation. They are used merely as voltage step-up devices, the secondary having 3 or 4 times as many turns as the primary and hence the secondary induced voltage being 3 or 4 times as large as the voltage impressed across the primary terminals. Since these transformers present special problems in design they will be discussed more fully in the chapter on audio amplification, (see Art. 427).

Power transformers which are used to supply the plate current at high voltage, and the larger filament currents at low voltage, to vacuum tubes in electric radio receivers, usually have a single primary winding and several secondary windings as shown at the left of Fig. 72. In this particular illustration, the difference in the number of turns on each winding and the size of wire used to carry the particular amount of current which the winding will be called upon to supply, are clearly shown. The primary winding which operates from the 110 volt a-c line is wound underneath and insulated from the windings which are visible. The upper secondary winding delivers 1.5 volts; the one below it has more turns, and delivers 2.5 volts at two amperes capacity for the filament of one 227 or 224 type tube; the one below this also delivers 2.5 volts (same number of turns), but since it has a larger current handling capacity (10 amps.) to supply filament current for up to six 227 or 224 type vacuum tubes, it is wound with thicker wire. The bottom winding has twice as many turns, and delivers 5 volts at 2 amperes for the filament of a 280 type rectifier tube.

112. The Auto-transformer: The ordinary type of transformer just studied, has its primàry and secondary windings distinct and insulated from each other. It is not necessary to have the two windings distinct however. In the *auto-transformer* shown in Fig. 73 the secondary winding is connected to the primary winding. This type of transformer may be built either to step-up the voltage as in (A), in which case the primary winding is a portion of the secondary; or it may be built to step-down the voltage as at (B) in which case the secondary winding is a portion of the primary. The position of the tap on the winding determines the voltage and current ratios of the primary and secondary. The voltage across the secondary winding bears the same relation to that across the primary part as though there were two separate windings, and the ratio of the voltages is the ratio of the number of turns included between the secondary and primary terminals, just as in the case of the ordinary transformer. The voltages and currents for a particular case are shown in Fig. 73.



(A) (B)

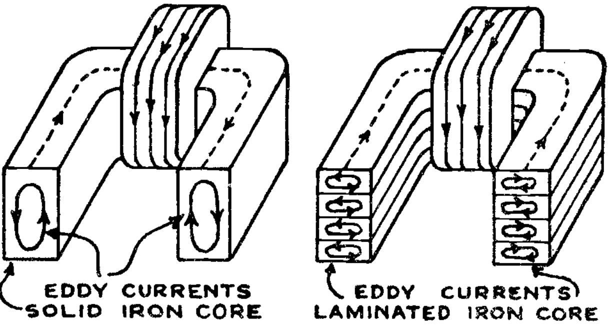


Fig. 73—(A) A step-up auto-transformer. (B) A step-down auto-transformer.
Fig. 74—The effect of laminating a magnetic core to reduce eddy currents.

Iron core auto-transformers are used for power work in low voltage circuits such as in the type of battery charger shown in Fig. 45. They are also used in motion picture work for efficiently reducing the 110 volts of the line to from 40 to 60 volts for the electric arc. They are usually called "economizers" in this case. They are also employed for audio frequency amplifier couplings in some forms of impedance or modified choke coupling, to provide a moderate voltage step-up. The "Autoformer" coupling unit described in the chapter on audio amplification is of this type. The transformation of the energy from the primary to the secondary circuit in an auto-transformer is partly by *transformer action* and partly by *straight electrical conduction* from one circuit to the other. For moderate ratios of transformation, the auto-transformer is much more economical in the use of materials, and has a much higher efficiency, than a transformer which *transforms* all the power. With the higher ratios of transformation, more and more of the power is transformed by regular transformer action and less by conduction. The auto-transformer is therefore economical only for small ratios. Also, as the low and high voltage sides are connected together conductively, in commercial power systems the low side should be grounded at the proper point for reasons of safety, if the high-side voltage is sufficiently high to be dangerous.

Air-core auto-transformers are often employed as couplings for the antenna circuit and first tuned circuit in radio receivers, and are sometimes used as interstage coupling transformers between radio frequency amplifying tubes as we shall see later.

113. Transformer-iron losses—eddy currents: The secondary winding is usually placed outside, and the primary winding is between the core and the secondary, see Fig. 71.

The cores in practically all the iron-core transformers are made up of a number of thin sheets of transformer iron or steel. These thin sheets are called *laminations*, and the core is said to be *laminated*. The purpose of the laminated construction is to greatly reduce the loss due to eddy currents, as we shall now see.

In a closed-core transformer with a *solid steel core*, the core can be considered as a single turn secondary which would have a low voltage induced in it by the rapidly varying magnetic field through it. This would produce circular currents flowing as shown at the left of Fig. 74, in a plane at right angles to the direction of the main field, and in such a direction as always to be opposed to the main magnetic field through the core. These currents would be very large, even though the induced voltage were low, since the resistance of the path in the core would be very low due to the large solid cross-section area. Of course these currents flowing around the closed ring core as shown (eddy currents always flow in planes perpendicular to the flux), would cause a considerable amount of heat which would quickly heat both the core and windings, and also result in a decrease in efficiency since this current is not useful but is wasted. These currents are called *"eddy currents."*

By constructing the core of thin laminations of steel, each one electrically insulated from the next by a specially formed film of oxide, a thin sheet of paper, or a coat of insulating varnish or enamel, the eddy currents are confined to the single laminations, and therefore they are weak, since the resistance of these paths is very much greater than the resistance of the paths in a solid chunk of steel, due to the fact that the length of each path is longer and the cross-section area is less, as shown at the right of Fig. 74. The iron is thus left continuous in the direction of the magnetization, but discontinuous in the direction of the flow of the eddy currents. The small transformers shown in Fig. 72 show the laminated core construction clearly. Because of the low efficiency of small transformers, the primary current is ordinarily 10 to 20 per cent greater than a consideration of the secondary current and turns ratio would indicate. Large transformers used in power work may have high efficiencies, of 95 per cent and over. Because of the space taken up by the oxide or varnish on the core laminations, the value of the true effective cross section area of the core may be 5 or 10 per cent less than the outside physical dimensions would indicate.

In order to further reduce the strength of the eddy currents, the steel used in most alternating magnetic circuits has from 2 to 4 per cent of silicon added to it. This is called *silicon steel* or *electrical sheet steel*. The 2 to 3 per cent of silicon added to the medium silicon steel used for most transformer cores, increases the electrical resistance of the steel from about 10 microhms per cubic centimeter to 45, an increase of 4.5 times. The eddy current loss is proportional to the square of the frequency of the varying flux through the core.

Unless the laminations are effectively insulated from each other, by the iron-oxide layer or other means, the eddy current losses may be much greater than would otherwise be the case, since the eddy currents would be able to flow across from one lamination to the next. By decreasing the thickness of the laminations, the eddy current losses can be reduced to any desired value but there is a limit, since if the material is made too thin, the space occupied by the insulating layers becomes excessive, thus producing higher net inductions in the steel and resulting larger losses and magnetizing current. Also, thin sheets cost more to manufacture than thick ones, and more to punch and assemble. Also they have higher hysteresis loss per unit weight, since the material has a finer grain and hence more internal friction due to the repeated rolling than thicker sheets. It has been learned that the best balance between these various factors is to use sheets having a thickness of from 12 to 18 mils (1 mil=.001 inch) for the cores of apparatus to be operated on 60 cycles. The steel is usually operated at a flux density of about 60,000 lines per square inch. 14-mil sheet is perhaps the most commonly used in America for this purpose. For special iron-core radio frequency apparatus, sheet from 1 to 3 mils thick is used. The laminations should be clamped tightly to prevent their tendency to vibrate at a frequency equal to that of the primary current, due to the changing magnetic field.

114. General transformer construction and application: Power transformers are heavily constructed, with large cores and heavy windings, since relatively large currents flow through them. They are usually enclosed in metal cases with either air or other cooling facilities provided to carry away the heat developed by the hysteresis and eddy current losses in the core material and the I^2R losses in the primary and secondary conductors. They are used for boosting and then lowering the voltages on long power transmission lines. By using high voltages of from 30,000 to 250,000 volts, the line losses are reduced, since only small currents are required to transmit a given amount of power at these high voltages, ($W=E\times I$), so it is possible to use smaller and cheaper conductors and supporting towers.

The electric lighting companies all distribute electrical power for home lighting, at rather high voltages to neighborhoods. It is then stepped down to 120 volts by transformers and supplied at this voltage to the consumers. Transformers are also used in a-c electric welding work, for a-c bells, etc. Small audio transformers and power transformers used in radio equipment are usually sealed in paraffin wax or pitch to "damp" any vibration of the laminations, since the noise produced by loose laminations is sometimes very objectionable. The metal containers around such transformers act as partial magnetic shields for the windings, provided they are thick enough and the stray fields of the transformers are not too excessive. In the shell type of transformer there is a minimum of leakage flux, and the iron of the core itself forms a partial magnetic shield.

Small power transformers used in radio receiving equipment usually are of the type shown at the left of Fig. 72, with several secondary windings to provide the various voltages required. When the cores are built of individual lamination strips stacked one over the other with their ends interleaved, the joints between the ends must be kept very tight to prevent any air gaps which would decrease the magnetic flux and so decrease the output voltages. Audio transformers have a large number of primary and secondary turns of fine wire. The step-up voltage ratio is usually 3 or 4 to 1. Loud speaker coupling transformers are also used to keep the direct plate current of the last audio tube in a receiver, out of the loud speaker winding. Transformers are also used to match impedances in radio and telephone circuits as we shall see later.

REVIEW QUESTIONS

1. What is meant by electromagnetic induction?
2. How is electrical energy produced today on large scale for commercial purposes? What electrical principle is involved?
3. The S pole of a permanent bar magnet is plunged into a solenoid, wound clockwise looking down at the top. Make a sketch showing the conditions. Determine the direction of the induced current through the coil and the magnetic poles produced by it.
4. Explain in detail by means of the electron theory of magnetism, just what happens in the above problem.
5. How long does an induced voltage last? How long does an induced current last?
6. When a very strong bar magnet is moved up and down 150 times a minute in a solenoid having 100 turns of No. 18 wire, a voltage of .02 volts is induced in the coil. State 3 different methods by which you could increase the value of the induced e. m. f. to .06 volts.
7. If the coil were wound with 100 turns of wire of larger diameter (say No. 10 wire) would the induced voltage be affected? How?
8. When a magnet is plunged into a coil of wire what is induced in it, e. m. f. or current? Explain.
9. Why is more power required to turn the armature of a generator at 1000 R. P. M. when it is delivering current, than when it is on open circuit.
10. State Lenz's law. Now state in your own words just what it means.

11. How would you move a wire across a magnetic field so that there would be no e. m. f. induced in it? Illustrate your answer with a sketch.
12. An alternating current generator contains 6 poles. How fast (R. P. M.) must its armature rotate in order to generate a 60 cycle current? How many alternations per sec. would this be?
13. The armature of the generator in the above problem contains 100 active inductors in series, cutting across the magnetic field. If the total flux of all the poles is 8×10^{10} lines of force, what is the total e. m. f. generated by the entire armature?
14. Define (a) steady direct current, (b) pulsating direct current, (c) alternating current.
15. What kind of current flows in the armature coils of an alternating current generator? In a direct current generator?
16. What are slip rings? What are they used for? On what kind of generator would you expect to find them?
17. Is the polarity of the slip rings constant or alternating?
18. What is the purpose of the commutator on a d-c generator? Describe its action (with sketches).
19. Draw a graphical representation of the currents of question 14.
20. How does the magnetic field produced by an alternating current differ from that produced by a direct current? By a pulsating direct current?
21. Why is thicker insulation needed for high-voltage "alternating current" apparatus than for "direct current" apparatus which is subjected to the same *effective* voltage?
22. What is meant by the effective or r. m. s. value of an alternating current? Explain. What is the mathematical relation between the peak voltage and the effective voltage?
23. Draw a diagram showing the position you would mount three radio frequency transformers in, to eliminate any magnetic coupling between them. Explain.
24. State how a transformer should be designed in order to have very low flux leakage.
25. Will a voltage be induced in the secondary of a transformer whose primary has a pulsating direct current flowing through it? Draw a graph of the voltage produced.
26. What is the theory regarding the production of an E. M. F. in the secondary of a transformer?
27. Draw illustrations of an open-core, closed-core and shell type transformer, and describe the construction and advantages of each.
28. How does the frequency of the voltage induced in the secondary compare with that of the current in the primary?

29. What must be the ratio of turns on a transformer designed to step 110 volts down to $2\frac{1}{2}$ volts? What will be the current in the primary if 10 amperes flow in the secondary?
30. How many turns of wire are required in order to induce 20 volts in a coil when the flux changes 60 cycles per second, and the maximum total flux is 60,000 lines of force?
31. Explain the advantage of silicon steel over ordinary steel for use in magnetic cores. Is silicon steel necessary for use in an electromagnet to be used on steady direct current?
32. Explain why a transformer core is built up of many thin laminations instead of being made of a single solid chunk of metal. How does laminating accomplish the desired result?
33. Discuss the commercial applications to which auto-transformers are adapted.
34. What change would be made in the commutator of a d-c generator if additional coils were wound upon the armature core? What change would this produce in the slight ripples in the output current?
35. What effect does self-induction have on the primary of a transformer if the secondary circuit is left open? Is this effect harmful or desirable?
36. A filament-heating transformer used in a radio receiver has four separate secondary windings delivering 2.5, 2.5, 1.5, and 5 volts respectively. The primary voltage is 110 volts. If the primary winding contains 100 turns, how many turns must each secondary winding have to deliver the above voltages? Draw a diagram showing these windings and the iron core.
37. If one of these secondary windings is not to be used, may its terminals be left disconnected without harm? Why?

CHAPTER 9

INDUCTANCE AND INDUCTORS

SELF-INDUCTANCE — UNIT OF INDUCTANCE — PRACTICAL INDUCTORS — NON-INDUCTIVE COILS — INDUCTORS IN SERIES AND PARALLEL — MUTUAL INDUCTION — MAGNITUDE OF MUTUAL INDUCTANCE AND COUPLING — VARIABLE INDUCTORS AND COUPLING — VARIATION OF INDUCTANCE WITH CURRENT AND FREQUENCY — COUPLING BETWEEN WIRES — REVIEW QUESTIONS.

115. Self-induction: Whenever an electric current flows through a wire, there is a magnetic field produced around the wire, the direction and intensity of the field depending upon the direction and strength of the current flowing. If the current is varied in any way, the magnetic field also varies correspondingly. This varying field sets up in the wire itself, a counter or self-induced e. m. f. which always opposes the change which produced it. (Lenz's Law.)

The effect of the self-induced e. m. f. in a wire may be illustrated by the following experiment which can be performed with the same apparatus used in the experiment of Article 101.

Experiment: Connect up the solenoid of 100 feet of wire used in Art. 101, a switch, a voltmeter and a battery as shown at (A) of Fig. 75. The voltmeter connected across the coil should have a suitable range for the particular battery voltage employed. When the switch K is closed, the voltmeter assumes a steady deflection, since the cur-

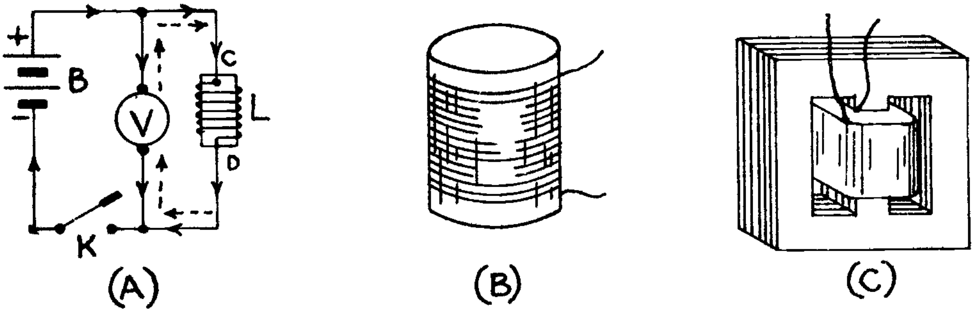


Fig. 75—(A) Circuit for showing Self-Inductive Effects. Forms of Inductors used in Radio Work. (B) Air-core Inductor of 200 Microhenries or so. (C) Iron-core Inductor of 30 Henries used in B-eliminator Filter.

rent flows in the direction shown by the solid arrows. Upon opening switch K, a very large deflection of the voltmeter occurs. The deflection is always in a direction opposite to the steady deflection caused by the battery current. This shows that after the main circuit containing the battery has been opened, and while the current is dropping to zero or the magnetic field is vanishing, a *momentary e. m. f.* is induced in the coil in such a direction as momentarily to maintain the current flowing in the coil. The current would therefore tend to flow from C to D in the coil and would thus have to flow into the meter in the direction shown by the dotted arrows. The meter therefore deflects in a direction which is opposite to the direction in which it previously deflected. Other experiments indicate that when the circuit is closed, and while the current in the coil is increasing in value, or the magnetic field is building up, a momentary e. m. f. is induced in the coil which is in opposition to the battery e. m. f., thus causing the current to increase gradually and not instantaneously, from zero to the final value given by Ohm's law. Thus, the induced e. m. f. in each case is in a direction such as to oppose the cause which produced it.

An electromotive force which is induced in a circuit by reason of a variation in the value of the current in the circuit, is called an *electromotive force of self-induction.*

Since the self-induced e. m. f. opposes any change whatever in the current flow, it is evident that the result is that it takes a longer time to build up the current to its final value when e. m. f. is applied, and a longer time for the current to fall to zero when the e. m. f. is removed, where this effect is present to any great extent in a circuit. The effect is somewhat similar to that of *inertia* in mechanical devices, the inertia tending to oppose either an increase or a decrease in speed of motion.

The effects of self-induction are very marked in circuits having the form of a helix, for in these circuits the added effect of the various turns creates a considerable magnetic field within the coil; the magnetic field of every turn cuts many adjacent turns, and the counter-e. m. f. is increased. The magnetic effect of a great length of wire is thus concentrated into a small space. Whenever strong self-induction is desired, the conductor is wound up into the form of a solenoid having a large number of turns as shown at (B) of Fig. 75. This greatly increases the magnetic field produced by the current flowing through the coil, and so increases the self-induction effect.

116. Unit of inductance: Since the effect of self-induction is due to the generation of a counter-e. m. f. in the circuit due to the action of its own magnetic field, we should expect that its effect would be proportional to the rate at which the lines of force link or unlink with the circuit, just as in the case of the generation of e. m. f. in an electric generator.

The self-induction effect of a coil or wire, by which it tends to prevent any change in the current flowing through it (whether the current is starting and then increasing; or decreasing and coming to a stop; or changing its direction of flow), is called its *inductance.* The unit of *inductance* is called the *henry* (h) named after Joseph Henry the famous experimenter who independently discovered the effects of electromagnetic induction only a few months after Faraday.

When a current change of one ampere per second in a circuit produces in it an induced e. m. f. of one volt, the circuit is said to have an inductance of one henry.

The symbol for inductance is L. The definition of the henry may be stated in algebraic form as follows:

$$L = \frac{E}{I/t}$$

in which L is the inductance in henries, E is the induced e. m. f. in volts and I/t is the change in current in amperes per second.

Except for the larger sizes of iron-core coils, the *henry* (h) is a larger unit of inductance than it is convenient to use. Therefore, most air-core radio inductances are measured in millihenries (m. h.) and microhenries, (μh). One millihenry is equal to one-thousandth of a henry. One microhenry is one-millionth of a henry (see prefixes in Appendix).

Inductance is sometimes found as an inseparable part of some electrical device or circuit. Thus, in a transformer, both the primary and secondary windings possess inductance. The inductance of the secondary winding of tuning transformers or coils used in radio receivers is an important factor which determines the frequency or wavelength range to which they may be "tuned" with a given tuning condenser. In some cases, inductance is purposely added to a circuit, as in the case of antenna loading coils, choke coils, etc. Devices which are purposely added to introduce the element of inductance to a circuit are called *inductors*. However, it has become a practice in radio and electrical work to call such devices by the names of choke coil, impedance coil, inductance coil, inductance, reactance coil, etc. Thus it is common to hear of radio frequency choke coils, filter chokes, etc. In this book, an attempt will be made to use both the standard term *inductor* and the terms in common usage, in a way which will enable the student to become thoroughly familiar with all of them.

It is evident that the cause of self-induction is due to the property possessed by the wire or coil by reason of its *physical* arrangement, such as number of turns, shape of coil, permeability of magnetic path of core, etc. This should be kept in mind. A coil or wire possesses the property of inductance whether a current is passing through it or not, (although the inductance of an iron-core inductor may be decreased by magnetic saturation of the core due to too much current flowing in the winding). Of course, the exact inductance value depends on the many factors mentioned above.

The self-inductance of an *air-core* solenoid is approximately:

$$L = .0251\ d^2\ n^2\ l\ K \times 10^{-6}\ \text{henries.}$$

where L=inductance in henries
- d=mean diameter of solenoid in inches
- n=the number of turns per inch (See copper wire table in Fig. 287 for the value for the particular size wire being used.)
- l=the length of the solenoid (when wound) in inches
- K is the form-factor (Nagoaka's correction factor) which depends for its value on the ratio of the diameter to the length of the winding. Values of K are given in the table in the chapter on R. F. amplifier design, (see Art. 400).

If L is to be expressed in *microhenries*, this formula becomes

$$L = 0.0251\ d^2\ n^2\ l\ K \quad \text{.................} (12)$$

Inductors of various shapes, numbers of layers, etc. can be calculated by special formulas which have been developed. The student will find these in Bulletin 74 of the United States Bureau of Standards. If iron is introduced in the magnetic circuit, the inductive effect is of course increased greatly, depending upon the permeability of the iron employed. The permeability of air is 1; that of iron may be as high as 25,000 to 100,000 or more. This means that the inductance of a given coil may be increased 25,000 times or more by winding it on a core of high permeability iron or special alloy. Of course the iron must form the *complete* path for the magnetic lines of force, or the increase in inductance will be less than these values.

Experiment: The effect of using an iron core may be illustrated convincingly by repeating the experiment of Article **115** with air as the core of the solenoid, and then placing iron nails, an iron rod, or a transformer core in the coil. The kick of the voltmeter needle will be very much greater when the circuit is now opened or closed.

In some cases iron cannot be used for the core, on account of the excessive eddy current and hysteresis losses which occur if the current and flux are changing rapidly. This is particularly true in radio frequency inductor or choke coils used in radio equipment. The induced voltage across an inductor depends upon the *rate* at which the current is changing, and the inductance of the coil. If the current changes rapidly, the induced voltage will be very much greater than if it changes slowly.

Formula 12 shows that the inductance of a coil increases as the square of the number of turns. Thus if a coil of 4 units inductance has its number of turns doubled, the inductance will have increased to 4×4 or 16 units. This is true provided there is good "coupling" between the turns, that is if the coil is on an iron core. If the coil has an air core this is only approximately true, because then some of the lines of force created say by the inner turns on the coil may go directly out into the air and not link with the end turns on the coil, especially if the coil is long. This is the reason for the correction factor K in formula (12). The detailed calculations of inductance coils will be taken up later in Chap. 23, in connection with radio frequency tuning coils.

117. Practical inductors: The inductors used in radio apparatus take many forms, depending on their particular application. Some have inductances of only a few microhenries, are wound on insulating forms, and have air cores. Broadcast frequency tuning coils of the type shown at (B) in Fig. 75 may be of the order of 200 to 300 microhenries and may be from 1 to 3 inches in diameter, wound with 50 to 100 turns or so of No. 20 to No. 30 wire. Radio frequency choke coils having an inductance of 85 millihenries are also used extensively. For short wave work, smaller values of inductance are used.

Iron-core inductances commonly used in audio amplifiers and in the filters of the "B"-power supply units of radio receivers have a great many turns of fine wire wound on laminated steel cores as shown at (C) of Fig. 75. Inductances as high as 100 henries are not uncommon in devices of this kind. The windings in inductances as large as this, contain thousands of turns of wire. Their particular applications will be studied later. The approximate inductance of iron-core inductor or choke coils built with silicon steel laminated transformer-iron cores, may be calculated from the following formula:

$$L = \frac{\text{core area} \times \text{turns}^2}{\text{air gap} \times 40{,}000{,}000}$$

A core flux density of 20,000 lines per square inch is assumed.

The inductance is in henries, the core cross-section area is in square inches, and the total air gap in inches is determined from the formula:

$$\text{Air gap in inches} = \frac{3.2 \times \text{turns} \times \text{amps}}{\text{flux density in lines per sq. in. (in air)}}$$

The size of wire with which to wind the coil is determined by the current the coil is to carry. The wire size may be obtained from the data in the magnet wire table in this book.

When an alternating current, or a varying direct current, flows through an inductive winding, a considerable counter-e. m. f. is developed due to the varying magnetic flux. This acts to oppose the flow of the current through the winding, as we shall see later.

The large spark noticed when opening the switch in an inductive circuit is caused by the high self-induced voltage which tends to keep the current flowing across the switch gap. Circuits having high inductance should not be opened suddenly, for dangerously high voltages may be developed in them by the self induction. These may be high enough to puncture the otherwise satisfactory insulation on the wires. Circuits of this kind should be opened gradually by inserting resistance in them to slowly reduce the current to a low value, then finally opening the switch.

118. Non-inductive coils: In some applications of coils where wire is wound up in the form of a solenoid in electrical and radio work, it is desirable that the solenoid should not possess any appreciable amount of inductance. Such windings are called *non-inductive windings*. For instance, when resistors are made of resistance alloy wire, the wire is usually wound up in the form of a solenoid of many turns, in order to make it compact in size. It is often desirable that the resistor not have any appreciable inductance due to this wound form, as in this case of the resistor coils used in Wheatstone bridges (see Art. 218), etc.

Self-inductance in a coil may be neutralized by winding one half of the coil in one direction and the remainder in the opposite direction as shown at (A) of Fig. 76. The wire is really doubled back on itself. This is accomplished by folding the length of wire to be used, at its middle point, and starting at this point, winding both halves at the same time as a single wire, until the ends or terminals are reached. The magnetic effects of the current flowing in one direction through half of the total turns is equal and opposite to that produced by the same current flowing in the opposite direction through the other half of the total turns. The magnetic fields thus neutralize each other, and hence no inductive effect is present. The winding is said to be non-inductive.

As this method is rather inconvenient when a long length of wire is to be wound up, since the entire wire must first be stretched out and the middle found, etc., it is common in manufacturing non-inductive coils or

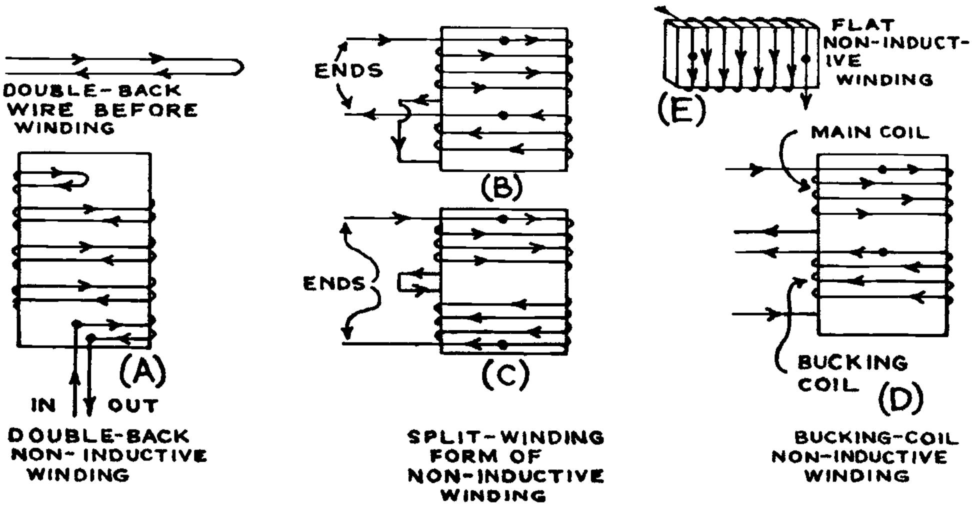


Fig. 76—Several Forms of Non-inductive Windings.

windings to simply wind the total wire up in the form of two separate coils, each having an equal number of turns equal to half the total turns required, as shown at (B) and (C) of Fig. 76, instead of in a single part. Then the proper ends of the coils are connected together as shown, so the current progresses from one end through the two coils in the opposite direction so the magnetic fields are neutralized. The coils need not be wound in the same direction. It is merely necessary to connect them properly so the current flows in the opposite direction in each. At (B) the coils are wound similarly. At (C) they are wound in opposite directions.

Sometimes the inductive effect of one coil is neutralized by current sent through a separate *"bucking winding"* of the proper number of turns, placed near it as shown at (C) of Fig. 76. The bucking coil is so wound or connected, that its magnetic effect equals and opposes that of the main field. In these methods, the two windings need not be in the same direction. The right-hand rule for the magnetic field of solenoids is employed for working out the proper current directions.

Another way of winding a coil non-inductively is to wind it flattened in shape on a thin flat cardboard or bakelite form about 1/8 inch thick

Such a coil has practically no inductance because the opposite sides of each turn of wire are so close together that the magnetic fields neutralize, since the current is flowing in the opposite direction in them as shown in (E) of Fig. 76. This is a simple, practical way of winding non-inductive resistors and is used extensively. It also presents considerable surface area for the rapid cooling of the resistance wire.

119. Inductors in series and parallel: Inductors connected in series as shown in (A) of Fig. 77 simply add their self-inductances together since each one helps to oppose any change of the current through the entire system, (provided the coils are so far apart or are placed at such angles with each other that there is no magnetic coupling between them). Thus, three coils having inductances of 100, 200 and 10 microhenries would have a combined inductance when connected in series, of $100+200+10=310$ microhenries. Should there be magnetic coupling between the inductors, the effect of the mutual-inductance considered in the proper direction will be added to the self-inductances only, depending on the relative directions of the magnetic fields of the coils as will be explained later. Thus, for inductances L_1, L_2, L_3, etc., in series, with no coupling between them, the total inductance L is:

$$L=L_1+L_2+L_3+L_4 \ldots\ldots\ldots \text{etc.}$$

It is common to connect separate inductors in series with a circuit to increase its total inductance. Such inductors are commonly called

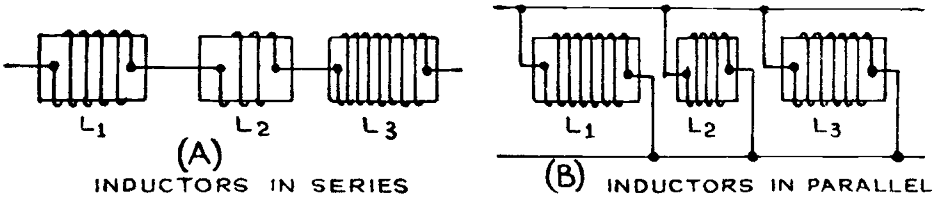


Fig. 77—Inductors in Series and Parallel.

"loading coils". Loading coils are sometimes connected in the aerial circuit or a tuning circuit of a radio transmitter or receiver for this purpose.

When inductors are connected in parallel with each other as in (B) of Fig. 77, their combined inductance is found from the formula:

$$\frac{1}{L}=\frac{1}{L_1}+\frac{1}{L_2}+\frac{1}{L_3}+\frac{1}{L_4}+\ldots\ldots\ldots \text{etc.}$$

Where L is the total or combined inductance of the coils whose separate self-inductances are L_1, L_2, L_3, L_4, etc. Here again no magnetic coupling must exist between the coils.

Example: What is the combined self-inductance of coils of 100, 200 and 10 microhenries when connected in parallel?

Solution: $\frac{1}{L}=\frac{1}{L_1}+\frac{1}{L_2}+\frac{1}{L_3}$ or $\frac{1}{L}=\frac{1}{100}+\frac{1}{200}+\frac{1}{10}$

From which L=8.7 microhenries. Ans.

The combined self-inductance of coils in parallel is always less than the self-inductance of any one of the coils considered alone. This is the same as for resistances.

When using these formulas, care should be taken to see that all the self-inductances are expressed in the same units. If the separate inductances are in henries, the total will likewise be in henries, if the separate inductances are in microhenries, the total will likewise be in microhenries.

120. Mutual induction: The electromagnetic induction due to two independent electric circuits reacting upon each other, is called *mutual-induction* (see Fig. 70). The previous examples of the induction of voltage in the secondary winding of a transformer due to the current flowing through the primary is an excellent illustration of mutual-induction. Parallel conductors carrying independent alternating currents react upon each other by reason of the mutual inductive influence between them. Mutual induction between wires in radio transmitters, and in radio receivers, is often the cause of howling, hum, etc., and certain steps may be taken to prevent this.

It is not necessary to again go into a detailed study of the actions taking place during mutual-induction, as this has already been covered during our study of the transformer. It should be remembered that induced voltage is produced in the secondary circuit whenever current in the primary starts to flow, ceases to flow, changes its rate of flow, or changes its direction of flow. The intensity of the induced voltage depends upon, and is proportional to, the rate at which current changes take place in the primary. The higher the frequency, the more rapid is the change of current, and so the greater will be the induced voltage. The greater the amplitude, or rise and fall, of current in the primary with a given frequency, the greater is its rate of change, and the higher will be its induced voltage. The primary and secondary circuits may be simply straight wires near each other, solenoid coils, etc.

From the point of view of the electron theory, the effects of mutual-induction may be explained simply by reference to Fig. 70. Electrons are flowing around the primary winding when current is sent through. While this stream of electrons is flowing, it causes electrons in the secondary to flow around in the direction opposite to those in the primary. The secondary electron streams by their movement, produce magnetic forces which exert a backward push on those in the primary, and try to stop their flow. If the primary circuit is opened, the stream of electrons in the primary comes to rest, and those in the secondary reverse their direction of flow and tend to make the electrons in the secondary keep on moving. Whatever change takes place in the stream of electrons in the primary, the electrons in the secondary oppose the change by means of the magnetic forces set up by their motion. The student should check up these forces by applying the right-hand rule to find the directions of the fields in each case, remembering that the right-hand rule refers to the direction of the current flow—which is opposite to the direction of the electron flow.

Self-induction can be easily understood by comparing it with the case of mutual-induction explained above. If a coil is connected to a source of alternating current a stream of electrons flows along from one turn to the next. The action between any two turns is the same as if they were two

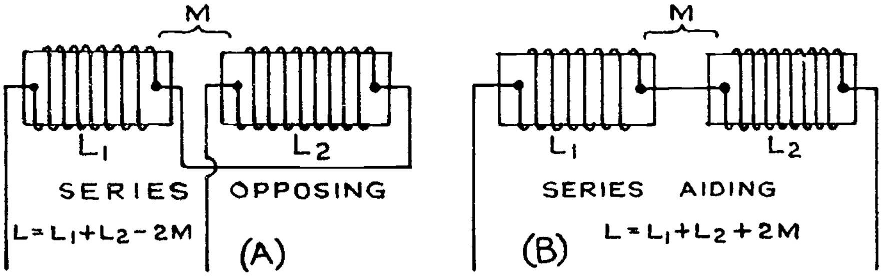


Fig. 78—Inductors may be connected and placed so their magnetic fields either buck each other or aid each other. The total inductance depends upon the connections and the spacing and placing of the coils.

separate coils. As the stream of electrons flow through say the top turn of the coil, they set up a magnetic force which tends to push all the electrons along in the other portion of the coil, that is, tend to increase the current.

121. Magnitude of mutual inductance and coupling: Two coils may be placed with reference to each other so that a part of the electromagnetic field of one coil passes or cuts through the conductors forming the other coil (Fig. 70). Then there is a mutual inductive effect between the coils and they are said to be *coupled.* The closer together the coils are, the greater are the number of lines of force due to the primary current that link with the turns of the secondary, and the *closer* or *tighter* the coupling is said to be. Also the better the permeability of the magnetic circuit, the better is the coupling.

The induced voltage across the secondary of such a two-coil arrangement as shown in Fig. 70 depends upon the sizes of both coils, their relative positions and distance apart, the permeability of the magnetic circuit, and the rate of change of the primary current. All of these *physical* factors, except the rate of change of the primary current, are collectively called the *mutual inductance* (M) of the circuit. The larger the coils are, the closer they are to each other, and the more nearly their axes coincide.

the greater is their mutual inductance M. Since the mutual inductance possible between two coils is affected by so many variable things, and since the design of radio apparatus is almost entirely tied up with mutual inductances and variations thereof, it is important that we study this subject in detail.

In many applications, inductors are connected in series, and are also placed near each other so that magnetic coupling exists between them. We found in Article 116 that the inductance of a coil depends, among other factors, upon the square of the number of turns of wire of which it is composed. Doubling the number of turns makes the inductance 4 times as large, etc. Suppose we have two coils, built exactly alike, as shown in (A) of Fig. 78, and having the same inductance. If they are connected together in series but kept apart to prevent magnetic interaction, the total inductance will simply be equal to the sum of the two. However, if they are connected in series and brought close together, we can have any of the conditions shown in Fig. 70. If they are placed so the direction of current flow and hence the lines of force of one are exactly opposite in direction to the lines of force of the other, at every instant as shown at (A) of Fig. 78, the total inductance will be zero. This is called the "series opposing" position.

If they are connected together in series with the currents flowing in the same direction and are brought up to each other so that every line of force of the primary links with every turn of wire of the secondary, and every line of force of the secondary links with every turn of the primary, and the fields of each are in the same direction at every instant, the result is the same as though we had a single coil made up of the two coils together, that is, a single coil having twice as many turns as each of these coils. This condition is shown at (B) of Fig. 78. Since the inductance is proportional to the *square* of the number of turns, it is evident that this combined inductance is equal to 2×2 or 4 times that of either coil alone. Therefore the combined inductance of two similar coils connected and placed so as to be "series aiding" is four times that the self inductance of either single coil.

In the case of series-aiding coils, the total inductance is made up of the self-inductances of coil 1 and coil 2, the mutual inductance due to the lines of force from coil 1 linking with coil 2, and the mutual inductance associated with the lines from coil 2 which link with coil 1. These two latter mutual inductances (M) are equal, since the coils are the same.

Therefore $L = L_1 + L_2 + 2M$.

Since $L_1 = L_2$ and $M = L_1$ if we substitute these values for L in the above formula, we have $L = L_1 + L_1 + 2L_1$

from which $L = 4L_1$

where L is the *total* inductance. If some of the lines of force from one coil do not link with the other coil—as is usually the case when "air" forms the core—the total inductance will be some value *less* than four times the inductance of one of the coils. In the series-opposing case, it will be less than that of either coil. In any general case the total inductance of two coils of any inductance value, connected so as to be series-aiding, will be:

$L=L_1+L_2+2M$

If they are connected in series-opposing, the total inductance is:

$L=L_1+L_2-2M$

In order to know then just what the total inductance will be, the degree of coupling must be known. The term "coefficient of coupling" enables us to predict just what the total circuit inductance will be if the amount of coupling is known. Of course the coefficient of coupling depends upon the total inductance in the primary and secondary circuits as well as upon the mutual inductance between the inductances. The coefficient of coupling is really a measure of the ease with which energy may be transferred from one circuit to the other. The coefficient may be found from $K=M/\sqrt{L_1 \times L_2}$, all units being in henries, microhenries or millihenries.

The maximum possible value of K is of course 1.0. This is called *unity coupling.* The value of 1.0 is only approached in well designed iron-core transformers where there is very little magnetic leakage. In air-core transformers the coupling may be very "weak" since a large portion of the lines of force of the primary may never reach the secondary. A low value of coupling for this type of coil would be about 0.1, and a high value 0.7. In a well designed iron-core transformer, coupling as high as 98 or 99% (K=0.98) may be obtained, depending upon the design and the amount of magnetic leakage present.

The mutual inductance depends only upon the two coils, and the coupling between them or $M=K\sqrt{L_1 \times L_2}$. The coefficient of coupling K, between any two circuits depends upon the total inductance in each circuit. Thus if one of the two circuits had two inductors in series, the total combined value of the two series inductances in this circuit would be substituted for L_1 in the above formula for K.

The various factors affecting the coupling between the primary and secondary windings in radio frequency tuning transformers and audio frequency transformers used in radio transmitters and receivers, will be discussed in detail when those subjects are studied. The measurement of inductance values will be studied in conjunction with the Wheatstone bridge in Art. 219.

122. Variable inductors and coupling: Inductors are often made so that their inductance can be varied by one means or another. The variation can be obtained by means of a slider as in (A) of Fig. 79; by means of taps and a switch as at (B); or by arranging the coil in two parts so that one can be rotated near the other as at (C), or within the other as at (D). They can also be arranged to move nearer or further away from each other as at (E); or the inductance can be varied by bringing a metal plate within the field of the coil as at (F). The eddy currents induced in the plate produce a field which opposes the field of the coil, thus reducing its inductance. This latter method is not recommended as it usually results in a rather large loss of energy. Small changes in inductance can be obtained by spreading apart a few of the turns near the ends of a coil as shown at (G). This increases the leakage flux and so reduces the inductance slightly. This method is often used for producing very slight changes in tuning coil inductance when "ganging up" a series of tuned circuits in a single-control radio receiver.

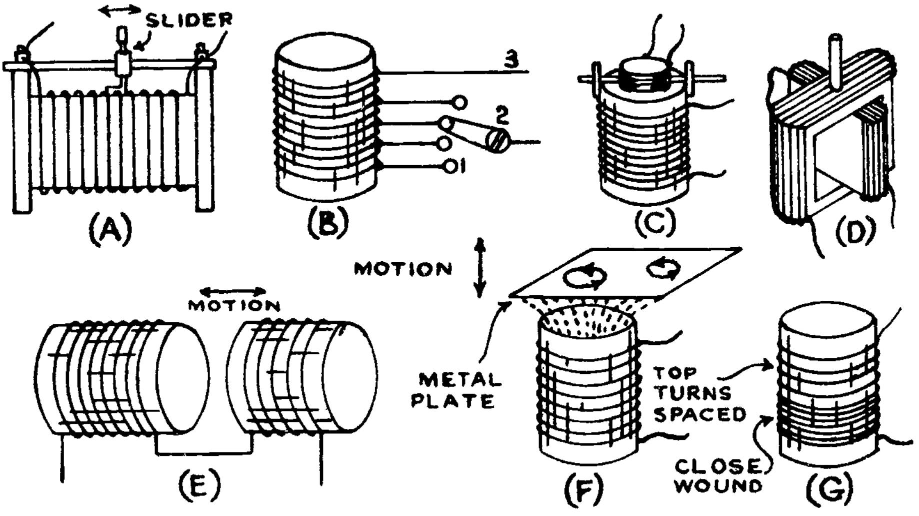


Fig. 79—Various Types of Variable Inductors.

The arrangement shown at (D) is commonly known as a variometer. The inductance is continuously variable from a low value when the coils are connected in series opposing to buck each other, to the maximum value when they are rotated so their fields aid, or are connected series aiding. One small commercial variometer used for radio laboratory work has an inductance variation from 0.1 to 1 millihenries when its two coils are connected in parallel and from 0.3 to 4.2 millihenries when its coils are connected in series with each other. Sometimes the two windings are not connected to each other. This forms a *split variometer.*

Somewhat the same result is obtained with the rotating coil arrangement at (C). In the case of the tapped coil at (B), the *dead-end* or unused portion of the winding 1-2 has a voltage induced in it, and this voltage causes a current to flow through the distributed capacity of the coil. This acts on the used part 2-3 of the coil in such a way as to increase its resistance or opposition to current flow. If dead-ends must be used on a coil, it is best to completely disconnect them from the remainder of the coil when they are not in use. This will reduce the loss considerably.

123. Variation of inductance with current and frequency: A well constructed and proportioned air-core inductance coil has practically a constant inductance at all frequencies (except near its natural frequency), and for all values of current through it. In the case of inductors constructed with iron cores, this is not so, because the permeability of the core is different for each value of flux density in the core, or current through the winding as shown in Fig. 61. This of course changes the inductance value.

Iron-core inductors are extensively used in circuits carrying both direct and alternating current, as in the case of filter chokes, plate impedance coils, output coupling chokes, etc. The steady direct current tends to magnetize the iron with a polarity depending on the direction of current flow around the winding.

If the d-c current is strong enough and the number of turns of wire is large enough (ampere-turns), it alone will saturate the core, thus greatly reducing the inductance of the coil. This condition and its remedy can be clearly shown by considering the magnetization curve A-B of ordinary transformer core steel as shown in (A) of Fig. 80. The direct current flowing through the winding produces a magnetizing force, C, which produces a flux corresponding to point D on the curve. Now when alternating current is applied to the coil, so as to continually vary the magnetizing force a certain amount above and below this value C, say from F to E, the magnetization is carried over the knee of the magnetization curve due to saturation, and the flux only varies between the values G to H. The inductance is of course dependent on the magnitude of this flux variation. If the iron could be worked below the saturation point

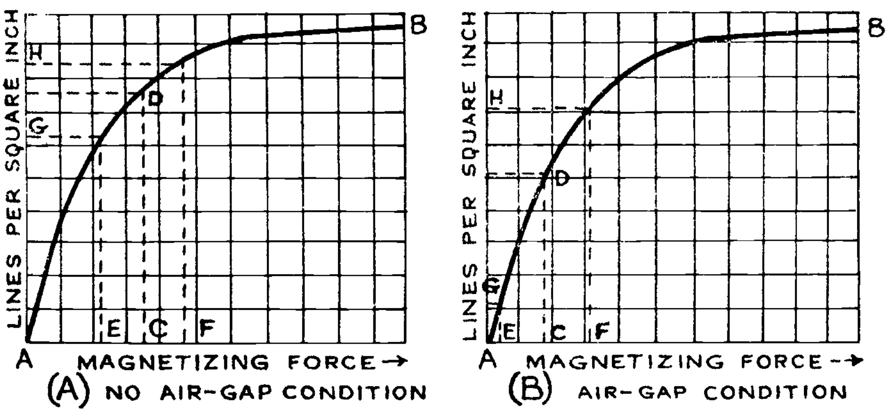


Fig. 80—Effect of placing an air-gap in the iron core. The inductance is maintained more constant under varying load conditions.

(say by introducing an air gap in the core) the steady flux due to the direct current would be reduced say to C, in (B) of Fig. 80. Then the same alternating current would vary the flux between G and H. Since this is a greater variation than G to H in (A) the inductance of the coil is now higher for the loaded condition than it was when no air gap was used, because the inductance depends on the variation of the magnetic flux. Of course under conditions of low load, where saturation is not reached, the effect of the air gap is to decrease the resulting inductance.

In order to prevent saturation and keep the inductance value more constant, one or more air gaps are always built into the core as shown at (A) of Fig. 81. The effect of the air gap is of course to increase the magnetic reluctance of the total magnetic path, and so decrease the flux. This is accompanied by a slight decrease in inductance at no load but the air gap makes the inductance more constant with change of current. The

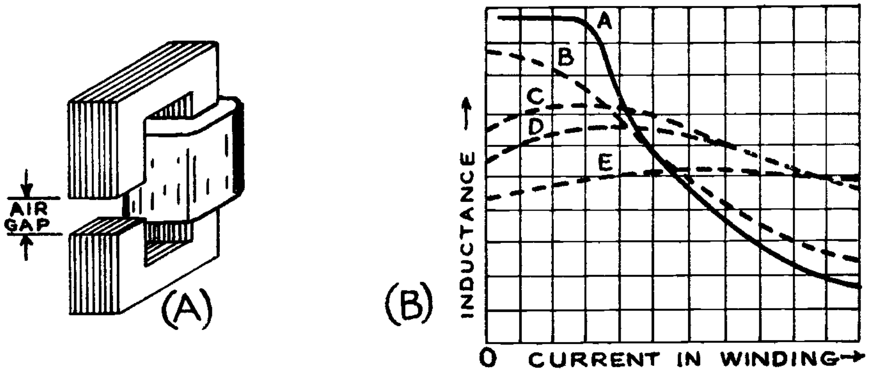


Fig. 81—Air Gap in Iron-core Choke Coil and its effect on the Inductance Value.

total air gap must be wide enough to prevent core saturation, yet the gap must not be so wide as to reduce the flux and the inductance below the required minimum value. The effect of leaving a small air gap in the core is shown at (B) of Fig. 81. Curve A shows how the inductance rapidly decreases as more and more current is sent through a particular choke coil having no air gap. Curves B, C, D, and E show the effect of larger and larger air gaps. Notice that as the air gap is increased, the inductance decreases, but the curve flattens out, showing that the inductance is more constant with load. This fact is important in the design of choke coils for B-eliminator filters where a pulsating direct current is flowing through the windings, and the filtering or inductance value of the choke is very much decreased when the load is increased, unless a proper air gap is included in the core.

The inductance of an inductor to be used under conditions where its coil will be carrying both a-c and d-c current, should always be rated by considering its inductance measured with the d-c current flowing through its windings. Thus, a choke coil used in the filter system of a B-eliminator may have an inductance at 30 henries when a d-c current of 50 milliamperes is flowing through it. This is the current flow at which it is designed to be used. At currents higher than this, it will have less effective inductance, at currents lower than this, its effective inductance will be greater.

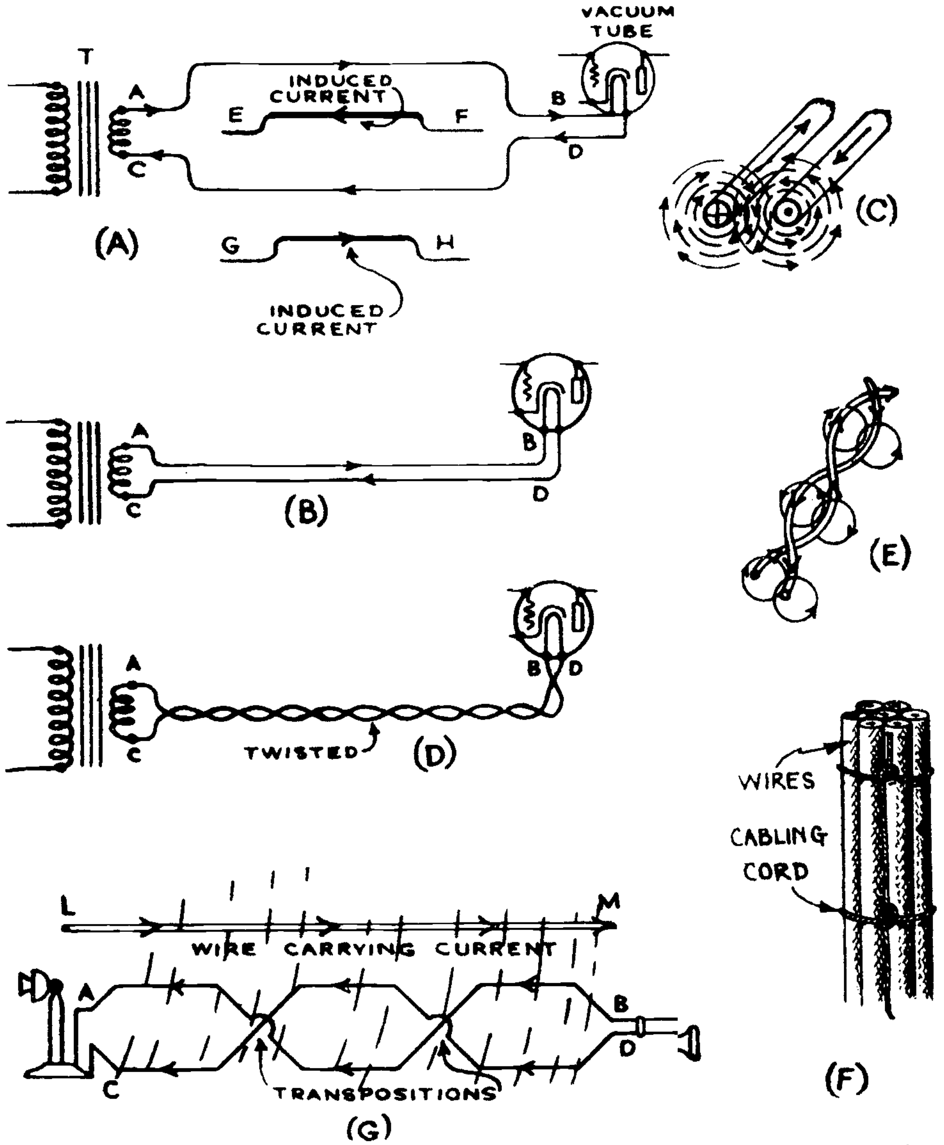


Fig. 82—Various ways of preventing mutual induction effects between wire circuits.

124. Coupling between wires: Mutual inductance effects between parallel wires, or between wires forming a loop and other wires lying outside the loop, are often very troublesome in radio and telephone equipment. For instance in (A) of Fig. 82, let the two conductors A-B and C-D be employed to connect the step-down transformer T to the filaments of an a-c type vacuum tube. As wires A-B and C-D are spaced quite far apart, they form a one-turn loop or coil. The direction of current flow for some particular instant is shown, the current going out along one wire and returning along the other. An alternating magnetic field will be produced in the area inside the loop as well as around it. If other independent wires such as E-F and G-H should be in the vicinity of this loop, they will have e.m.f.'s induced in them by this changing field. If they are parts of closed circuits, currents will flow in them in a direction such as to oppose the field of the loop. If these wires form part of a telephone circuit, or happen to be certain sensitive grid or plate wires in a radio receiver, the e. m. f. or current set up in them might cause a loud 60 cycle hum or other objectionable noise. This can be very materially reduced by running wires A-B and C-D close together as shown at (B). The field will now be very feeble except in the immediate vicinity of the wires, since the space between the wires is very small and the aiding field is therefore weak as shown at (C). The external field may be further weakened by twisting the wires as shown at (D). This makes the external field produced by the wire between each twist, opposite in direction to that produced by the wire between the next twist as shown at (E), thus practically reducing the external field to zero. Twisting of the filament circuit wires in a-c electric receivers has become very common practice to avoid hum due to possible induction effects of the alternating current flowing through them. However, recent investigations have shown that the extra work of twisting the wires is really not necessary in most cases, the external field being practically negligible if the wires are run parallel and close together as shown at (B). This makes the wiring easier, and if the wires are long they may be held together or "cabled" by tying them with light string as shown at (F). If the cabling is done as shown in this sketch, the string is self-locking and will not all come loose if it should happen to break at some point.

Telephone wires usually consist of "twisted pairs" to reduce induction effects from other outside current-carrying wires. The effect of transposing, or twisting, the wires in this case (where the twisted wire is having voltage *induced* in it) is shown at (G). Since the average distance between the inducing wire L-M and each side of the telephone circuit is the same, the total e. m. f. induced in wire A-B will be exactly equal and opposite in direction to that induced in wire C-D. Hence the e. m. f. induced in A-B neutralizes that in C-D, and so eliminates any noises due to induction. The induction between two or more parallel circuits may be detected by the faint sound of voices from the other line. This is known as "cross talk". The "twisted pair" wire generally used for telephone circuits is an example of the practical application of the transposed wire principle, and effectively eliminates mutual induction in such circuits.

(Review Questions on following page.)

REVIEW QUESTIONS

1. What is meant by self-induction? Mutual induction?
2. When does self-induction occur in a coil?
3. Is the self-induction of a wire increased or decreased by winding it up in the form of a solenoid? Why?
4. What is an inductor? What is inductance?
5. What is the induced e. m. f. in a choke coil having an inductance of 30 henries, if the current changes at the rate of 0.01 ampere per second? If the rate of current change is 2 amperes per second?
6. What is the inductance in microhenries of a solenoid wound with wire having 30 turns per inch, on a 2-inch diameter cardboard tube. The length of the winding is 3 inches and assume the form factor to be 0.8?
7. What would be the inductance of this coil if its magnetic circuit were completely of iron having a permeability of 25,000?
8. You are to make up a resistor of 10,000 ohms from a long piece of very fine "nichrome" resistance wire. This resistor is to be non-inductively wound. Describe three different ways of accomplishing this.
9. An inductor of 60 microhenries is connected in series with one of 100 henries. They are kept far apart so that no magnetic interaction can occur. What is their combined inductance?
10. What is the total inductance if the coils of problem 9 are connected in parallel?
11. An inductor of 200 microhenries inductance is connected in "series-aiding" with one of 400 microhenries and placed so that mutual induction can take place. The coefficient of coupling K is 0.6. Calculate the mutual inductance, and draw a diagram showing the condition.
12. What is the total inductance of the circuit in problem 11?
13. What would be the total inductance if the coils were connected series-opposing?
14. In a screen grid radio frequency interstage coupling transformer, the primary inductance is 300 microhenries and that of the secondary is 200 microhenries. The mutual inductance due to their positions, is 160 microhenries. What is the coefficient of coupling?
15. Draw the primary and secondary coils of an air-core transformer. Explain why the coefficient of coupling is decreased as the primary is moved further away from the secondary. What is the maximum value the coefficient can have? Draw the positions of the coils for this condition.
16. Explain three ways of constructing an inductor whose inductance value can be varied easily.

17. A General Radio Company variometer has the following constants. Stator turns 1174. Rotor turns 1174. Total inductance with the two coils in series-aiding 626.5 millihenries. Total inductance with the two coils in series opposing 106.5 millihenries. What is the ratio of maximum to minimum inductance of this variometer? What is the mutual inductance?
18. Why does the inductance of an iron-core inductor or choke coil whose winding is carrying a direct current and an alternating current simultaneously, decrease as the current through the winding increases?
19. Why does an air gap in the core of the above inductor help to maintain the inductance more constant as the current is increased?
20. Explain why the alternating current filament circuit wires in radio receivers are usually twisted together? How may induction effects be greatly reduced without twisting?
21. Draw a sketch showing how long wires should be "cabled" with light twine in order to support them and hold them together.
22. Explain with sketches just why "twisted pair" wires eliminate mutual induction effects.

CHAPTER 10.

CAPACITANCE AND CONDENSERS

CONDENSER AND CAPACITOR — ACTION OF THE CAPACITOR — DIELECTRIC PROPERTIES — DIELECTRIC LOSSES — CHARGE AND DISCHARGE OF A CONDENSER — CONDENSER LOSSES — RESISTANCE LOSSES — LEAKAGE LOSSES — DIELECTRIC ABSORPTION LOSS — DIELECTRIC HYSTERESIS LOSS — VOLTAGE BREAKDOWN OF CONDENSERS — BREAKDOWN VOLTAGE RATING OF CONDENSERS — FACTORS AFFECTING CAPACITANCE — DIELECTRIC CONSTANT — CALCULATION OF CONDENSER CAPACITANCE — DRY FIXED CONDENSERS — THE PAPER DIELECTRIC — THE CONDENSER PLATES — INDUCTIVE CONDENSER WINDINGS — NON-INDUCTIVE CONDENSER WINDING — CONDENSER BLOCKS — ELECTROLYTIC CONDENSERS — THEORY OF ELECTROLYTIC CONDENSERS — MECHANICAL CONSTRUCTION OF ELECTROLYTIC CONDENSERS — SELF HEALING DIELECTRIC — FORMING THE CONDENSER — DRY ELECTROLYTIC CONDENSERS — VARIABLE AIR CONDENSERS — MIDGET CONDENSERS — GANG CONDENSERS — SHIELDED TUNING CONDENSERS — CONDENSERS IN PARALLEL — CONDENSERS IN SERIES — TIME AND QUANTITY OF CHARGE OF A CONDENSER — REVIEW QUESTIONS.

125. Condenser and capacitor: Every radio circuit is merely a combination of resistors, inductors and capacitors, arranged to produce certain desired characteristics. These three elements form the basis of all electrical circuits we will come in contact with. A complete knowledge of the action and construction of all forms of capacitors is essential in radio work. We have already studied the behavior of resistors and inductors, and will now consider the capacitor. The term *capacitor* has lately been adopted as the correct one to designate devices which are used in electrical circuits to purposely introduce the element of capacitance. While the term capacitor is a very good one, the term *condenser* used commonly to denote the same thing, is perhaps used much more in radio and electrical work. The term condenser is a very poor one, for it has no relation to the action of the device in a circuit. The so-called "condenser" does not "condense" anything, except possibly the negative electrons crowded into the negative plate. As we will see presently, a capacitor or condenser stores an excess of electrons on one set of plates when charged. The condenser is the only electrical device which actually stores electricity, that is, electrical charges. Its capacity for storing electrical charge or electrons is called the *capacitance*. The term *capacity* is commonly used in practice instead of capacitance. The student should become familiar with all of these terms, for while it is desirable to use the correct one always, one must sometimes do as the Romans do when in Rome. Many manufacturers still mark their units as "condensers of so-and-so much capacity."

Also both sets of terms are found in radio and electrical literature. It is very difficult and almost impossible in some cases, to change a term which has been in common use for years, so it is doubtful if the terms *capacitor* and *capacitance* will ever entirely supplant the more popular terms *condenser* and *capacity.*

126. Action of the capacitor: We saw in Article 22 and in Fig. 21, how the application of an e. m. f. to a conductor would cause a transfer or "drift" of electrons around the circuit. If the circuit is continuous, a continuous flow of electrons takes place around it, and we have a continuous electric current. If the circuit is not continuous, but terminates in two ends separated from each other, a somewhat similar action takes place for a short time. A general definition of a condenser or capacitor would be, *any two conductors between which a difference of electrical potential exists, and which are separated by an insulator.* Thus the ends of two wires held apart in air really form a capacitor if an e. m. f. is applied to them, but as we shall see later such a device would have very little capacitance or ability to store electric charges simply because its surface area is too small.

The action of capacitors is so intimately tied up with electrons and electric charges, that it would be well at this point to briefly review the theory of the electron structure of matter which we studied in Chapter 3.

Let us consider the capacitor shown in (A) of Fig. 83, consisting of two sheets of metal separated by some insulating material. The insulating material between the plates is called the *dielectric.* If the plates are separated by air, then air is the dielectric. If separated by mica, then mica is the dielectric, etc. The plates of a condenser merely act as storage places for the collection of electrons and for applying electric fields to the dielectric material. It is the electronic distortion of the atomic structure of the dielectric material that is responsible for the capacitive action, as we shall see.

A source of e. m. f. is connected in the circuit through a switch K. We know from our previous study that all materials are composed of molecules which are made up of atoms of basic materials known as elements. These atoms are cômposed of electrons revolving about the central portion in established circular orbits, just as if each atom were a miniature solar system (see Fig. 17). In any such material, we also have free electrons not permanently attached to any one atom, moving around more or less in the same manner as comets in our universe. In materials which are good conductors of electricity, a large number of these free electrons are roaming about the interior structure of the material, occasionally breaking their way into one of the small solar systems, and usually in such cases bumping one of the planets or electrons free to wander around, until it in turn strikes another planet and knocks another electron loose, etc. Each of these free electrons carries a small negative charge and if a sufficiently large number of them are set in motion by the application of an e. m. f., we have an appreciable electric current and the material is said to be a conductor. On the other hand, in some materials there are almost no free electrons, that is, the electrons are bound tightly to their own orbits. These materials are known as insulators.

Part (A) of Fig. 83 shows the conditions existing in a condenser having no charge. The switch K is open, the plates each contain their

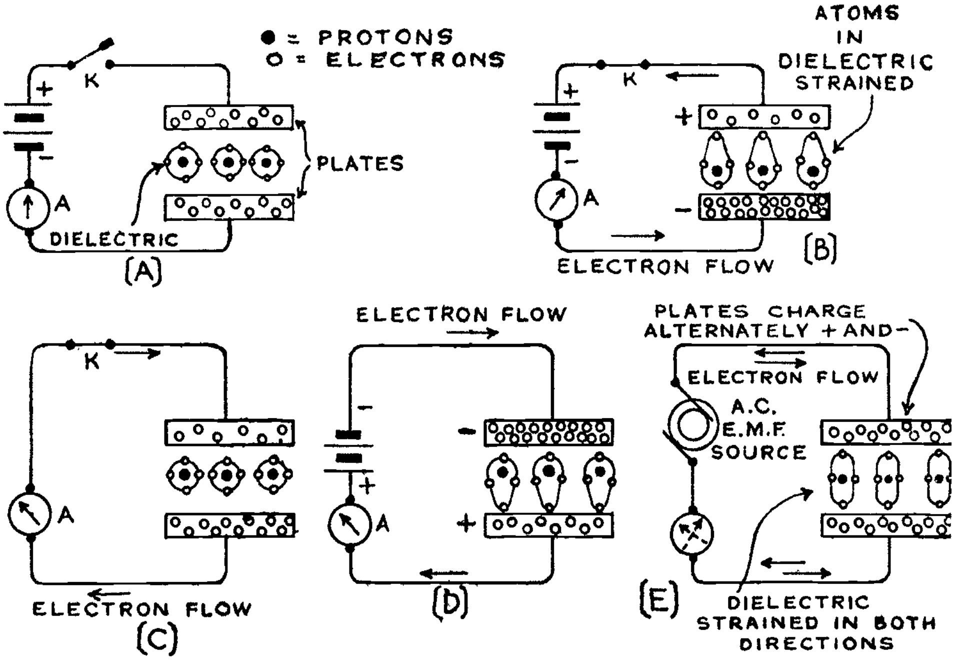


Fig. 83—Electron Movements During Charging and Discharging of a Condenser (Conductor). The Electrons in the Atoms of the Dielectric are strained out of their Normal Orbits by the Electric Charges of the Electrons Transferred Around to the Negative Plate During Charge.

normal number of free electrons represented by small dots, and the dielectric material has all its atoms in a regular form as shown, with the electrons revolving undisturbed in their circular orbits.

At (B) the switch is closed, making the applied e. m. f. effective in causing a *flow of electrons* around through the wire from the positive to the negative terminal as shown. An ammeter connected as indicated will show that a momentary current is flowing through the circuit. The free electrons are removed from the upper plate causing a deficiency of electrons and hence a positive charge there, and are transferred around through the circuit and crowded into the lower plate, causing an excess of electrons or negative electric charge there. The introduction of the excess of negative electrons on this plate causes a charged condition in the dielectric between the plates. Depending upon the strength of the charge, the large number of electrons forced around to the negative plate builds up a strong negative charge on it. This increases the repulsive effect on the negative electrons in the dielectric material. On the other side, the positive plate attracts the electrons in the dielectric and therefore the *orbits* of the dielectric electrons are distorted, causing them to assume the shapes shown in exaggerated form at (B). Since most of the electrons in the dielectric are tightly bound to their atoms, they cannot actually leave the dielectric or flow directly through it if it is a good insulating material, but are simply strained out of their normal positions and paths as shown. The operation just described is called *charging* the condenser or capacitor. An electrostatic force is said to exist between the positive and negative plates of the condenser. As the electrostatic forces act in straight lines, they are sometimes called *electrostatic lines of force* and are represented by straight lines. It is evident that the greater the applied voltage is, the greater will be these electric forces acting to displace the electron orbits of the dielectric. Also the *quantity* of the electrons, or *electric charge* stored in the plates will be proportional to the value of the applied e. m. f. and the total surface area of the plates.

If the source of e. m. f. is now removed, and the terminals of the condenser are connected together as shown at (C), the electrons on the lower plate will flow back around to the upper plate until the normal condition of (A) is reached. The ammeter will indicate another momentary current flow while this is taking place—opposite in direction to the flow during charging. This is called *discharging* the condenser.

If now the polarity of the e. m. f. is reversed and applied again as shown at (D), the atomic structure will pass through the same conditions as at (B) but in the opposite direction, as shown at (D). Current will again flow through the external circuit momentarily during charge and discharge of the condenser. If an alternating source of e. m. f. were applied to the condenser as at (E) this action would be repeated over and over, a stream of electrons (electric current) flowing through the external circuit and into one plate and out of the other during each charge and discharge of the plates. Thus, we see that in a capacitive circuit it is possible to have a transfer of electrons (or a current) flowing continually in the external circuit between the plates without actually going across or through the dielectric from one plate to another. Current does not flow *through* a condenser for the simple reason that the plates are insulated from each other by the dielectric. Current does flow in and out of the metal plates, and through the external circuit however.

If the polarity of the charge is rapidly reversed, as in the case of the application of the alternating e. m. f., there will be a steady straining of the electron orbits in the dielectric, first in one direction (B) and then in the opposite direction (D), resulting in appreciable friction. This generates heat, the quantity of course depending on the extent of the motion (the applied e. m. f.), and the rate or frequency of reversal. That is, the more volts e. m. f., the more motion and heat, also the more speed (cycles per second), the faster the motion, and the more heat developed. If sufficient heat is generated, it will melt the impregnating material used in the condenser, weakening the dielectric structure mechanically and perhaps causing the condenser to break down due to a few electrons breaking through the weakened material.

Since the electron orbits are displaced during the charging and discharging of a condenser, and since the movement of electrons constitutes an electric current flow, it is common to talk of these electron displacements in the dielectric as "displacement currents" Displacement currents do not consist of any actual flow of electrons as in the case of a condenser, but simply a small displacement against the surrounding electrical forces.

In a capacitor used in a direct current circuit in which the voltage is fluctuating, (as in the filter circuit of a radio B power device), there is never a complete reversal of charge, but the change in condition from that in (A) to that of (B) and back, will have just as much destructive effect as though complete reversals with approximately half the voltage were to take place.

From the foregoing description of the action of a condenser or capacitor in a circuit, it is evident that a condenser really stores electrical charges or electricity. It is unlike the storage battery in this respect, for the storage battery really stores up chemical energy when being charged and is ready to convert this back into electricity on discharge. In a charged condenser, we actually have an object in which a large number of electrical charges (electrons) from one set of plates have been pushed around to the other set of plates and left there. They will tend to return to the other plates if given the slightest opportunity to do so. If they are allowed to return, by providing a conducting path between them. the plates become electrically neutral again, the condenser is said to be *discharged* and a current flows through the conductor while this is taking place.

Experiment: Connect a 1 or 2 microfarad condenser such as is employed in radio receivers, as shown in (A) of Fig. 84, with a switch and a 0-100 d-c milliammeter in series. The entire combination is connected to a 110 volt direct current circuit. Quickly close the switch and notice that the milliammeter needle kicks over momentarily while the transfer of electrons is taking place from one plate around through the circuit to the other, as shown at (B). As soon as the applied e. m. f. has transferred enough electrons around so that the potential built up by the excessive electrons on the negative plate just equals the applied e. m. f., no further electron transfer can take place and the current flow in the external circuit ceases, so the milliammeter needle returns to zero. Now if the 110 volt line is disconnected and a 1000 ohm resistor is connected in its place across the condenser circuit, as soon as the switch is closed the needle will kick over in the opposite direction, as shown at (C), showing that now the excess electrons on the negative plate are flowing around through the circuit to the positive plate, and continue to do so until the charges are equalized.

If now an a-c 0-100 milliammeter is substituted for the meter just used, and a 110 volt alternating source of e. m. f. is applied as shown at (D), the needle of the meter will indicate steadily showing that a transfer of electrons is continually taking place from one plate to the other, and back around through the circuit, during each cycle of the a-c. We thus have an alternating current flowing in the circuit, but it should be remembered that the current flows only from one plate to the other and not through the dielectric between the plates.

If a condenser of large capacitance (about 10 or 15 microfarads) is used, an ordinary 25 watt incandescent lamp bulb can be used instead of the milliammeter. It will indicate by lighting up, every time a current flows through it. The exact amount of condenser capacity to be employed for proper lighting up of the bulb depends on the particular size of bulb used.

If after the condenser has been charged, it is disconnected from the circuit and a wire is brought up to its two terminals, a snapping blue spark will take place when the electrons from one plate rush around through the wire to the other plate, discharging the condenser.

127. Condenser losses: Theoretically, any insulator is suitable for use as the dielectric in a condenser. However, only a few materials are used extensively for this purpose, simply because they are the only ones which possess certain properties which make them particularly suited for

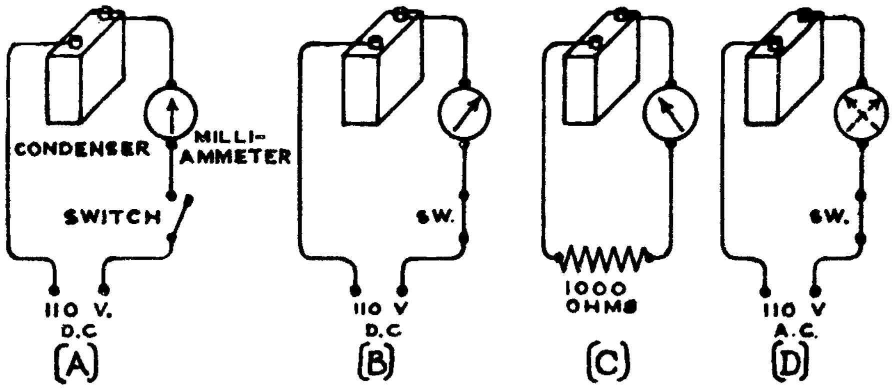


Fig. 84—Experiment to Illustrate the Charge and Discharge Currents of a Condenser

the types of condensers in which they are employed. They will be discussed later.

In Article 126 we assumed a perfect condenser, that is, one which does not leak, has no resistance in its leads and no losses in its dielectric. When a condenser is charged by a source of electrical energy it would be very desirable to have it give back all of the energy upon discharge. We would like to have condensers act as perfect electrical storage devices. Unfortunately this is not absolutely possible.

128. Resistance losses: Since the electrons must flow through the connecting wires and through the metal of the plates themselves, any resistance which these parts have will impede the flow of the electrons, and heat will be produced proportional to $I^2 R$. Therefore, it is important that the resistance of both sets of plates, all contacts and the condenser leads be kept as low as possible to prevent this loss. This is not difficult, for the large cross-section area of the condenser plates results in very low plate resistance in practically all cases.

129. Leakage loss: If the dielectric used in the condenser does not have a very high insulating value or insulation resistance (see Article

27), a flow of electrons (current) will take place right through the dielectric from the negative plate (excess of electrons) to the positive plate (scarcity of electrons) depending on the value of the voltage applied to the plates. This is called *leakage.* It not only tends to discharge the condenser by reducing the quantity of free electrons stored in the negatively charged plate, but also produces some detrimental heating effect in the dielectric itself. Leakage may also take place between the terminals of a condenser, either through the insulating material, or over its surface in damp weather. It is due to leakage that an ordinary condenser will not hold its charge indefinitely. Theoretically, we ought to be able to charge a condenser, then store it away for a month or a year and be able to utilize the full charge after that time. Actually, however, the charge would disappear within a few hours or days due to leakage through the dielectric. Leakage losses are very small in well constructed condensers using air or mica as the dielectric, but they may be very large in poorly constructed paper or electrolytic condensers.

Experiment: Charge several similar 1 or 2 mfd. filter condensers of the type used in radio receivers, from a 110 volt d-c source. After 10 minutes, discharge the first one by touching a wire across its terminals, noting the intensity of the spark. After 10 minutes more, discharge the second one, etc. You will notice that the charge on the last few condensers has leaked off considerably as evidenced by the fact that a very weak spark or no spark at all is obtained when they are tested.

130. Dielectric absorption loss: The other losses in the dielectric itself are known as *dielectric hysteresis,* and *absorption loss.* These are important when the condenser is used in alternating current circuits of high frequency, as in radio work.

When a steady voltage is applied to a condenser having paper for a dielectric, careful measurement will show that the charge will sort of "soak" into the condenser for a considerable length of time. Similarly it will gradually soak out on discharge. If a charged paper-insulated condenser is discharged, and then left for a short interval, a further small voltage will appear at its terminals, and it may be discharged again. It appears that it requires some time for the electron orbits in the dielectric to re-adjust themselves to their normal shapes and positions (see Fig. 83), and it is for this reason that all of the excess electrons in the negative plate are not immediately repelled back around through the circuit to the positive plate when a complete circuit is provided. At the high frequencies used in radio work, the condenser does not have much time between alternations to give back all of the absorbed or residual charge left from one voltage peak, before the next one comes along. Therefore most of the absorbed charge is lost and never recovered from the condenser. This loss is called the *dielectric absorption loss.* It depends on the material used for the dielectric. Air, mica, and oil have very low dielectric absorption loss. Cheap grades of wood-pulp paper, etc. may have very high loss.

131. Dielectric hysteresis loss: When an alternating e. m. f. is applied to a condenser, the electron orbits in the dielectric between it become alternately strained from their normal positions as shown in Fig.

83 and there is a lag in the dying away of the electrostatic field in the dielectric. This action is similar to the lag in the magnetic field of a magnet, (magnetic hysteresis), and is called *dielectric hysteresis.* It is reasonable to suppose that when the electron orbits have been altered during charging of the condenser as in (B) of Fig. 83, there is some restraint to their returning to their original shape (A) of Fig. 83, immediately upon removal of the electric forces of the plates during discharge. Therefore some energy on the reverse charging cycle is required to force them around to the reverse condition shown at (D). This energy is called the *dielectric hysteresis loss.* It increases as the frequency is increased, since then there is a greater number of reversals of the electron orbits per second. Condensers used in radio frequency circuits where the current may reverse as many as a million times every second, should preferably have low hysteresis loss.

All of the losses in a condenser are sometimes considered to be combined to form a total single loss which may be represented by a resistance, called the *equivalent series resistance.* The equivalent series resistance of a condenser, is the amount of resistance which if placed in series with a perfect condenser of the same capacity would allow the same current to flow that actually flows in the condenser being considered. The losses in the air-dielectric tuning condensers used in radio equipment are usually so low as to be neglected. The losses in paper dielectric or electrolytic condensers may be quite high if poor grades of material are employed, or the design is faulty.

132. Voltage breakdown of condensers: We saw in Arts. 28 & 29 how the application of a difference of potential to opposite sides of an insulator caused a strain on the electron orbits in the material, the intensity of the strain depending upon the applied difference of potential. The student is advised to read this over again at this time. Likewise, when condensers are connected in actual circuits, a potential difference, or difference of electrical pressure exists between one plate (or set of plates) and the other. If the impressed voltage is great enough, it may cause a considerable force to act upon the electrons in the dielectric. In some cases, this may produce a spark discharge to take place through the dielectric, in which case free electrons are caused to pass physically through the dielectric whether it be air, glass, paper, mica or what not. This actually punctures the insulating medium. In insulators like paper, mica, etc., a tiny hole is actually burned through by the spark. The voltage required to cause this effect, is called the *breakdown voltage* of the condenser or the dielectric. The voltage required to completely break down or puncture samples of various insulating materials of .001 inch thickness are given in the table in Article 29. As the actual breakdown voltage depends upon various factors, such as composition of the sample tested, temperature, length of time of application of the test voltage, whether the voltage is applied between two needle points or between two large surfaces, etc., these values should be considered merely as average values for the materials listed. Notice that very thin pieces of mica and paraffined paper can stand quite high voltages. This is one of the reasons for the extensive use of these two materials for the dielectric of fixed condensers.

When the dielectric of a condenser of the mica or waxed-paper type becomes punctured by the application of excessive voltage, a permanent short-circuit occurs between the plates through the dielectric, and the condenser is worthless and is discarded. If the dielectric in an "electrolytic" or "air" type condenser becomes punctured by excessive voltage, a short-circuit also occurs between the plates, but as soon as either the voltage is removed or the condenser is disconnected from the circuit, the insulating value of the dielectric is automatically restored and the condenser is ready for normal use again. Dielectrics of this type are said to be "self-healing"

133. Breakdown voltage rating of condensers: The breakdown voltage of solid dielectric materials becomes lower as the temperature is raised. For this reason, condensers should be mounted so they are not too close to hot objects such as vacuum tubes, power transformers, etc., and plenty of ventilation should be provided around them. Breakdown is a function of time as well as voltage. A condenser that stands up satisfactorily under several thousand volts for a few seconds, might break down when connected to a 2000 volt line for several hours. For this reason, a "flash-voltage" test given to condensers for a few seconds at the voltage they are to work at in practice, is not a reliable indication of the voltage they will be able to stand under steady service. Obviously it is not practical in quantity production of condensers to apply the correct test voltage for hours. Therefore the R. M. A. specifies the voltage test for fixed paper condensers as: *"A single application of two times the rated working voltage for 15 seconds, and the immediate discharge through a resistor of sufficient ohmic resistance (50 ohms or more) to limit the discharge current to not more than one ampere."* The use of the resistor in discharging the condenser is to prevent damage to the condenser by the too rapid discharge which would occur if its terminals were merely "shorted" by a wire.

The *working voltage*, that is, the maximum voltage which may be applied steadily to the condenser without harm, is usually marked on the case. Condensers connected in non-pulsating direct current circuits are subjected to a voltage equal to the normal d-c voltage of the circuit. In alternating current circuits, the voltage rises from zero to its peak value (see Fig. 69) twice during each cycle, or 120 times a second for a 60 cycle current. The maximum or "peak" value of a sine-wave alternating voltage is 1.41 times the effective value. The effective value is that value which an a-c voltmeter reads when connected in the circuit. Since the dielectric is subjected to, and must be able to stand without breakdown, this peak value twice during every cycle, it is the peak value of the voltage which must be considered when selecting a condenser which is to work in an alternating current circuit, or in a pulsating direct current circuit where the current is varying in value, as in the case of the filter condensers in the positions immediately following the rectifier tube in the output circuit of B-eliminators. For instance, in a filter circuit in which a sine-wave voltage having an effective value of 500 volts exists, the peak voltage applied to a condenser in the circuit is 500×1.41=705 volts, as shown at (C) of Fig. 85. Therefore, a condenser having a rated maximum working voltage of at least 750 volts or over should be used in this circuit instead of a 500 volt condenser. At (A) is shown the condition where 500 volts steady d-c is connected to the condenser. At (B) a pulsating d-c having an effective voltage of 500 volts is applied. The peak voltage is somewhat higher than 500 volts.

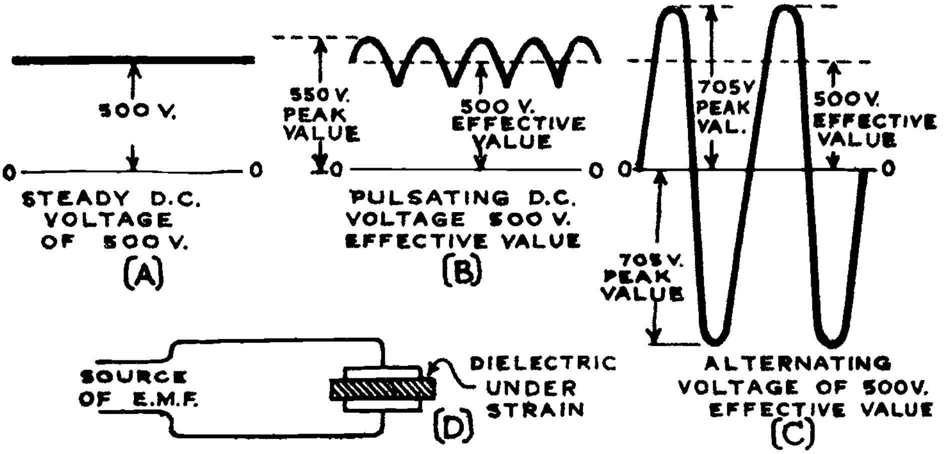
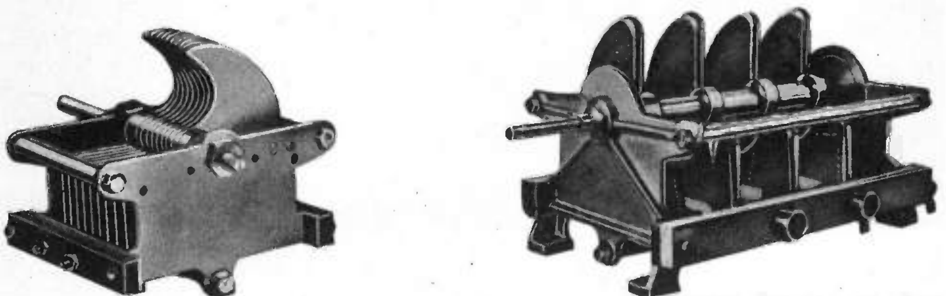


Fig. 85—The Dielectric in a Condenser must be able to safely withstand the "Peak" Voltage in the Circuit.

In some circuits in which a pulsating direct voltage is applied, the extent of the pulsations may not be known. In such cases it is always best to be on the safe side, and figure that the pulsations are such that the peak value will bear the same relation to the effective value that an alternating current would, that is, 1.41.

As the manufacturers of condensers have no way of knowing whether their condensers will eventually be used in smooth d-c, pulsating d-c, or a-c circuits, many of them mark both the d-c and a-c rated working voltages on them to eliminate the necessity for calculation on the part of the purchaser. Thus, a representative commercial filter condenser examined may have the following marking on its label: Cap. 2 mf., Working voltage 400 Volts D-C, 250 Volts A-C. It must be remembered that the maximum or "peak" value is 1.41 times the effective value only in the case of a sine-wave voltage. If the sine-wave variation of voltage does not exist, this relation will be greater than 1.41 if the wave is greatly peaked and less than 1.41 if the wave is more flattened. In filter circuits of B-eliminators, the voltage wave existing immediately following the rectifier tube is usually not of true sine-wave form, so that the allowable a-c working voltages of filter condensers for use in these circuits are usually less than would be obtained by the use of the factor 1.41. For instance, in the 2 mf. condenser considered above, 400 divided by 1.41 would give 283 volts for the a-c working voltage on the basis of a sine-wave voltage. As the voltage wave-form existing in the usual B-eliminator is more peaked



Courtesy Cardwell Mfg. Corp.

Fig. 86—Two Condensers which illustrate the effect of thickness of the Dielectric on the Breakdown Voltage of a Condenser. The Plates in the Radio Receiving Circuit Condenser at the left have a separation of .03 inches. The Breakdown Voltage is 1500 Volts. The Transmitter Condenser at the right has Plates separated .75 inches. Its Breakdown Voltage is 26.000 Volts.

than this, the a-c working voltage of only 250 volts is allowed in the particular filter condenser mentioned. If the voltage is not of the sine-wave form, the peak voltage may be measured either by means of an oscillograph or a special "peak voltmeter".

The breakdown voltage of a condenser depends mostly upon the material used for the dielectric and the thickness of the dielectric, or separation between the plates. Since most solid insulating materials require more voltage to break them down than air does, a condenser built to stand a certain voltage can be built with the solid dielectric thinner and therefore more compact than if air were used for the dielectric. For instance, in a certain paper-dielectric type condenser having a maximum d-c working voltage rating of 1,000 volts, the paper dielectric is .003 inches. In an air-dielectric variable condenser rated at 1,000 volts, the air dielectric or separation between the plates is 0.025 inches, over 8 times as much.

The thicker the dielectric is made, the greater is the breakdown voltage. Thus, the condenser shown at the left of Fig. 86 has a separation of 0.03 inches between its plates. Its breakdown voltage is approximately 1500 volts. The condenser shown at the right is used in high-voltage radio transmitters. The separation between its plates is 0.75 inches, and its breakdown voltage is 26,000 volts. Factors which affect the breakdown voltage of dielectrics will be discussed later when studying these dielectrics. As we shall see later, the greater the separation between the plates the less is the capacitance of the condenser. Thus these two factors conflict, for while manufacturers would like to make the dielectric as thin as possible in order to make the condenser more compact and cheap, the dielectric must be made thick enough to stand the voltage which the condenser will be called upon to withstand in service.

134. Units of capacitance, the Farad: The capacity of a condenser for storing electrical charge, is called its *capacity* or capacitance. The term "capacity" is probably in more common use than "capacitance". Since the quantity of electrical charge (electrons) which can be stored in a condenser of given size depends upon how much e. m. f. or "pushing force" is applied to keep the electrons crowded into the negative plate, see (B) of Fig. 83, against the force of their mutual repulsions, it is only natural that the unit of capacity or capacitance should be defined in terms of not only how much charge is stored, but also on how much voltage is applied. The unit of capacitance is the *farad*, named after Michael Faraday, and is defined as: *the capacitance of the condenser in which an applied e. m. f. of one volt will store one coulomb (6.28×10^{18} electrons) of electricity; or vice versa, the capacitance of a condenser whose voltage is raised one volt when one coulomb of electricity (6.28×10^{18} electrons) is added to it.*

The farad is a very large unit, and a condenser having this much capacitance would be too large in physical size to be constructed in practice. The condensers dealt with in ordinary electrical and radio work have capacitances of "millionth" parts of a farad, i.e., *microfarads*, (abbreviated mf.). A still smaller unit, the *micro-microfarad*, is commonly used in radio work in connection with very small condensers. This is equal to 10^{-12} farads (see Appendix C at back of this book for prefixes and prefix

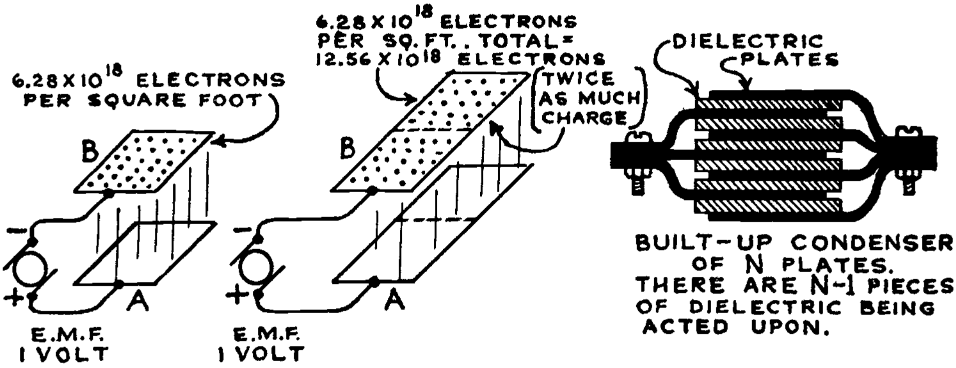


Fig. 87—The Capacitance of a Condenser is Proportional to the Surface Area of the Plates, since the larger the Surface Area is the more space the transferred electrons have to spread over. Mica-type Condensers have alternate sheets of tin foil and mica stacked up as shown at the right to form Compact Condensers.

relations). Another unit used extensively in Europe is called the *centimeter of capacitance.* It is equal to 1.1126 micro-microfarads—or 1.1126 $\times$ 10^{-6} microfarads.

135. Factors affecting condenser capacitance: The capacitance of a condenser depends entirely upon three main things: (1) the "total" surface area of the plates *in actual contact* with the dielectric; (2) the separation of the adjacent plates (or the thickness of the dielectric between them) ; and (3) the kind of dielectric (or the nature of the material) between the plates. Let us see just how and why each of these factors affect the capacitance.

Suppose an e. m. f. of one volt is applied to the condenser shown at the left of Fig. 87. We will assume this to have a capacitance of one farad, and to have two plates, each one foot square. Then 6.28×10^{18} electrons will be transferred around from the plate A which becomes positive, to the plate B which becomes negative. These will distribute themselves uniformly over the entire surface of the negative plate and their combined charge will act on the dielectric. Now, suppose that we had the denser shown at the center, with the plates 2 feet by one foot each (twice as much area), and apply one volt to them. Since the transferred electrons can now spread over a surface twice as large, twice as many electrons can be transferred around from plate A to plate B before the electric charge builds up to a sufficient *intensity* to equal the applied e. m. f. and stop the transfer of electrons. Thus, doubling the area of the plates doubles the electron charge stored for a given applied voltage, that is, doubles the capacitance. In most commercial condensers instead of having just two very large plates to obtain the required amount of capacitance, the condensers are built up more compactly with alternate layers of plates and

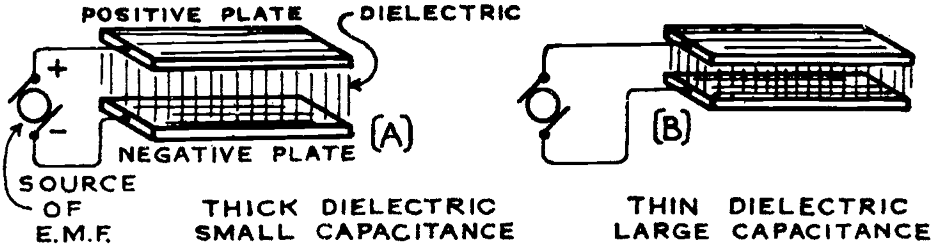


Fig. 88—All other factors being equal, the Condenser with the thin Dielectric has the Higher Capacitance.

dielectric, and the plates are connected as shown at the right of Fig. 87. All the positive plates are connected to form a common positive terminal, and all the negative plates are connected to form a common negative terminal as shown. Both sides of each plate are effective in acting on the dielectric between the plates. Condensers of this type may be built in very compact form. The air dielectric variable condensers shown in Fig. 86 are also of this type.

If the distance between the plates is decreased one-half, the thickness of the dielectric is decreased one-half, and the capacitance is increased, for then there are only half as many electron orbits in the dielectric to be deformed by the electric forces of the electrons. Hence the electrons being crowded into the plate which becomes negative must only act against half as much opposition from the electrons in the dielectric and a given applied e. m. f. can crowd twice as many electrons into the negative plate, resulting in twice as much stored charge and twice as much capacitance. The effect of thickness of the dielectric is shown in Fig. 88. The thickness of the metal plates themselves has no effect on the capacitance. The plates are usually made as thin as possible in the various types of condensers, so as to make the condenser compact. How thin the dielectric can be made depends upon how thin it is physically possible to roll out the particular dielectric material used and also what voltage the dielectric must be able to safely withstand. As we shall see later, the thinnest dielectric used in practical condensers is the aluminum oxide and gas film which is formed in the electrolytic condensers. This makes it possible to build electrolytic condensers of large capacitance in very small spaces.

136. Dielectric constant: It has been found experimentally by actually inserting similar size sheets of different materials between the plates of a given condenser, that the capacitance of a condenser also depends on the kind of material used for the dielectric. Thus if the plates of a simple two-plate condenser are separated by air and the capacitance is say 1 microfarad, the capacitance will be increased to about 2 or 3 mf. by simply filling the space in between the plates with a dielectric of paraffined or waxed paper. If the paper is taken out and sheet mica is substituted, the capacitance will increase to from 3 to 7 mf. The ratio of the capacitance of a condenser of given size having some particular material for the dielectric, to the capacitance which the same condenser would have with dry air as the dielectric, is called the *dielectric constant, specific inductive capacity,* or *relative permittivity* of that material. These names are all used to represent this constant, but the first is probably the most popular. Since air has the lowest dielectric constant of the various common insulating materials, it is taken as the standard and has the arbitrary value of 1. The dielectric constants of several insulating materials which may be used in condensers are given in the table on the following page.

The variations between the low and high limits given in this table are due to possible differences between the grades and qualities of representative samples. The dielectric constant also changes with the frequency if the measurement is made with a. c. For the table of values of the breakdown voltages of the various materials the reader is referred to Article 29.

The reason for the fact that various materials affect the capacitance of a condenser differently when used as the dielectric, lies in the structure of their atoms. The dielectric constant depends on the number of electrons which can be displaced out of their normal positions when under the influence of an external electric force. It thus depends on the material, for all materials have different atom and electron arrangements.

137. Calculation of condenser capacitance: We have learned that the capacitance of a condenser or capacitor is directly proportional to the total area of the plates which is exposed to the dielectric, is inversely proportional to the distance between the plates (thickness of the dielectric) and directly proportional to the dielectric constant "k", which depends upon the dielectric material.

TABLE OF DIELECTRIC CONSTANTS (k) OF VARIOUS MATERIALS

Dielectric Material	Constant	Dielectric Material	Constant
Air (taken as standard)	1.0	Oil, petroleum	2.0 to 2.2
Alcohol	15.0 to 26.0	sperm	3.0 to 3.2
Bakelite, C	4.0 to 8.5	transformer	2.2 to 2.7
dielectro	5.0 to 7.5	turpentine	2.1 to 2.3
micarta	4.5 to 6.0	Paper, insulating, untreated	1.6 to 2.5
Beeswax	3.0 to 3.2	oiled or waxed	2.0 to 3.2
Cèlluloid	4.0 to 6.0	cardboard, pressboard	3.0
Ceresin Wax	2.5	blotting, porous	5.0
Collodion	3.7 to 4.0	Paraffine wax (solid)	2.0 to 2.5
Cloth, oiled or varnished	3.0 to 5.0	Phenol composition,	
Ebonite (see *Rubber, hard*)		moulded	5.0 to 7.5
Fibre, uncolored	5.5	Porcelain	4.0 to 6.0
black	7.5	Quartz	4.5 to 5.0
red	5.0 to 8.0	Resin	2.5
Film, photographic	6.8	Rubber, gum	2.3
Gelatine	4.0 to 6.0	soft, vulcanized	2.0 to 3.0
Glass, window	7.5 to 8.0	hard	2.0 to 3.5
plate	3.0 to 7.0	Shellac	3.0 to 3.6
heat resisting (Pyrex)	5.0 to 6.0	Silk	4.6
Gutta, percha	3.0 to 5.0	Slate, electrical	6.0 to 7.0
Isolantite	3.6	Sulphur	2.5 to 4.0
Marble	9.5 to 11.5	Varnish	4.5 to 5.5
Mica, sheet	3.0 to 7.0	varnished cambric	4.0
built up	5.0 to 7.0	Vaseline	2.0
Oil, castor	4.5 to 4.8	Water, distilled	81.0
cottonseed	3.0 to 3.3	Wood: bass, cypress, fir	2.0 to 3.0
Oil, neatsfoot	3.0 to 3.2	maple	2.5 to 4.5
olive	3.0 to 3.3	oak	3.0 to 6.0

The capacitance of a condenser having any number of plates can be calculated from the equation:

$$C=\frac{2235\times A\times k\times(N-1)}{10^{10}\times t} \qquad (13)$$

where C=capacitance in microfarads. (uf.)

k=dielectric constant (or specific inductive capacity) of dielectric (see table above).

A=the area of one side of one plate. This is the area actually in contact with the dielectric, (square inches).

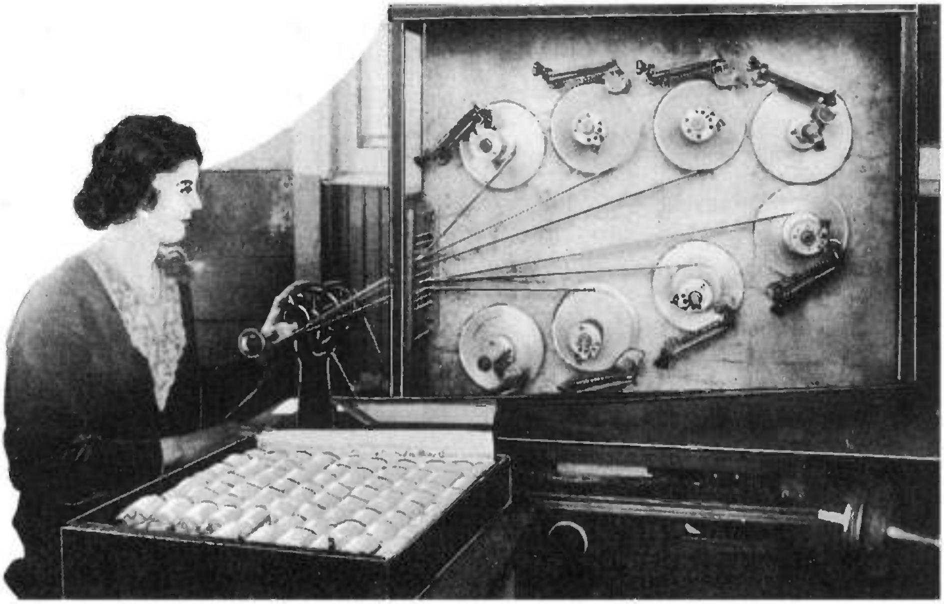
t=separation of the plates in inches (thickness of the dielectric between any two adjacent plates).

N=total number of plates.

Example: What is the capacitance of a condenser having 51 plates each 5 by 5 inches? They have a separation of 0.1 inch with air between.

Solution: $C=\frac{2235\times A\times k\times(N-1)}{10^{10}\times t}=\frac{2235\times 25\times 1\times(51-1)}{10^{10}\times 0.1}=0.00279$ microfarads. Ans.

138. Dry fixed condensers: Condensers constructed so their capacitance cannot be changed or varied are known as *fixed condensers.* Most small fixed condensers (Fig. 90) employ thin mica sheets about 1 inch square for the dielectric, because its low losses and high dielectric constant (3 to 7) makes possible the construction of such condensers in small compact form, very cheaply. Also since mica has a high breakdown voltage strength only very thin sheets need be used if medium voltages are to be employed. Mica can easily be split up into the very thin sheets required,



Courtesy Pilot Radio & Tube Corp.

Fig. 89—Side View of a Condenser Winding Machine. The sheets of Paper Dielectric and Metal Foil Plates feed through the end of the dust-proof case on to the rotating mandrel. The Alternate Layers of Paper and Metal-Foil feed off from the rolls shown.

so it admirably meets these conditions. The layers of mica and tin-foil are stacked one over the other as shown at the right of Fig. 87. A small margin of dielectric material overhangs the metal plates, for insulation purposes. The stacked-up elements are usually moulded in a Bakelite casing, with brass terminals for connection. This keeps out all moisture and prevents variation of capacitance with age. They are made in sizes from about 0.00002 mf. up to 0.015 mf. and are used extensively in radio equipment as grid condensers for detectors, as by-pass condensers, as coupling or blocking condensers, etc. The capacitance value marked on them is usually accurate to within about 10 per cent, unless they are specifically intended to be accurate in value, in which case they are slightly more expensive.

Example: What would be the capacitance of the condenser in the previous problem, on P. 198, if mica (dielectric constant 7) were used as the dielectric instead of air?

Solution: $C = \frac{2235 \times 25 \times 7 \times (51-1)}{10^{10} \times 0.1} = 0.0195$ microfarads. Ans.

The capacitance of this condenser is 7 times as great as the previous one, even though its physical dimensions have not been changed. Also, this condenser can stand about 40 times as much voltage without breaking down as the other one could, because mica has a breakdown voltage about 40 times as high as that of air.

Larger condensers of the "dry type", of 0.2 mfd. capacity and over, are made more economically by using special thin, high grade linen paper for the dielectric and very thin sheets of tin or aluminum-foil for the plates. The tin-foil strips are long and narrow, as are also the paper strips. They are rolled up together with two long tin-foil strips separated by several sheets of linen paper to form a compact rolled-form as shown in Figs. 90 & 91. The condensers are wound up in a dust-proof enclosure as shown in Fig. 89. The linen paper dielectric and tin-foil strips all come off from continuous rolls as shown, being wound together on the collapsible mandrel at the left. When the proper amount of tinfoil and paper dielectric have been wound for the particular capacitance required, the condenser is cut loose from the rolls of tin-foil and paper, and the next one is started. A flexible metal soldering tab is fastened to each tin-foil plate for connection purposes. Then the condensers go through the impregnating process in which all the air is pumped out and the empty spaces are completely filled up with paraffin or "halowax". This increases the breakdown voltage strength and prevents moisture from entering the condenser at any time later. The process of condenser impregnation is as follows:

The apparatus consists chiefly of a shelf vacuum dryer which can also be used as an impregnator, so that the dried and evacuated condensers do not have to be transferred from one apparatus to another between the two processes.

Auxiliary apparatus used consists of a compound melting and storage tank, jacketed piping connecting it with the vacuum chamber, a surface condenser and a vacuum pump capable of producing a very high vacuum in the chamber. A "Frigidaire," or other small refrigerating unit may be used in connection with the condenser.

The compound, usually paraffin or "halowax," is melted in the compound melting tank, and sheet metal boxes containing the condensers to be treated are placed on the shelves of the dryer-impregnator. Steam at 25 to 40 pounds pressure is admitted to the hollow shelves and a vacuum is drawn in the chamber. The vacuum eventually reaches 2mm or even less as the drying proceeds. Water vapor is removed by means of a surface condenser which is cooled with refrigerated water. Steam connections to the condenser allow the steaming out of condensed compound vapors which gradually accumulate. The evacuating process ordinarily requires 5 to 6 hours, although in summer months when the humidity is high, the paper will carry more moisture and the drying will be proportionately longer. The drying is uniform and all condensers are of the same temperature.

When the necessary dryness and height of vacuum have been attained, a valve is opened admitting the hot molten compound into the dryer-impregnator, completely flooding the chamber and submerging the condensers. The vacuum is then broken and the pressure of the atmosphere forces the compound into the condensers, filling all spaces between the papers and the tin-foil, and also completely saturating the paper.

In about one hour the impregnation is complete. The excess compound is then drawn back into the storage tank and the condensers are removed from the boxes after cooling.

In order to prevent the introduction of metallic particles into the impregnating chamber, which might lodge in the condensers and cause failure under test, a fine mesh filter is inserted in the line coming from the compound tank.

After the condensers are impregnated, they are placed into cardboard or metal containers and sealed with wax or pitch as a protection against moisture absorption and mechanical injury. The connection terminals protrude either in the form of soldering tabs, pigtail wires, or binding posts, as shown in Fig. 91.

139. The paper dielectric: Roughly the voltages which condensers of the paper dielectric type are able to withstand without breaking

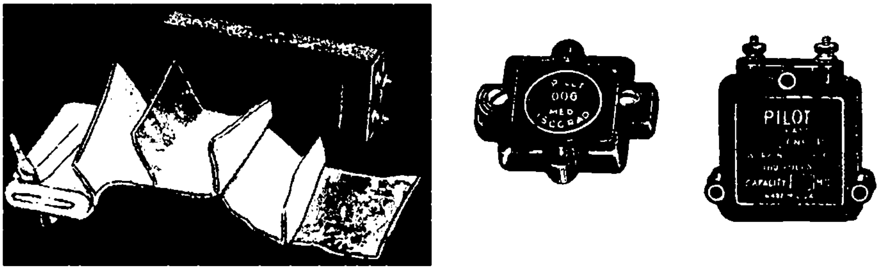
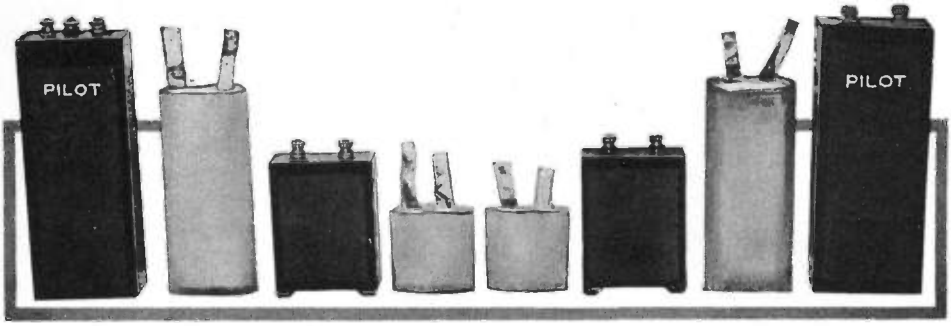


Fig. 90—Left: Fixed Condenser opened to show Metal-foil Plates and Paper Dielectric. Condenser is sealed in metal can shown in the rear.
Middle: Small Fixed Mica-type Condenser in Bakelite Case.
Right: 0.5 Mf. Fixed Paper-type Condenser in Bakelite Case.

down depends upon the grade of paper employed as well as its total thickness. Paper type condensers always have three or more strips of paper between the tinfoil plates instead of a single sheet of equivalent total thickness. One reason for this is that all very thin paper has microscopic pin-holes which are caused by the manufacturing processes. There is very little likelihood of these little pinholes occurring in all three papers at exactly the same place to cause breakdown. Just one pinhole would be enough to cause a breakdown or short-circuit in a single-paper condenser.

The dielectric of the paper condenser is a pure linen rag paper manufactured in mills specializing in this kind of paper stock. It resembles a thin bond paper, and is produced in continuous rolls of the requisite width. Yet despite the most scrupulous care of the paper makers, the product may have tiny metal particles and invisible defects which present weak electrical spots when incorporated in a condenser. Chemists have worked out simple tests for locating and thereby constituting a potential weak spot. The paper is treated with chemicals, whereupon any metal particles which may be present, even if invisible to the eye, appear as discolorations of considerable diameter. Since an absolutely pure paper is impossible to obtain in commercial production, a maximum of spots per square foot is set as the standard.

The quality of paper used as the dielectric plays a very important part in the efficiency and life of the condenser. Pure 100% linen paper is the highest grade known to the art, and is the most expensive. This paper is



Courtesy Pilot Radio & Tube Corp.

Fig. 91—A Group of Fixed Paper-type Condensers, showing the Wound Units before being sealed, and the completed Condensers in the Metal Cans. Notice the copper connection strips projecting from the tops.

free from acid, alkali, or bleaching material of any kind. Condensers made of linen paper, even with a small percentage of impurities, or wood pulp paper, which may test well when made, gradually lose their dielectric strength and finally break down because of the disintegration of the paper. A 100% pure linen paper will not deteriorate with age. Wood-pulp paper such as is used in most of the very low grade filter condensers due to its cheapness, is the poorest paper dielectric. Its losses are very high and it cannot be relied upon for continuous operation under a-c stresses greater than one-tenth its test voltage. Incidentally, wood-pulp paper has another great disadvantage. Condensers are usually wound on a cylindrical form and are then pressed flat. Wood-pulp paper is very brittle and apt to crack, while linen paper will stand a great deal of crushing and squeezing without affecting the continuity of its surface.

The impregnating compound must be carefully developed for satisfactory melting point, insulating qualities, mechanical properties and chemical inertness. Some manufacturers use special impregnating compounds which melt at about 175 degrees Fahrenheit.

When condensers are used in alternating current circuits, the constant reversal of strain or distortion of the electron orbits of the paper dielectric gradually weakens its dielectric strength and eventually failure occurs at the weakest spot. This gnawing away at the weak spots of the condenser dielectric means that the condenser will have a definite life. Manufacturers of high quality paper filter condensers try to build them to last at least 10,000 hours, or about 10 years of normal radio service in the home. Of course sudden voltage surges, or high operating temperatures will materially reduce the life.

140. The condenser plates: The conducting plates of paper-dielectric condensers are made of either tin or aluminum foil. As tin-foil is much softer, it will flatten out and conform to the surface of the paper better than aluminum-foil. At the present time aluminum is cheaper than tin-foil per unit area, but it does not permit the manufacture of the more desirable non-inductive condensers because terminals cannot be easily soldered to aluminum. The best type of tin-foil employed, consists of 86% pure tin and 14% lead, which proportion is used as it permits the rolling of a very thin, soft foil of great tensile strength.

141. Inductive type condenser construction: Paper condensers can be constructed in either of two forms—*inductive* or *non-inductive*. In the first type of construction, the foil used is narrower than the paper, and contact is made with the foil plates by brass or copper strips inserted into the winding at one end, as shown at the left of Fig. 92. Each strip makes contact at only one point with its foil plate, which in some condensers may be as much as 50 feet long depending on the condenser capacitance. Obviously the current must enter the plates from the ends and flow around the many turns of tinfoil in order to distribute the charge over the entire plate surface. This is practically the same as sending the current in and out of a coil of wire. The inductance possessed by condensers of this type may be appreciable.

Inductive type condensers heat up considerably more than the non-inductive type, due to eddy-currents set up in the tin-foil. This decreases the dielectric strength and increases the possibility of breakdown. In radio receiving circuits, the inductive type should not be used in radio-frequency circuits because of the field set up around the condenser, and

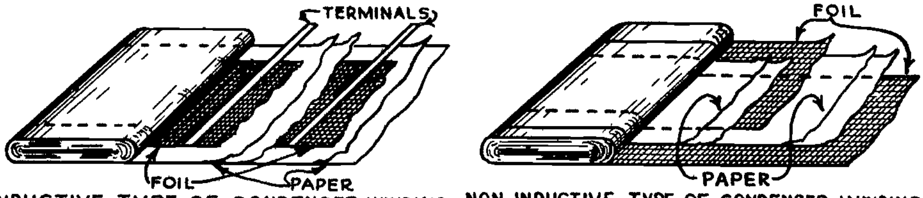
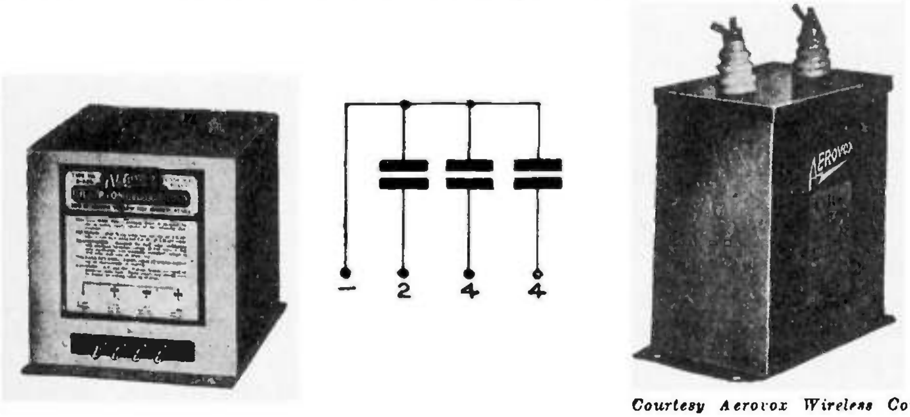


Fig. 92—Inductive and Non-inductive Types of Condenser Construction. The Non-inductive Type is used extensively now.

because it is not as efficient at radio frequencies as the non-inductive winding,—especially in short wave equipment.

142. Non-inductive type condenser construction: This form of condenser is wound with foil which is usually the same width as the paper. The winding is staggered so that a condenser plate is visible from each end, as shown at the right of Fig. 92. Each terminal is a metal strip soldered to the entire edge of the foil extending across the end, to which a flexible lead is soldered. One terminal thus makes contact with every turn of each strip of foil, and that is why the condenser is non-inductive. The current enters and leaves the side edges of every turn of foil and does not have to flow around the individual turns. Since the length of the curren-flow path is thus simply equal to the width of the condenser and the surface area is very large, the direct-current resistance of each plate of the condenser is decreased to practically zero, which cuts down the losses and heat generated in the unit.

143. Condenser blocks: Where paper-dielectric type condensers of capacitances of 4 mfd. and up are required, they are usually made up by connecting the proper number of standard 1 mf. or 2 mf. units in parallel, and enclosing the entire units in single metal containers as shown in Fig. 93. These condenser blocks are commonly used in the filter circuits of B



Courtesy Aerovox Wireless Corp.

Fig. 93—Condenser Blocks used in Radio Filter Circuits. The Block at the left has a common terminal and three taps connected as shown in the diagram at the center to provide capacities of 2—4—4 Mf. It is rated at 440 V. A-C and 800 V. D-C. The High-Voltage Condenser at the right is employed in Radio Transmitters and Heavy Duty Amplifiers. It has a Capacitance of 1 Mf. and is rated at 3000 Volts D-C Working Voltage. Glazed Porcelain Corrugated Terminal Insulators eliminate Leakage and prevent Breakdown or Short-Circuits to the Metal Can

power supply units or B-eliminators. They are made up in various combinations of capacitances for use in standard circuits of these devices. Whenever required, taps are brought out to provide several capacitance values, as shown in the condenser at the left. One side of each condenser section is connected to form the common ground or B-terminal of the block, as shown in the schematic circuit diagram in Fig. 93.

If one condenser in a block should become short-circuited or open circuited, the entire block may be replaced or the particular condenser may be disconnected from the circuit and another single condenser of the same capacitance and voltage rating may be mounted externally and be connected in its place.

The condenser shown at the right has a capacitance of only one mfd. and is rated at 3000 volts d-c working voltage. Its larger physical size is due to the fact that many layers of paper insulation are used between the tin-foil strips in order to withstand the high voltage.

The testing of condensers for open or short circuits will be taken up in Art. 626.

Commercial paper-type condensers usually vary as much as 10 per cent above or below the rated marked capacitance value, since in practically all radio filtering and by-passing applications in which they are used, the capacitance required is not critical. Where closer tolerances are required, condensers are manufactured to rigid capacity values, but of course they cost somewhat more.

Condensers are not used very much in electric light and power work except for correction of power factor in lines of medium power rating.

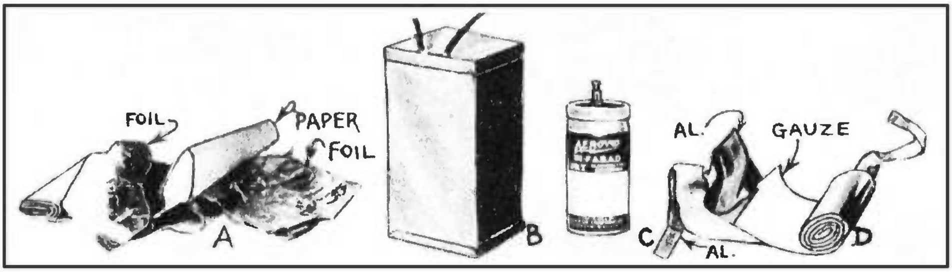


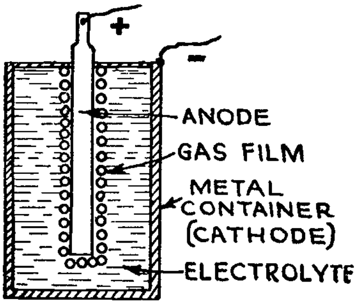
Fig. 94—Illustration showing the Comparative Size of a Paper-type Condenser at B and a Dry Electrolytic Type Condenser of similar rating at C. At the left is the Paper and Tin Foil of the Condenser at B, spread apart to show its construction. At the right are the rolled-up Aluminum Sheets with Saturated Gauze in between, of the Dry Electrolytic Condenser at C.

144. Electrolytic condensers: During the past few years, a continually increasing number of electrolytic condensers have been used as standard equipment in the filter circuits of power units in radio receivers. The rising popularity of the electrolytic condenser is due to several factors, of which cost is one of the most important, and compact size and a self-healing dielectric are others.

Electrolytic condensers are much cheaper than paper condensers of equal voltage rating and capacitance. They are also very much smaller. In B of Fig. 94 is shown a paper type filter condenser of 8 mf. capacity and d-c voltage rating of 450 volts. At C is shown a dry type electrolytic condenser of similar capacitance and voltage rating, photographed alongside of it. Notice the comparative size of the two units. The dry electrolytic condenser occupies a space of 7.5 cubic inches, whereas the paper-dielectric condenser occupies a space of 50 cubic inches!

145. Theory of electrolytic condenser: When certain metals such as aluminum or tantalum are put into suitable electrolytes, it is possible for current to flow *from the electrolyte to the metal* when voltage is impressed across them, but an exceedingly high resistance is offered to passage of current in the reverse direction, so that practically no current can flow in this direction *from the metal to the electrolyte.* This principle of one-way current conduction was utilized for many years in electrolytic rectifiers. The wet-type electrolytic condenser will be described first.

There are numerous theories as to what happens in the electrolytic condenser, the most generally accepted one being that as soon as a direct voltage is impressed across the electrodes, the positive terminal being connected to the aluminum electrode at the center (see Fig. 95) and the negative to the solution, a current first flows through. Soon however, the aluminum becomes covered with a thin coating of an aluminum oxide or hydroxide layer. Over this thin solid layer is a thin gas film of oxygen generated by the electrolytic action. This combination of the solid oxide layer and the thin gaseous oxygen film constitutes the dielectric.



WET-TYPE ELECTROLYTIC CONDENSER

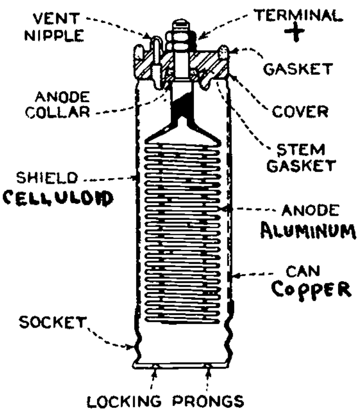


Fig. 95—Left: Simple Electrolytic Condenser showing Gas Film around Positive Aluminum Electrode.
Right: Commercial Wet-type Electrolytic Condenser showing Corrugated Aluminum Anode, employed to obtain a large surface area with an anode of small size.

This combined oxide-film and gas layer is of a thinness expressed in *molecular* dimensions rather than even small decimals of an inch. In the case of a condenser rated at 500-volts breakdown, it is of the order of from .00001 to .000001 inch thick. It is all that separates the conductive aluminum from the conductive electrolyte liquid around it. Thus we have two conductors of rather large surface (because all sides of the aluminum electrode are immersed in the liquid), separated by an insulator of extreme thinness. This forms a condenser, the dielectric being the thin gas and oxide films. Since the capacitance of a condenser is inversely proportional to the thickness of the dielectric, it is evident that since the dielectric film is very thin, and the film is formed on all surfaces of the aluminum electrode, the capacitance obtainable per square inch of the aluminum electrode surface is very high, especially when sheet aluminum is used as the positive electrode, or "anode" of the condenser. Thus it is possible to construct electrolytic condensers of large capacitance in very compact form (see Fig. 94).

The *extreme "thinness"* of this oxide-dielectric film, compared with the much *greater "thickness"* of the waxed-paper dielectric used in paper condensers, accounts for the much higher capacity obtainable in a given space in the electrolytic form of condenser.

Tantalum is not used commercially in electrolytic condensers, since it requires an acid electrolyte for this action. The corrosive properties of the acid make it objectionable. Aluminum can be used with any of several non-acid electrolytes which are suitable. When the condenser is off the circuit, as well as when potential is impressed across it, there is a tendency for the gas film to dissolve in the electrolyte and form aluminum hydroxide in the solution. With impressed potential, new film forms under the influence of the leakage current to replace that which is dissolved, but in time the fluid becomes saturated with aluminum hydroxide, which may precipitate as a white jelly and adversely affect the life of the condenser.

The second consideration involves corrosion of the positive electrodes. The susceptibility of aluminum to corrosion is well known, and in the use of wet electrolytic condensers, corrosion is the most damaging irregularity that can occur.

Obviously then, an electrolyte must be chosen that does not rapidly dissolve the film and the material of the electrodes. The electrolyte must be selected and prepared to prevent serious corrosion of the "formed" aluminum plates. Solutions of borax and boric acid have been used extensively in electrolytic condensers, both on account of their non-corrosive properties and the fact that films formed with them will stand as high as 480 volts. Also various concentrations of phosphates, borates, tartrates, and carbonates, in which films can be formed to withstand voltages over 300 volts, may be used.

146. Mechanical construction of wet electrolytic condensers: A single electrolytic condenser unit consists of a single aluminum electrode (*anode*) in the solution, together with an inactive electrode (*cathode*) which serves merely to make electrical connection from the solution to the negative side of the circuit. In practically all commercial wet electrolytic condensers, the container can serves as this inactive electrode since it makes direct connection to the electrolyte solution, as shown in Fig. 95. It is usually made of copper or aluminum.

Many schemes are employed for increasing the *surface area* of the "cathode" electrode in order to increase the capacitance. At the right of Fig. 95 is shown an interior cross-section view of the Sprague condenser in which the pure aluminum "cathode" electrode is hollow and corrugated as shown. Other forms of "crimped", and "corrugated" aluminum electrodes are also employed. The solution fills up the hollow part so that a large active surface area is obtained. The containing can is of pure copper, with the bottom threaded to screw into a screw socket similar to that of the ordinary incandescent lamp socket, for mounting. The can is filled to a level near to its top with the electrolyte.

The anode is supported by a hard rubber cover. The stem of the anode protrudes through a tight-fitting hole in the cover and is threaded to receive terminal nuts for attaching the connecting wire.

To prevent leakage around the anode stem, a rubber stem gasket is provided. The cover is also provided with a soft rubber check-valve forming an integral part thereof. This check-valve is provided with a needle hole which permits the escape of gases, but does not permit dust to enter the can, nor liquid to escape. The gasket around which the rim of the can is crimped, provides for air-tight sealing of the cell.

As a rule, there is also provided a perforated shield of insulating material between the anode and the can to prevent accidental contact and short-circuits between them. This usually consists of a sheet of celluloid perforated with holes to permit circulation of the electrolyte.

Where several condenser units are required, it is common to place several anodes in a single container and the separate anodes are provided with celluloid insulators to resist differences in voltages applied to them, also with an electrostatic shield to reduce the capacitance between the individual sections. The terminals protrude from the top of the can as shown at the center of Fig. 96. The connections of units of this type in B-power supply unit circuits will be shown later, in Chap. 27.

147. Self-healing dielectric: Unlike ordinary condensers, the electrolytic type is polarized, that is, the aluminum electrode (usually the center one) must always be connected to the positive terminal of the circuit. If it is connected reversed, the leakage current through the condenser will be so great that the condenser will soon heat up and become damaged. Thus, electrolytic condensers cannot be used in alternating current circuits. They can however be used in direct current circuits in which the current is pulsating, as in the filter circuits of B-eliminators. Another peculiarity, is the fact that there is a small leakage current which flows all the time from the aluminum electrode to the solution and negative terminal. In modern electrolytic condensers this has been reduced to the very low value of one microampere per square centimeter of film surface. This amounts to about 1 or 2 milliamperes for each 10 mf. of capacitance, with 300 volts applied to the terminals.

A great advantage of the electrolytic condenser is that it is not harmed by breakdown. With paper-dielectric type condensers, over-voltages may cause permanent breakdown of the condenser. However, should momentary over-voltages be applied to the electrolytic condenser, its film gives way while the surge lasts, but as soon as the excessive strain is over, the film is restored, for it is an oxide which is rapidly produced by the electrochemical action of the leakage current itself. In this way, the condenser almost immediately regains its normal operating characteristics. Therefore, excessive voltages do not permanently destroy the dielectric layer. This characteristic makes the condenser immune to ordinary temporary surges.

148. Forming the condenser: The capacitance of the electrolytic condenser depends upon (1) the surface area of the aluminum electrode, (2) the material of the electrode, (3) the thickness of the oxide and gas film. The thickness of the film depends on the voltage which is applied when the film is first formed during the *forming process*. The higher the voltage applied during forming, the thicker will be the film and consequently the *higher* will be the breakdown voltage and the *less* will be the capacitance.

After the condenser elements are assembled, a direct voltage is applied for 8 or 10 hours. This causes the formation of the oxide and gas film. The maximum working voltage of the condenser when finally placed in service must be less than the voltage used during the forming process. Most condensers are formed so as to have a breakdown voltage around 450 volts d-c. It is therefore recommended to operate the units at peak voltages not exceeding 430 volts. The maximum forming voltage which may be applied, depends upon the chemical used for the electrolyte. Various chemicals can withstand certain maximum critical voltages, and if these are exceeded, the gas layer will be punctured. This allows the condenser

Courtesy Aerovox Wireless Corp

Fig. 96—Left: 8 Mf. 500 V. Max. Peak Voltage Dry Electrolytic Condenser.
Center: 3-section Dry Electrolytic Condenser of same Voltage Rating, but with Total Capacitance of 24 Mf.
Right: Single 16 Mf. Dry Electrolytic Condenser of same Voltage Rating Designed for Inverted Mounting on Top of Sub-panel.

to break down, and causes a short-circuit between its terminals. Upon reduction or removal of the applied voltage, the break will be mended by the formation of a new insulating film. A well formed condenser will remain formed indefinitely, even with only occasional use, provided its working voltage rating is not exceeded.

As is the case with waxed paper condensers, it is essential that all types of electrolytic condensers be placed in the coolest section of the receiver or amplifier assembly. If the temperature of the air surrounding any electrolytic condenser is not raised above 140 degrees Fahrenheit 60 degrees Centigrade), no harm or appreciable change in characteristics will occur.

While electrolytic condensers can be used at somewhat higher temperatures without apparent trouble, operation under higher temperature conditions over a long period of time will result in impairment of their electrical and mechanical characteristics, and an increased leakage current.

149. Dry electrolytic condensers: Electrolytic condensers having large capacitance within a small space are also constructed in so-called "dry form". They are "dry" in the same sense that dry-cells are dry, that is to say, dry in the sense that the electrolyte cannot be poured or spilled out of the container. The anode (forming the positive electrode and term-

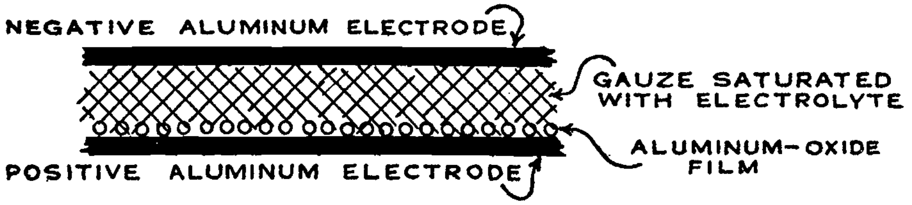


Fig. 97—Cross-section view of Dry-electrolytic Condenser Element. The Two Aluminum Electrode Sheets are separated by the Thin Film of Aluminum Oxide and Gas, and the Electrolyte is held in place by the Gauze. The Electrolyte consists of a mixture of the Following proportions of materials; 1000 grams of Glycerine, 620 grams of Boric Acid, and 50 cubic centimeters of 26% Ammonia Water.

inal) consists of a thin sheet of pure aluminum, on the surface of which is formed a thin film of aluminum oxide and oxygen gas acting as the dielectric. Another aluminum sheet placed on the other side merely serves as a convenient means of making contact to the electrolyte soaked up in the cotton gauze in between. A strip of this absorbent gauze is placed between the aluminum sheets and is rolled up with them (see D in Fig. 94), the gauze being saturated with the electrolyte solution and holding it much as a sponge holds water. This construction reduces the internal or electrolyte resistance to a minimum. A cross-section view of this is shown in Fig. 97. The entire unit is wrapped in heavy paper. The long tab left on the anode (positive) aluminum sheet (see D of Fig. 94) is connected to the screw terminal at the top of the can. The short tab on the cathode sheet, which completely surrounds the anode sheet, thus shielding the anodes from each other in multiple section units, connects to the aluminum can. A soft rubber gasket seals the top of the can. As in the case of the wet electrolytic condensers, the dry type are also made with 2, 3 or 4 units in a single container which appears like the center one shown in Fig. 96.

Dry electrolytic condensers are formed in the same way as the wet type, and should not be used in alternating current circuits.

Aside from the low cost per microfarad and the increased filtering efficiency, two important features of dry electrolytic condensers are their compactness and light weight, as compared to other condensers. These features result in reduction in space requirements and shipping weights and costs, and have been largely instrumental in bringing these condensers to the fore in radio receiver construction.

The dry construction eliminates the disadvantages resulting from the use of a liquid electrolyte, such as splashing, spilling and leakage of the electrolyte when subjected to jarring, vibration or tilting during transportation or normal use in automobiles, trains, airplanes, boats, etc.

Dry electrolytic condensers having a maximum peak voltage rating of 500 volts are obtainable in single 8-mf units and in multiple units. When used in circuits of higher voltage than this, two or more units may be connected in series. The total breakdown voltage of the combination will be the sum of the breakdown voltages of the individual units. The total capacitance will be less than that of one unit above, as will be explained in Art. 155. Testing of condensers will be studied in Art. 626.

150. Variable air condensers: Condensers having air dielectric find their greatest use in the high frequency (radio frequency) tuning circuits of radio transmitters and receivers. They are commonly made *variable*, that is, their effective capacitance may be changed at will while the condenser is being used in the circuit. As a rule, such condensers are made continuously variable, so that the capacitance may be gradually increased or decreased, and not changed in abrupt steps.

A consideration of formula (13) in Article 137 shows that the capacitance of a condenser can be varied by varying the number of plates, the active area of the plates, the material of the dielectric, or the separation between the plates. Variable air condensers employing practically all of these methods have been developed at one time or another, but the type in which the area of the plates actually effective between adjacent plates is varied, is practically the only one which has survived. This type of condenser is shown in Fig. 99 and illustrations which follow.

Variable air condensers which are used extensively for tuning radio-frequency circuits, consist of a group of stationary plates (stator) ar-

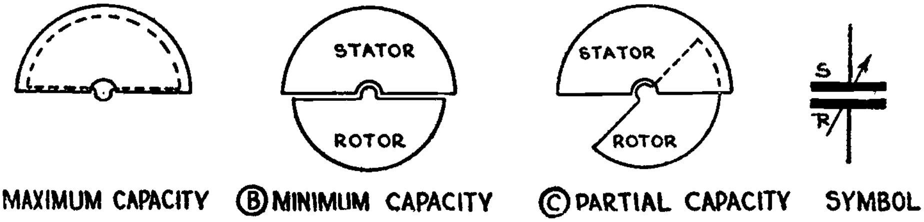


Fig. 98—The Capacitance of a Variable Air Condenser is varied by moving the Rotor Plates so they mesh more or less with the Stator Plâtes. When they mesh completely, the Capacitance is Maximum.

ranged so that a set of rotating plates (rotor) can be moved in and out between them without touching. The dielectric (the space between them) is air. When the plates are all meshed (Fig. 98), the full areas of the plates are exposed to each other and the maximum capacity exists; when they are all out of mesh, the minimum capacity exists; and for any positions in between these, various intermediate capacities exist. Any desired rate of variation of capacitance can be obtained by properly shaping the plates, as will be seen later when studying tuning.

The plates are usually made of thin, hard, brass or aluminum, stamped out on punch-presses. The brass plate has the advantage of being easily soldered to the rotor shaft or stator block for good electrical connection, and of requiring less thickness of plate for proper stiffness. The aluminum plate condenser is light in weight. Brass is subject to corrosion while aluminum is not, under ordinary conditions. Brass condenser plates are often lacquered or given a special finish to prevent this corrosion. The rotor plates are swedged into grooves cut on the rotor shaft. The stator plates are swedged into grooves cut on the stator support blocks. The blocks are fastened to two small strips of hard rubber or Bakelite which in turn are fastened to the metal frame. The rotor turns in bearings in

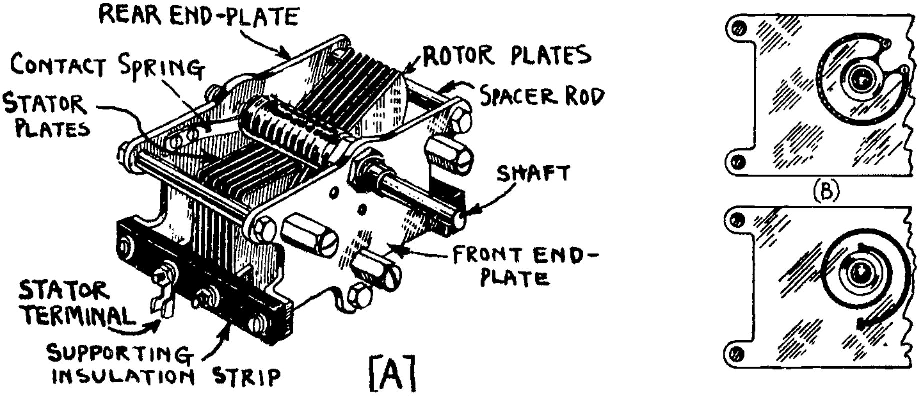


Fig. 99—Left: Construction Features of Typical Variable Air Condenser used for Tuning. Right: Two Forms of Pigtail Connections to Rotor Shaft used in Variable Condensers.

the end plates. The insulating strips serve to insulate the stator assembly from the end plates and rotor. These strips should be mounted outside of the dense electrostatic field of the condenser, to avoid dielectric losses. The stator and rotor plates should not touch, for a short-circuit would then result. Rotor bearings should work smoothly and the entire condenser should be rigidly constructed.

The clearance between the plates is usually governed by mechanical considerations in most cases where the condenser is to be used in circuits where the voltages are low, as in the case of radio receivers. In radio transmitters where the condensers are in high voltage circuits, the operating voltage determines the allowable spacing between the plates as shown in Fig. 86. Theoretically it is desirable to mount the rotor and stator plates as close together as possible, so for a given capacitance the physical size of the condenser will be small. However, enough mechanical clearance must be left, so that the rotor plates will not touch or scrape against the stator plates if they should become slightly bent out of shape. If they touched, a short-circuit would occur and the radio receiver would either become noisy or would stop operating altogether. Also the plates must be thick enough so that mechanical vibrations due to the loud speaker in the receiver, do not make them vibrate enough to vary the clearance between the plates and thus vary the capacitance. This would result in a howl from the loud speaker.

Some variable condensers are still made with Bakelite or other insulating material for end-plates. The use of metal end-plates has become more common due to their greater strength and rigidity, and the ease and cheapness of manufacture by stamping. As the entire frame of a metal end-plate condenser is at the same potential as the rotor plates and shaft, and this is usually wired into the receiver so it connects to the B- or ground terminals, hand capacity effects are greatly reduced by this construction since the front metal end-plate acts as an electrostatic shield.

The terminals for the stator plates are usually arranged at the supporting insulating blocks. The connection to the rotor side is made at the frame. The symbol for a variable condenser is shown in Fig. 98. The arrow denotes that it is variable.

Variable air condensers are made with various standard capacitance values. The number of plates in each size is not standard, but varies among those of various manufacturers. Of course the number of plates for a given capacitance depends upon the area of each plate and the distance between the stator and rotor plates. Thus a .00035 microfarad condenser of one make may have a total of 17 plates, and that of another may have 19 smaller or more widely spaced plates, while still another may have 21 plates. It is not possible to tell the capacitance of a variable air condenser accurately just by looking at it, although a fair approximation may be made by using the following as a rough guide for the values of capacitances and number of plates.

7	plates—	usually	.00015	microfarads.
11	" —	"	.00025	"
13	" —	"	.00025	"
17	" —	"	.00035	"
21	" —	"	.000365	"
23	" —	"	.0005	"
43	" —	"	.001	"

The .00035 and .000365 microfarad sizes are used most for the tuning circuits of modern broadcast range radio receivers. Short wave receivers usually employ the .00015 microfarad size for tuning.

In order to provide positive direct connection from the rotor shaft to the rear end-plate, some condensers are provided with a *pigtail*. This has been found very necessary on condensers used in short wave equipment, on account of microphonic noises which otherwise result. Pigtails are made either from stranded or braided flexible copper wire, or from loosely-coiled spirals of thin phosphor bronze strips as shown at (B) of Fig. 99. The ends of the pigtails are generally soldered to the parts they connect, although their ends are sometimes bolted in place. When pigtail connections are used, the rotor plates must be provided with a "stop" to limit the rotation to 180 degrees instead of a full 360 degrees. This is to avoid twisting and breaking the pigtail. In other condensers, as shown at (A) of Fig. 99, a short spring contact is arranged to wipe against the rotor shaft while turning.

151. Midget condensers: Variable air condensers of low capacitance values are usually called *midget* condensers. These midget condensers ranging in maximum capacity sizes from about .000015 microfarads to .0001 microfarads, find a variety of uses as verniers for the larger condensers, for neutralizing, etc. A typical vernier condenser is shown at the left of Fig. 100. Notice that it is built exactly like the larger condensers, only it has less plates and they are much smaller in size.

152. Gang condensers: In modern radio receivers where four, five and even six variably tuned circuits are used to obtain the necessary

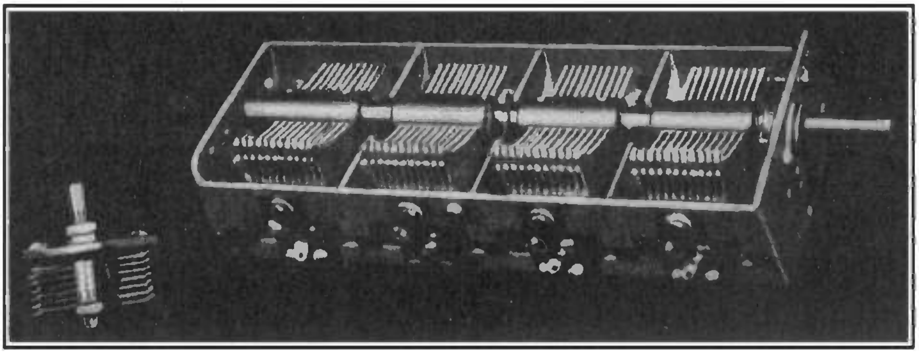
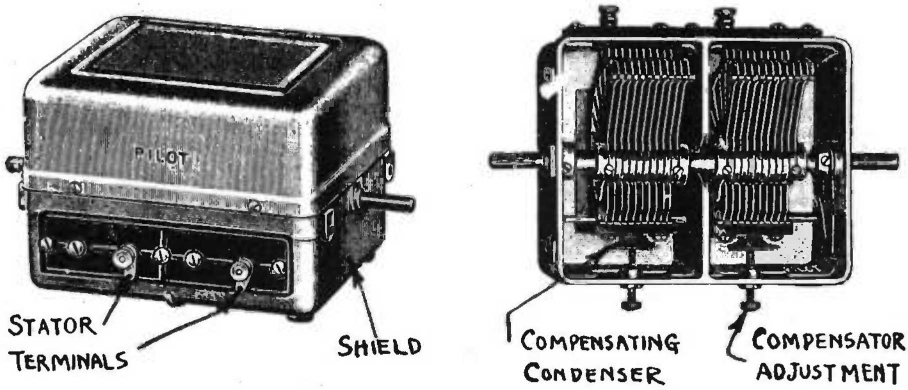


Fig. 100—Left: Small Midget Condenser of .00005 Mf. Capacitance.
Right: 4-Gang Tuning Condenser used in Modern Radio Receivers. The Capacitance of each section is .00035 Mf. Its Compensating Condensers are shown in the foreground.

amount of selectivity, it is common to build the rotor-plate sections of all of the individual condensers on a common shaft, and mount all of the stator-plate sections at the proper places along the stator frame, as shown in Fig. 100. Each stator section is independently insulated from the others and from the frame. All of the rotor sections form a common circuit with the shaft. This is known as a *gang condenser*, because turning of the shaft varies the capacitances of all of the condenser sections simultaneously and this permits of a single tuning control. As the condenser in Fig. 100 has four sections, it is called a *4-gang condenser*. The electrical symbol for a gang condenser will be found in the radio symbol chart in Appendix A.

As it is hardly possible in practice to have the tuned stages (each consisting of one section of the gang condenser and the tuning coil with its wiring), absolutely similar to each other, a small adjustable compensating condenser is sometimes built on to each section of the gang. This usually takes the form of a small 2-plate condenser with a strip of mica between to act as a dielectric. The small capacitance is varied by the adjusting screw which squeezes the two plates together more or less depending upon the capacitance desired. Compensating condensers should be constructed so that the movable plate and adjusting screw connect to the rotor plates and frame of the condenser. This places them at ground potential so they can be adjusted with the fingers while a receiver is in operation, without causing any detuning effects due to hand capacity. Each compensating condenser is already connected in parallel with its own particular section of the condenser so its capacitance adds to that of the section. The exact procedure followed when adjusting these compensators will be studied later in connection with single control receivers (see Arts. 638 and 639). Another form of capacity-compensation construction is described in Art. 373.



Courtesy Pilot Radio & Tube Corp

Fig. 101—Exterior and Interior views of a 2-gang shielded variable tuning condenser. The metal enclosing case acts as an electrostatic shield and dust-proof protection for the condenser. Each section has a capacitance of .000375 mf.

In the "gang" or "bathtub" condenser shown in Fig. 100, an electrostatic shield consisting of a metal plate is placed between the stator plates of each section to reduce the stray capacitance between adjacent condenser sections in the gang.

The shafts of tuning condensers are usually arranged to be turned by dials. These usually carry an illuminated scale which is calibrated simply with equal divisions from 0 to 100 for 180 degree rotation, or else with wavelength in meters, or frequency in kilocycles. These dials are usually designed to produce a reduction of 3 or 4 to 1 between the motion of the tuning knob and the motion of the condenser shaft, so that the condenser capacitance may easily be adjusted very accurately when tuning.

153. Shielded tuning condensers: In modern high-gain radio receivers built in compact form, it is usually desirable to entirely shield the tuning condensers in a metal enclosure to prevent any stray electrostatic field from acting on surrounding coils, wire, etc. The shield also serves to prevent the accumulation of dust between the plates of the condenser. An accumulation of dust sometimes results in very noisy reception, due to the minute current leakage discharges taking place from the rotor plates to the stator plates through the more or less conducting dust particles. Interior and exterior views of a shielded 2 gang tuning condenser are shown in Fig. 101. Notice the small compensating condensers and adjusting screws at the bottom of the open condenser. Of course tuning condensers of this type can be made with any number of sections required.

154. Condensers in parallel: When condensers are connected in parallel as in (A) of Fig. 102, the effect is to increase the total surface area of the plates connected on each side of the line. Thus in (A) of Fig. 102 the area of plate A is added to that of D, and the area of plate B is added to that of E, etc. The result is that the plate surface area is increased to the sum of the individual surface areas, as shown at (B), and the total combined capacitance is equal to the sum of the individual capacitances connected in parallel. This may be stated thus:

$$C=C_1+C_2+C_3+C_4+\text{etc.} \qquad (14)$$

where C=the combined capacitance

C_1, C_2, C_3, etc. are the individual capacitances.

Example: What is the total capacitance of the following capacitances connected in parallel, .0005; .001; .0001; and .01 microfarads respectively?

Solution: $C=.0005+.001+.0001+.01=.0116$ microfarads. Ans.

This fact may be made use of in making up condensers of odd capacitances by connecting several condensers of standard size in parallel. Thus, to make up a capacitance of say .00075 mfd., a standard size condenser of .0005 mfd. and one of .00025 mfd. can be connected in parallel.

With condensers connected in parallel, the voltage rating of the combination is limited by the safe working voltage rating of the lowest-voltage

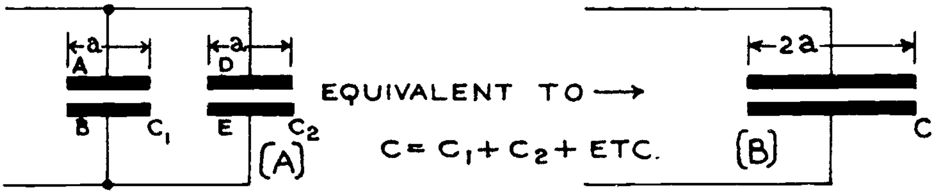


Fig. 102—When two or more condensers are connected in parallel, we obtain the effect of adding their plate surface areas, thus increasing the total capacitance.

condenser in the group, and the voltage applied across the combination should never exceed this value.

155. Condensers in series: When two or more condensers are connected in series as shown at (A) of Fig. 103, the effect is really to increase the total dielectric thickness and thereby reduce the capacitance. However, the increase in total dielectric thickness makes the series combination able to safely withstand higher voltage without breaking down.

Thus, in (A) electrons are transferred from one outside plate around through the external circuit to the other outside plate during charging of the condenser. The two center plates really do not add to the capacitance in any way, as any charges induced on them will be electrically opposite and will therefore neutralize each other. The effect then is the same as though the two inner plates were eliminated and the individual condensers C_1 and C_2 were replaced by a single condenser C, having a

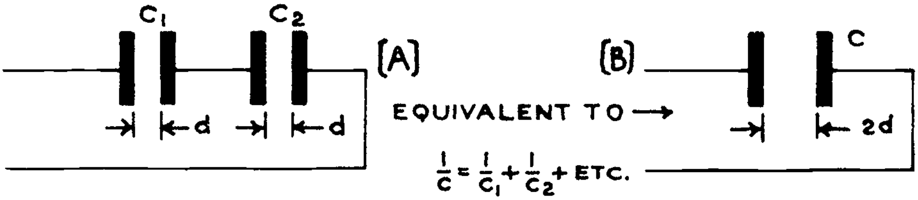


Fig. 103—When two or more condensers are connected in series, the effect is to increase the thickness of the dielectric between the active plates. This results in a decrease of the capacitance, and an increase in the breakdown voltage which would be required to rupture the dielectric.

total thickness of dielectric equal to the sum of the dielectric thickness of the individual condensers, as shown at (B). If the condensers are of unequal capacitances, the plate area must also be considered.

The total capacitance of two or more condensers in series is found from the formula:

$$\frac{1}{C}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\text{ etc.} \qquad (15)$$

where C=the total combined capacitance

C_1, C_2, C_3, etc. are the individual capacitances.

Formula (15) may be put into a somewhat more convenient form for calculation, as follows:

$$C=\frac{1}{\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\ldots\text{etc.}}$$

The total capacitance of any number of condensers in series is smaller than the capacitance of the smallest condenser in the group. It is thus possible to obtain capacitances of smaller value by using two or more condensers in series.

Example: What is the total capacitance of the condensers of the previous problem if connected in series?

Solution: $\frac{1}{C}=\frac{1}{.0005}+\frac{1}{.001}+\frac{1}{.0001}+\frac{1}{.01}=.00008$ microfarads. Ans.

Condensers of medium voltage rating are very often connected in series where high voltages are to be withstood, but it should be remembered that in any case of series condenser connection, the resultant capacitance is less than that of the smallest condenser in the group. The calculation of the resultant voltage rating of condensers connected in series is rather complicated, unless the condensers connected in series are of the same capacity, voltage rating and power factor.

When condensers of equal capacity are connected in series, any voltage applied across the combination will distribute itself equally across each condenser and the voltage across each condenser will be equal to the voltage across the combination divided by the number of condensers connected in series, provided the insulation resistances or power factors of the condensers are equal. When the insulation resistances are not the same for each condenser, the voltage distribution across the condenser will be affected to a greater or lesser extent, depending on the wave-form of the applied voltage. The effect of unequal voltage distribution can be minimized by the use of resistor balance (high value resistors across the condensers).

The voltage distribution among several condensers connected in series, for condensers of fairly low power factor, will be proportional to the product of the capacity by the power factor.

Problem: Suppose a serviceman had a number of 2 mfd.-200 volt condensers but required a condenser of 4 mfd. to work on 400 volts. How could he arrange these units?

Solution: Connect up the 2 mfd.-200 volt condensers in series banks of two each. Each bank would then be able to stand 400 volts, but its capacitance would only by one mfd. Therefore to obtain 4 mfd., connect four such series banks in parallel. Ans.

156. Time and quantity of charge of a condenser: As one ampere is a rate of current flow of one coulomb (6.28×10^{18}) electrons per second, it is possible to calculate the rate at which current flows into a condenser if the total quantity of charge Q and the time t are known. As the rate of current flow (amperes) at the beginning of charge is zero, the average rate is secured from the equation:

$$I = \frac{Q}{t}$$

Putting the equation in another form we have:

$$Q = I\,t.$$

from which we see that the total quantity of electricity stored in a condenser is equal to the current flow into it in amperes multiplied by the time t in seconds during which it flows. Since the quantity of charge Q is also proportional to the capacitance and the applied voltage, we also have

$$Q \text{ (Coulombs)} = C \text{ (Capacitance in farads)} \times E \text{ (volts)}.$$

Thus if an e. m. f. of one volt is applied to a condenser of one farad capacitance for one second, one coulomb of electricity will be stored in it; or expressing this in terms of electrons, 6.28×10^{18} electrons will be transferred from its positive plates, around through the circuit, into its negative plates.

REVIEW QUESTIONS

1. What is the difference between the current obtained from a battery and that obtained during the discharge of a condenser?
2. Describe in detail what happens when a condenser is being charged by a source of direct e. m. f. (sketch required).
3. Describe in detail what happens during discharge (sketch required).
4. Describe in detail what happens when a condenser is connected to a source of alternating e. m. f. (sketch required).
5. What is the dielectric of a condenser? What purpose does it serve in the condenser?
6. Name three dielectrics commonly employed in condensers. Give the advantages and disadvantages of each.
7. Why is mica employed as the dielectric in small fixed condensers?
8. What is the dielectric in the usual type of dry electrolytic filter condenser? What comprises the "plates" in this type of condenser?
9. What losses of energy may occur in condensers?
10. What is meant by dielectric absorption loss? Explain.
11. What causes leakage loss in condensers? How may this loss be reduced?
12. What is dielectric hysteresis loss? Does the dielectric hysteresis loss increase or decrease as the frequency of the charging e. m. f. is raised? Why?
13. What factors determine the maximum voltage a condenser can stand without breakdown of its dielectric?
14. Why are paper type filter condensers constructed with two or more thin papers between their plates rather than a single paper of equivalent total thickness?
15. Distinguish between (a) maximum a-c working voltage, and (b) the normal operating voltage of a condenser.
16. If a condenser is to be connected across a sine-wave a-c voltage source of 250 volts, what must be its maximum voltage rating?
17. What is the difference in construction between (a) a high-voltage air dielectric condenser, and (b) a high voltage paraffined-paper dielectric fixed condenser?
18. State the factors upon which the capacitance of a condenser depends, and explain in detail just how each factor affects it.
19. What is meant by "specific inductive capacitance" of a material?
20. Name three materials having high value of the above and discuss their suitability for use as condenser dielectrics.
21. A condenser having a capacitance of one farad is to be built of a number of square tinfoil and waxed paper sheets stacked one on top of the other. The active surface of each plate is 12 inches by 12 inches. Each plate is .001 thick, and the adjacent plates are separated by paraffined paper having a thickness of .002

inches, (a) How many tinfoil plates or sheets are required? (b) What will be the total height of the condenser when completed? (*Note*: This gives an idea of how large a unit the *farad* is, and how large in physical dimensions a 1-farad condenser would be.)

22. What is the maximum capacitance of a variable condenser having an air dielectric, if it has 23 semicircular plates each three inches in diameter, and the clearance between plates is 0.1 inches?
23. How would you connect a number of standard condenser units of 0.1, 0.0025 and .0001 mfd. capacitance to obtain a total capacitance of 0.3053 mf? Draw a sketch showing the connections.
24. How could you connect standard condenser units of 0.5 mf. capacitance to obtain a capacitance of 0.1 mf? What would be the breakdown voltage of this combination as compared to that of a single similar 0.1 mf. unit? Draw a sketch of the connections.
25. What is a condenser block? What could you do to repair a condenser block in which but one section of the condenser has become defective? (With sketch.)
26. Explain the theory of operation of the wet electrolytic condenser.
27. Draw a diagram showing the internal construction of such a unit.
28. Explain the theory of operation and construction of a dry-electrolytic condenser. What materials does the electrolyte consist of?
29. State the advantages and disadvantages of the dry type over the wet type, giving the reasons for each. Which is used most?
30. What is meant by a self-healing dielectric. What happens when a solid dielectric like paraffined-paper or mica breaks down?
31. What is a fixed condenser, variable condenser, midget condenser, gang condenser, compensating condenser, rotor plates, stator plates, end frame?
32. How is the variation in capacitance between the sections of a gang condenser compensated for in practice?
33. What is the difference between a condenser and an ordinary conductor of electricity, such as a piece of copper wire?
34. Dry electrolytic condenser units having a rating of 8 mfd. and maximum a-c peak working-voltage of 500 volts are to be connected as a bank of condensers having a total capacitance of 16 mf. The entire bank is to be connected across a filter circuit in which a pulsating sine-wave d-c voltage having an effective value of 650 volts exists. How many of these condenser units must be employed, and how should they be connected to accomplish this? Draw a diagram of the connections.
35. What determines the voltage rating of electrolytic condensers? What determines the capacitance?
36. How are electrolytic condensers "formed"?

CHAPTER 11

ALTERNATING CURRENT CIRCUITS

A-C CIRCUITS — RESISTANCE IN A-C CIRCUITS — INDUCTANCE IN A-C CIRCUITS — CURRENT LAG IN INDUCTIVE CIRCUIT — INDUCTIVE REACTANCE — PHASE DISPLACEMENT — INDUCTIVE REACTANCE TRIANGLE — CAPACITANCE IN A-C CIRCUITS — CURRENT LEAD IN CAPACITIVE CIRCUIT — CAPACITIVE REACTANCE — CAPACITIVE REACTANCE VECTOR RELATION — CIRCUITS HAVING INDUCTANCE, CAPACITANCE AND RESISTANCE — OHM'S LAW FOR ALTERNATING CURRENTS — IMPEDANCES IN SERIES AND PARALLEL — POWER IN A-C CIRCUITS — RESONANCE — SERIES RESONANCE — VOLTAGE RELATIONS IN A SERIES TUNED CIRCUIT — RESONANCE CURVES — WAVELENGTH AND RESONANCE RELATIONS — PARALLEL RESONANCE — ALTERNATING CURRENT FREQUENCIES — FILTERS — LOW PASS FILTERS — HIGH PASS FILTERS — BAND PASS FILTERS — REVIEW QUESTIONS.

157. A-C circuits: A continuous or direct current is one which flows always in one direction, and is usually assumed to be of constant strength. A pulsating direct current is one which flows always in one direction but which may vary in strength. An *alternating current* is one which not only changes its direction of flow periodically, but also varies in strength. These three forms of electric current are shown diagramatically in Fig. 68. While all three forms of current exist in radio transmitting and receiving circuits, alternating and pulsating direct currents and voltages play the most important part in their operation. We shall now see that circuits in which alternating or pulsating direct current flows, usually behave entirely differently than those in which steady direct current flows. It is very important for us to know and understand just what causes these peculiar effects.

158. Ohmic resistance in a-c circuits: If an alternating e. m. f. is applied to a circuit containing a resistor, an alternating current will flow through the resistor. If it has no associated inductance or capacitance whatsoever, it is called a "pure" resistor and it will behave exactly as it does in a direct current circuit. The relation of the voltage and corresponding current at any instant will be exactly in accordance with Ohm's Law $I=\frac{E}{R}$. The opposition which a circuit or electrical device offers to the flow of current through it, merely because of the natural resistance properties of the material of which it is made, is often called its *ohmic resistance.*

159. Inductance in a-c circuits: We found in Article 115 that whenever an electric current flows through a conductor, a magnetic field is produced around it. If the current varies in any way, the magnetic field varies correspondingly. If an alternating current flows through a conductor, the field around it will be changing periodically both in direction and strength, and consequently a counter or self-induced e. m. f. will be set up in the conductor by self-induction. The e. m. f. is always in such a direction as to oppose the change which produced it. The higher the frequency of the alternating current, the faster the magnetic field varies and

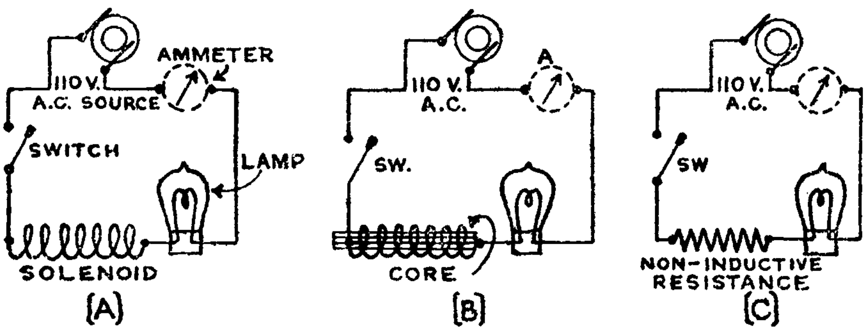


Fig. 104—Experiment showing the effect of connecting an inductance in an A.C. circuit.

so the greater is the self-induced counter-e. m. f. The effect is greater if the conductor is wound in the form of a coil, because then the field is concentrated into a relatively small space and the magnetic field of every turn affects every other turn. If an iron core is put into the coil, the magnetic field is greatly strengthened and the self-induced e. m. f. is stronger. As this self-induced counter-e. m. f. is at every instant opposite in direction to the applied e. m. f., (Lenz's Law), it tends to reduce the effect of the applied e. m. f. in producing a flow of current through the conductor. This opposition to the current flow caused by the self-induced e. m. f. in an alternating current circuit (essentially the same effect exists in a pulsating direct current circuit) is called the *inductive reactance.* If the circuit also has resistance, this will exert an additional opposition to the flow of current. The effects of inductance in an a-c circuit may be shown by the following experiment:

Experiment: Connect the solenoid used in Article 101, in series with a 110 volt 110 watt incandescent lamp across a 110 volt source of alternating e. m. f. as shown at (A) in Fig. 104. If an alternating current ammeter with a range of 0 to 2, or 0 to 5 amperes is available this may also be connected in series with the circuit. Notice that the lamp does not light up to full brilliance, due to the fact that the ohmic resistance and the self-induced counter-e. m. f. of the solenoid are opposing the applied e. m. f. and thereby reducing the current.

Now slowly move an iron core into the hole in the solenoid, as shown at (B). Notice that the lamp gets dimmer and dimmer as the core is pushed in and the magnetic flux is increased. The increase of flux increases the self-induced counter-e. m. f. and thereby reduces the current. The resistance of the solenoid of 100 feet of No. 18 wire is approximately 0.65 ohms. If the solenoid is now removed from the circuit and a non-inductive resistor of 0.65 ohms is connected in its place, as shown at (C), the lamp will burn brighter than when the coil was connected in the circuit, indicating that the flow of electrons or current was not only opposed or "impeded" by the "ohmic" resistance of the solenoid, but also by the counter-e. m. f. of self-induction developed in it by the alternating magnetic flux. If an ammeter is used in the circuit the exact amount of current flowing in each case may be determined. If a non-inductive resistor of 0.65 ohms is not available, the solenoid itself may be unwound and straightened out so its inductance is practically zero, and it may then be connected back into the circuit since its ohmic resistance only will now be present.

160. Current lag in an inductive circuit: As we shall now see, the self-induced e. m. f. set up in any inductor connected in an alternating current circuit not only "impedes" or opposes the current flow, but also *makes the variations in the alternating-current flow*, "lag" behind the corresponding *variations in the applied e. m. f.*

Let the diagram at the left of Fig. 105 represent an inductor connected across an alternating source of e. m. f. Let us suppose for simplicity, that the wire of which this inductor is made does not have any resistance whatsoever, so that any opposition offered to the flow of current is due solely to its self-inductive effects.

Let curve (A) at the right of Fig. 105 represent the sine-wave voltage applied to the inductor. The current flowing as a result of the application of this e. m. f. to the circuit produces a varying magnetic field around the inductor which sets up in it a self-induced e. m. f. which is opposite in direction and value to the applied e. m. f. at every instant (Lenz's Law). Therefore this e. m. f. also varies exactly as the applied e. m. f. does, but since it is always opposite in direction its curve may be drawn as shown by (B).

Since the value of the self-induced e. m. f. induced in the inductor at any instant is proportional to the *rate of change* of the current flowing through the inductor at that instant, it will have its maximum value when the current is *changing fastest* in value (not when the current is *greatest*) and will have its minimum value when the current is changing slowest. When the current flow, and therefore the magnetism, is at the *maximum* value in either direction (as at points F and J), its strength varies very little within a given momentary period of time, as indicated by the fact that the curve is almost *horizontal* at these points. Consequently the self-induced e. m. f. is zero at the moment the current and magnetism are at maximum value. When the current flow and therefore the magnetism is going through its zero value as at point H, it is changing in strength rapidly (as shown by the fact that the slope of the curve is steep at this point) so the self-induced e. m. f. is at maximum value. Therefore at the point R, when the self-induced e. m. f. is zero and just about to increase in the positive direction, the current must be maximum (minimum rate of change) at point F, and just ready to decrease down to zero value. Likewise at the point M, when the self-induced e. m. f.

is maximum and just about to decrease, the current must be at minimum value (maximum rate of change) at point H, and just ready to increase in the opposite direction. Thus the current wave may be constructed as shown through points D-E-F-G-H-I-J-K-L.

Examination of these curves shows that when the applied e. m. f. starts at the instant O and increases in strength from O to P, the current is not yet flowing. In an inductive circuit it takes a definite time, perhaps a small fraction of a second, for the current to reach some steady value. After the applied e. m. f. has gone through one quarter of a cycle from O to P the current is just beginning to flow at D. Now as the applied e. m. f. decreases from P to R, the current starts to increase from D to F.

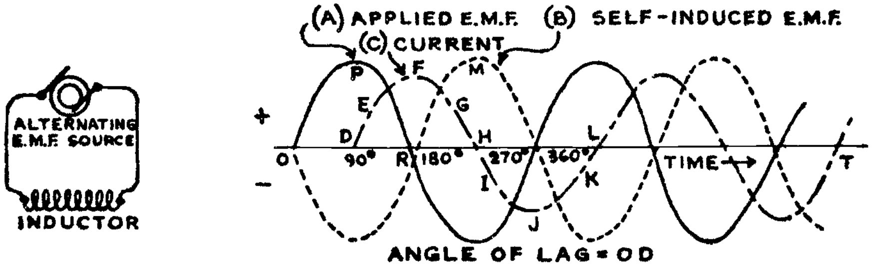


Fig. 105—Effect of inductance on the phase relation of the current and voltage in an A-C circuit.

Therefore *the changes in the current lag the changes in the applied e. m. f. by one quarter of a cycle, or 90 electrical degrees.*

This is an important characteristic of an alternating current circuit in which pure inductance is present. As we shall see later, if resistance or capacitance is also present in the circuit, the amount of *lag* of the current variations depends upon the relative values of the resistance, inductance and capacitance. It may be less than 90 degrees, or the current variations may not even lag at all but may *lead* those of the voltage.

161. Inductive reactance: The applied e. m. f. in a *direct current* circuit *is opposed only by the ohmic resistance* of the circuit. The applied e. m. f. in an *alternating current* circuit however, *is opposed not only by the resistance but also by the self-induced e. m. f.* of the circuit, (which is opposite in direction to it at every instant). Self-induction therefore acts like resistance in the sense of "impeding" or opposing the flow of current. The effect of a given e. m. f. of self-induction in impeding the flow of current is equivalent to a certain number of ohms resistance which would have exactly the same effect. This effect of self-induction in impeding the flow of current is known as *inductive reactance.* It is represented by the symbol X_L and is measured in ohms exactly like resistance. The symbol X is the general symbol for reactance. The subscript L indicates that the reactance is that caused by an inductance. As we shall see later reactance caused by a capacitance is represented by the symbol X_c.

While in one sense reactance is like resistance, in that it opposes the flow of current, it is different in other respects. The *ohmic* resistance of a wire depends only on its material, length, area and temperature. A given wire has the same resistance whether it is straight or coiled up. The *reactance* of a wire increases if it is coiled up, and also increases if a good magnetic path through iron or steel is provided for its magnetic field. At low frequencies the *ohmic* resistance is independent of the frequency. The *reactance* increases directly as the frequency is increased, for then the magnetic field around the conductor varies a greater number of times per second and the wires are cut by it more frequently. The mathematical expression for the inductive reactance of a circuit is:

$$X_L = 2\pi\ f\ L \qquad (16)$$

in which X_L is the reactance in ohms, π is a constant equal to 3.1416 (called "pi"), f is the frequency in cycles per second, and L is the inductance in henries. Stated in words, the inductive reactance equals 2π times the frequency times the inductance in henries. The mathematical derivation of this formula as well as that for capacitive reactance will not be given here. If the reader is interested in studying it, he will find it in almost any text on electrical engineering.

Very often it is necessary to quickly find the reactance of some particular inductor at some frequency. For this reason, the following table of reactances of inductance coils between 0.01 and 100 henries at frequencies from 60 to 100,000 cycles is given for convenience, since it eliminates the need for the calculation.

INDUCTIVE REACTANCES

Coil Inductance in Henries	Reactance in Ohms at Various Frequencies (Cycles)						
	60	100	250	500	1000	10,000	100,000
0.01	3.7	6.28	15.7	31.4	62.8	628	6,280
0.05	18.8	31.4	78.5	157	314	3,140	31,400
0.1	37.7	62.8	157	314	628	6,280	62,800
0.5	188.5	314	785	1,570	3,140	31,400	314,000
1.0	377	628	1,570	3,140	6,280	62,800	628,000
2.0	754	1,256	3,140	6,280	12,560	125,600	1,256,000
5.0	1855	3,140	7,850	15,700	31,400	314,000	3,140,000
10.0	3,700	6,280	15,700	31,400	62,800	628,000	6,280,000
20.0	7,540	12,560	31,400	62,800	123,600	1,236,000	12,360.000
30.0	11,310	18,840	47,200	94,200	188,400	1,884,000	18,840,000
40.0	15,080	25,120	61,800	123,600	247,200	2,472,000	24,720,000
50.0	18,850	31.400	88,500	157,000	314,000	3,140,000	31,400.000
100.0	37,700	62,800	157,000	314,000	628,000	6,280,000	62,800,000

Note: 1 Henry=1,000,000 microhenries. 1 Kilocycle=1,000 cycles.

Note on Use of Above Table: From Formula No. 16, it is evident that the reactance of a coil is directly proportional to the inductance of the coil and also directly proportional to the frequency. Doubling the inductance of the coil gives twice the reactance, and twice the reactance is also obtained if the frequency is doubled. Also, halving the inductance gives half the reactance, etc. If these factors are remembered it is a simple matter to calculate mentally, the reactance of any coil not given in the table.

For example a 10 henry coil has one-sixth the reactance of a 60-henry coil at say, 100 cycles. Since the reactance of a 10-henry coil at 100 cycles is 6280 ohms, it follows that the reactance of a 60-henry coil at the same frequency must be 6×6280, or 37,680 ohms.

The calculation of inductive reactance may be illustrated by the following example:

Example: What is the reactance of a 30 henry filter choke coil at 60 cycles, neglecting its resistance? At 120 cycles?

Solution: $X_L = 2\pi f L$. At 60 cycles, $X_L = 2 \times 3.1416 \times 60 \times 30 = 11{,}310$ ohms. Ans at 120 cycles, $X_L = 2 \times 3.1416 \times 120 \times 30 = 22{,}620$ ohms. Ans.

Note: It should be remembered that L in the above formula must be expressed in henries. The microhenry is so often used in practical work that one often forgets to change microhenries to henries when using this formula.

Notice that the reactance or opposition to current flow is twice as much at 120 cycles as it is at 60 cycles. Notice also how much an inductor of only 30 henries opposes the flow of current. At 60 cycles it opposes it just as much as a pure resistor of 11,310 ohms would, and at 120 cycles, it opposes it as much as a resistor of 22,620 ohms would.

162. Phase displacement: If we refer to Fig. 66, we see that the e. m. f. varies according to the angle through which the armature coil in the alternating current generator has turned. The e. m. f. passes through various "phases" corresponding to the various angles. The current also passes through "phases" just as the e. m. f. does. The term "phase" whether applied to voltage or current refers to the position in the alternating cycle. If there is only resistance in a circuit, the current is zero at the instant that the e. m. f. is zero; it is maximum at the instant that the e. m. f. is maximum, etc., that is, it goes through its successive variations in *value* and *direction* in step with those of the applied e. m. f. The current is then said to be *in phase* with the e. m. f.

When there is self-induction in the circuit, the current variations do not keep in step, or in phase, with those of the e. m. f. In a pure inductive circuit, the current *variations* are 90 electrical degrees out of phase with those of the applied e. m. f., as shown at the right of Fig. 105. Likewise, there is a difference in phase of 180 electrical degrees between the *applied* e. m. f. and the *self-induced* e. m. f. variations.

The case of a pure inductance thus far considered, is really an ideal case impossible to attain in practice, for it is impossible to have a circuit with zero resistance. It is closely approached however in certain inductor or choke coils, and certain transformer windings in which the resistance is very low and the inductance is very high due to the use of a fairly large number of turns of wire and a well designed magnetic core.

163. Inductive reactance triangle: In practical circuits in which there exists not only inductance but resistance also, it is necessary to know not only how to calculate inductive reactances but also how to combine reactance with resistance. The combined effect of all the reactance and all the resistance in a circuit is called the *impedance*. This is represented by the symbol Z. The *impedance* is the *total* opposition offered to the flow of current in an alternating current circuit by both the actual ohmic resistance, and the *reactance*—the "reactance" being the "opposition" due to the counter-e. m. f. of self-induction (or to the "capacity," as we shall see later). The applied alternating e. m. f. has to send the current or electrons through the circuit against the opposition of this *impedance* of the circuit.

The impedance in ohms of any alternating current circuit is expressed by the formula:

$$\text{Impedance} = \sqrt{\text{resistance}^2 + \text{reactance}^2}$$

If the circuit contains resistance and inductance only (no capacitance) this may be expressed as

$$Z = \sqrt{R^2 + X_L^2} \text{ or } Z = \sqrt{R^2 + (2\pi\ f\ L)^2}$$

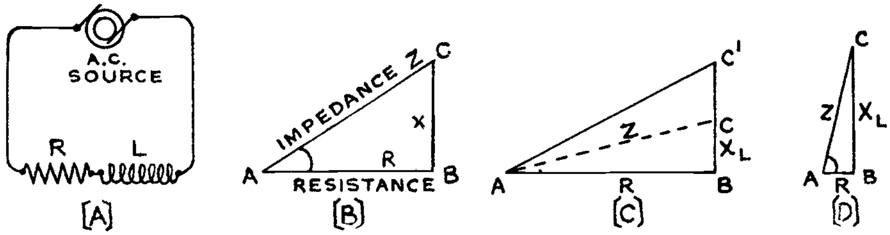


Fig. 106—Vector relations of resistance, reactance and impedance in an inductive circuit.

Example: What is the impedance of the choke coil of the Example in Art. 161 at 60 cycles, if the ohmic resistance of the wire of which it is wound is 25 ohms?

Solution: $Z = \sqrt{R^2 + (2\pi f L)^2} = \sqrt{25^2 + (2 \times 3.1416 \times 60 \times 30)^2} = 11{,}310$ ohms. Ans.

Example: A coil has a resistance of 30 ohms and an inductive reactance of 40 ohms. What is its total opposition (impedance) to alternating current flow?

Solution: The impedance is not 30 ohms + 40 ohms as one would suppose off-hand, but is equal to $\sqrt{30^2 + 40^2}$ or 50 ohms. Ans.

The relations expressed by the above formula may be represented by the right-angled triangle ABC shown at (B) of Fig. 106. At (A) is shown the circuit condition of a resistor connected in series with an inductor. In (B) the true ohmic resistance R is laid off to a convenient scale to form the base line; the reactance X is laid off also in ohms to form the perpendicular; and the impedance in ohms is found by measuring the hypotenuse of the triangle (to scale), since the hypotenuse of any right-angle triangle is equal to the square root of the sum of the squares of the other two sides. This is merely a mathematical coincidence however, resulting from the sine-curve variations of alternating e. m. f.'s and currents. Such a triangle is very frequently used to represent the relations between resistance, reactance, and impedance and also for convenience in obtaining other quantities. It is called a *vector diagram.* Another way of looking at this, is that since the voltage drop across the resistance is in phase with the current, and the e. m. f. of self-induction is 90 degrees out of phase with the current, resistance and reactance are really like two forces at right angles to each other, and the common principle of the parallelogram of forces which is applied for solving problems involving forces in mechanics, can be applied to them.

When the inductive reactance is small compared with the resistance, as shown at (C), it has very little effect. The line B C is short compared with AB, and the impedance line AC is not much larger than the resistance AB. If the resistance is kept the same and the reactance is doubled, or BC^1 equals $2 \times BC$, the impedance AC^1 is very much increased over its former value AC. When the reactance is very large compared to the ohmic resistance, as shown at (D), the impedance AC is very much greater than the resistance AB. This important fact should be remembered for it is one of the reasons for making the inductance and inductive reactance of a tuned circuit as large as practical in order to obtain high gain.

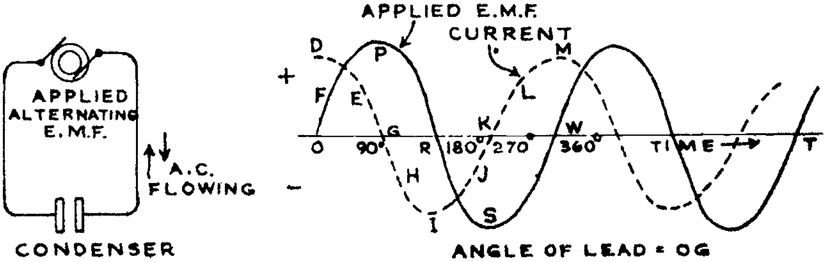


Fig. 107—Effect of capacitance on the phase relations between current and applied voltage in an alternating current circuit.

In inductors where the inductance is very large compared to the ohmic resistance, the resistance may often be entirely neglected, and the total impedance of the coil may be considered as being due wholly to its inductive reactance. If the frequency is doubled in such cases, the reactance is also doubled and the current at the same applied e. m. f. is reduced to one-half.

164. Capacitance in a-c circuits: When a condenser is connected in an alternating current circuit as shown at the left of Fig. 107, a periodic transfer of electrons takes place from one plate around through the circuit toward the other plate and back again many times every second. This gives rise to a flow of alternating current in the external circuit. We have already studied the actions of condensers in detail in Figs. 83 and 84, but it is important to consider at this point, the phase relations between the variations in the applied e. m. f. and those in the current in a condenser circuit. This can be understood best by considering the action of the electrons.

165. Current lead in capacitive circuit: Consider the condenser connected to a source of alternating e. m. f. as shown at the left of Fig. 107. Let the sine-wave applied e. m. f. be represented as shown at the right. We will assume that the condenser has no ohmic resistance. At O the e. m. f. starts from zero and rises rapidly along OF, and drives electrons out of one set of plates (which become positively charged due to lack of electrons) around through the external circuit into the other set of plates (which become negatively charged due to excess of electrons). During this time a strong flow of electrons (current flow) takes place because there is nothing to oppose them. Now the e. m. f. approaches its maximum value at P. A large number of electrons have accumulated on the negative plate and have built up a negative charge which repels those that are now being forced in. Although the e. m. f. is near its maximum value, electrons cannot flow into the plate so rapidly as before because the negative charge caused by the accumulation of the electrons already there, is now almost equal to the applied e. m. f. This means that the electron or current flow becomes less as the applied e. m. f. approaches its maximum value. During this time the current or electron flow is therefore represented by the part of the current curve between D-E-G. As the applied e. m. f. decreases from P to R, the electrons begin to flow around in the opposite direction from the negatively charged plate to the positively charged plate against the applied e. m. f. which is still in the same direction as before. This gives rise to a current flow in the opposite direction as represented by part G-H-I of the current curve. After the applied e. m. f. passes through zero at R and reverses in direction from R to S, it begins to charge the condenser in the opposite direction and so the electrons and current continue to flow in the same direction as before, as shown from I to J to K. When the e. m. f. decreases toward zero again at W, the plate which is now negative begins to discharge electrons around the circuit to the positive plate. Hence the current is flowing in the opposite direction along K-L-M. This action repeats itself over and over for each cycle of the applied alternating e. m. f.

It will be seen from this that in a purely condensive circuit (no resistance and no inductance), when once the action starts, the current or rate of flow of electrons is greatest when the applied e. m. f. is near the zero value, and dies down to zero as the e. m. f. approaches the maximum. In other words, the current variations lead the e. m. f. variations by 90 electrical degrees. This is shown in Fig. 107, by the fact that whereas the current has already completed a quarter cycle at M, the e. m. f. is just beginning a cycle at the corresponding point W, i.e., the variations in the current occur one quarter of a cycle *ahead* of the corresponding variations in the applied e. m. f.

166. Capacitive reactance: It is evident from our study of the action of a condenser in an alternating current circuit, that the greater the capacitance of a condenser, the more electrons will be transferred around through the external circuit from one set of plates toward the other during each charge and discharge, and consequently the larger will be the current in the external circuit. In other words the greater the capacitance the less the opposition or *capacitive reactance* to flow of electrons or current. Also the more rapidly the applied e. m. f. changes, the greater is the total flow of electrons around through the circuit in one second. In other words, the greater the frequency, the stronger the current and therefore the less the reactance. In all of these respects, capacitive reactance acts in a manner just opposite to that of inductive reactance. It is important to remember the opposite effects of inductive reactance and capacitive reactance.

If we let X_C represent the capacitive reactance in ohms, C the capacitance in farads, and f the frequency in cycles per second, then

$$X_C = \frac{1}{2\pi f C} \qquad (17)$$

Calculation of capacitive reactance may be illustrated by the following problem:

Problem: What is the reactance offered by a 2 mf. condenser when connected in a circuit to which a 60 cycle e. m. f. is applied? What is the reactance if the frequency of the e. m. f. is 500,000 cycles?

Solution: At 60 cycles $X_c = \frac{1}{2\pi f C} = \frac{1}{2 \times 3.1416 \times 60 \times .000002} = 1{,}327$ ohms.

At 500,000 cycles $X_c = \frac{1}{2 \times 3.1416 \times 500{,}000 \times .000002} = 0.16$ ohms. Ans.

Note: It should be remembered when working problems involving capacitive reactance, that C in formula (17) must be expressed in farads. Thus in the foregoing problem 2 mf. = .000002 farads. The microfarad is so commonly used to express capacitances in practical work that one often forgets to change microfarads to farads when using this formula.

It is evident from the above example that a given condenser offers much less reactance or opposition to the flow of currents of high frequency than to currents of low frequency. This is to be expected of course since at the high frequencies the plates are being more frequently charged and discharged, resulting in a greater total flow of electrons around the circuit

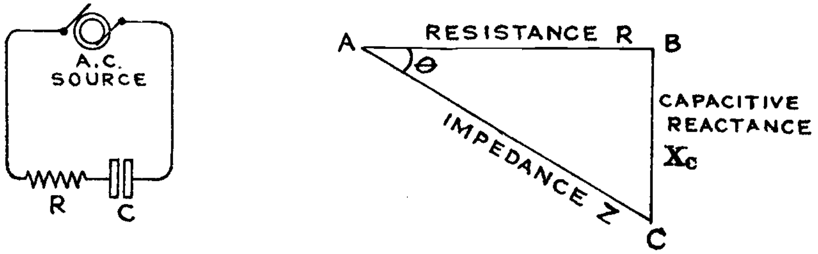


Fig. 108—Vector relations of resistance, capacitive reactance and impedance in an a-c circuit containing resistance and capacitance.

each second and hence a greater current. This means it has less reactance. This is particularly important in filters used in telephone and radio circuits where condensers are used to by-pass currents of high frequencies due to the low reactance offered, and choke back currents of low frequencies due to the higher reactance offered. Specific cases of the uses of condensers for these purposes will be studied later at the proper places.

As the calculation of capacitive reactance is rather tedious due to the large numbers involved, the following table of capacitive reactances is published below for convenience by courtesy of the editors of the Aerovox Research Worker in which it first appeared.

REACTANCES OF CONDENSERS OF STANDARD CAPACITANCES AT COMMONLY USED FREQUENCIES

CAP. IN MFDS	FREQUENCY IN CYCLES PER SECOND						
	Broadcast Radio Frequencies		Audio Frequencies		Power Supply Frequencies		
	500,000	1,500,000	50	10,000	25*	60	120
	CAPACITIVE REACTANCE IN OHMS						
.00005	6,369.4	2,123.1	63,694.267	318,471	127,388,534	53,078,503	26,539,252
.0001	3,184.7	1,061.6	31,847,133	159,235	63,694,267	26,539,252	13,269,626
.00025	1,273.8	424.6	12,738,853	63,694	25,477,706	10,615,600	5,307,850
.0005	636.9	212.3	6,369.426	31,847	12,738,853	5,307,850	2,653,925
.001	318.5	106.2	3,184,713	15,924	6,369,427	2,653,925	1,326,963
.005	63.7	21.2	636,943	3,185	1,273,885	530,785	265,393
.01	31.8	10.6	318,471	1,592	636,943	265,393	132,696
.015	21.2	7.1	212,314	1,061	424,629	176,929	88,464
.02	15.9	5.3	159,235	796	318,471	132,697	66,348
.05	6.4	2.1	63,694	318	127,389	53,078	26.539
.1	3.2	1.1	31,847	159	63,694	26,539	13,270
.25	1.28	.42	12,739	64	25,478	10,616	5,308
.5	.64	.21	6,369	32	12,739	5,308	2,654
1.0	.32	.11	3,184	15.9	6,369	2,654	1,327
2.0	.16	.05	1.592	7.9	3,184	1,327	668
4.0	.08	.03	796	3.9	1,592	664	332
6.0	.05	.02	531	2.6	1,062	442	221
8.0	.04	.01	398	2.0	796	332	166
10.0	.03	.01	318	1.6	637	265	133
15.0	.02	.01	212	1.1	425	177	88

*Full wave rectification of 25-cycle current is equivalent to 50-cycle column under "Audio Frequencies".

Half wave rectification of 25-cycle should never be used because of hum.

Note on use of above table: Examination of formula (17) shows that the reactance of a condenser is inversely proportional to the frequency and the capacitance. Doubling the capacitance of the condenser gives one-half the reactance. If these two factors are remembered it is an easy matter to calculate mentally, the reactance of almost any capacitance not given in the table, and at almost any frequency.

For example a 20 mf. condenser has one-half the reactance of a 10 mf. condenser, at say 50 cycles. Since the reactance of a 10 mf. condenser at 50 cycles is found from the above table to be 318 ohms, it follows that the reactance of a 20 mf. condenser at the same frequency would be $318 \div 2$ or 159 ohms.

Likewise the reactance of a 2 mf. condenser at 10,000 cycles is 7.9. Therefore the reactance at 100 cycles (not on the table) would be 7.9×100 or 790 ohms.

167. Capacitive reactance vector relation: In practical circuits in which there exists not only capacitance but resistance also, it is necessary not only to know how to calculate the capacitive reactance but also how to combine it with the resistance. The impedance in ohms of a circuit containing a capacitance and resistance may be expressed as:

$$Z = \sqrt{R^2 + X_C^2} \text{ or } Z = \sqrt{R^2 + \left(\frac{1}{2\pi f C}\right)^2}$$

Since capacitive reactance is 90 degrees out of phase with the current, and resistance is in phase with the current, there is a difference of phase of 90 degrees between them as shown in the vector diagram at the right of Fig. 108. It is customary to draw the line representing capacitive reactance below the resistance line as shown, because in circuits containing both inductance and capacitance, the inductive reactance line is drawn above the resistance line as shown in Fig. 109, since the effects of both, on

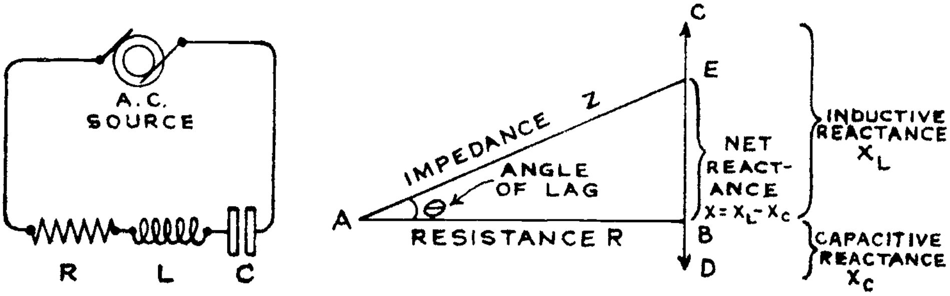


Fig. 109—Vector relations of resistance, capacitive reactance, inductive reactance, and impedance in an a-c circuit.

the e. m. f. and current in the circuit, are directly opposite. The impedance is represented by the hypotenuse A-E of the triangle, (to scale).

168. Circuits having inductance, capacitance and resistance: When a circuit contains inductance, capacitance and resistance, the net reactance, X, is equal to the arithmetical difference between the inductive reactance X_L and the capacitive reactance X_C or $X = X_L - X_C$. In any case the smaller reactance is subtracted from the larger one, and the net reactance has the characteristics of the larger one. Therefore the net impedance of a circuit containing inductance, capacitance and resistance, is equal to

$$Z = \sqrt{R^2 + X^2} = \sqrt{R^2 + (X_L - X_C)^2}$$

$$\text{or } Z = \sqrt{R^2 + \left(2\pi f L - \frac{1}{2\pi f C}\right)^2} \quad \text{..........} (18)$$

Example: What would be the combined impedance of a circuit having a coil of 5 ohms resistance and 10 henries inductance, in series with a condenser of 50 microfarads capacitance, to an alternating current of 1,000 cycles?

Solution: By formula (16) $X_L = 2\pi f L = 2 \times 3.1416 \times 1000 \times 10 = 62{,}832$ ohms.

By formula (17) $X_c = \frac{1}{2\pi f C} = \frac{1}{2 \times 3.1416 \times 1000 \times .00005} = 3.2$ ohms.

By formula (18) $Z = \sqrt{R^2 + (X_L - X_c)^2} = \sqrt{5^2 + (62{,}832 - 3.2)^2} = 62{,}839$ ohms. Ans.

When a circuit contains both inductance and capacitance, the difference between the lengths of the lines representing the inductive and capacitive reactances will represent the resultant or net reactance, X, of the circuit as shown at the right of Fig. 109. Here the capacitive reactance (Xc) line BD, is drawn below the resistance line AB, one fourth as great as the inductive reactance (X_L) line BC which is drawn above the resistance line. Since the inductive reactance predominates, the current will lag the voltage. The net reactance is represented by BE and is equal to X_L—Xc. The impedance line is drawn from the left hand end of the resistance line to the E point three fourths up on the inductive reactance.

In the diagrams such as those of Figs. 106, 108, and 109, the angle of lag between the current and the e. m. f. in the circuit is the angle BAC formed by the impedance line and the resistance line. Its value may be calculated from the other known factors in the triangle by means of trigonometry. If the vector diagrams are drawn as shown, and the angle comes out above the resistance line, as in Figs. 106 and 109, it indicates that it is an angle of lag, i.e., the current variations in the circuit lag behind the e. m. f. variations by that part of a cycle. This condition is represented by the e. m. f. and current curves in (A) of Fig. 110. If the angle comes out below the resistance line as in Fig. 108, it is an angle of lead, i.e., the current variations lead those of the applied e. m. f. This condition is represented by the e. m. f. and current curves in (B) of Fig. 110.

It is obvious from a consideration of Fig. 109, that when the values of inductance and capacitance in a circuit happen to be such as to make X_L and Xc equal, the difference between them is zero, making the impedance Z equal to $\sqrt{R^2}$ which is simply equal to R. Under these conditions, the circuit operates as though there were neither inductance or capacitance

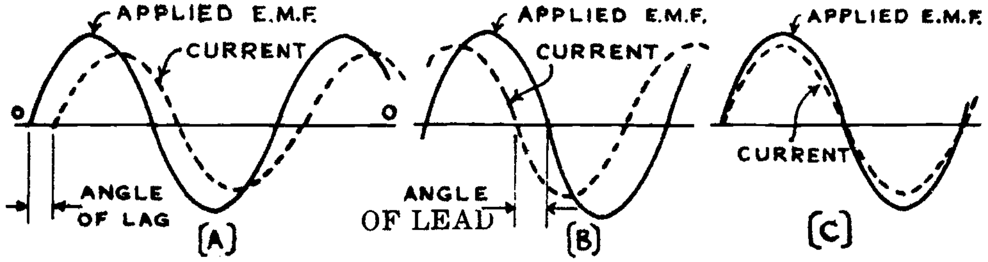


Fig. 110—Voltage and current waves for three conditions in an A-C circuit.
(A) inductive circuit; current variations lagging e.m.f. variations.
(B) capacitive circuit; current variations leading e.m.f. variations.
(C) resistive circuit; current and e.m.f. variations are in phase.

present, the current rising and falling in unison or *in phase* with the applied e. m. . This condition is also represented by the e. m. f. and current curves of (C) in Fig. 110. Referring to Fig. 109, if the lines X_L and Xc were of equal length, their difference would be zero, and the impedance line would be identical with the resistance line. Such a circuit is said to be in *resonance* or *tuned* with the impressed alternating e. m. f. As we shall see later, since at resonance the total opposition to the current flow is simply equal to the resistance of the circuit, the maximum amount of current flows through the tuned circuit. The principle of resonance is one of the most important things in radio work for it is the foundation of all tuning in radio transmitters and receivers. This will be discussed in detail later.

169. Ohm's Law for alternating currents: The total opposition to current flow in alternating current circuits is called the *impedance* (Z). We found, when dealing with direct current circuits, that the relation existing between current strength, applied e. m. f., and resistance was fully explained by Ohm's law and the relation $I=E \div R$. This law also applies to alternating current circuits, but instead of dividing by the resistance R of the circuit we must divide by the total opposition or *impedance* Z, of the circuit. Thus for alternating current circuits we have:

$$I=\frac{E}{Z};\ E=IZ \text{ or } Z=\frac{E}{I}$$

Substituting the value of Z as given in equation (18), in the above, we obtain:

$$I=\frac{E}{\sqrt{R^2+\left(2\pi f L-\frac{1}{2\pi f C}\right)^2}} \quad \text{(19)}$$

This general modification of Ohm's law applies to alternating currents flowing in any circuit. From this equation any one of the values may be found if all of the others are known. If the circuit contains inductance only, the expressions for resistance and capacitive reactance in the denominator drop out, etc.

Example: The primary coil of a certain power transformer has a resistance of 5 ohms and an inductance of 10 henries. What current will flow through this coil if it is connected to a 110 volt 60 cycle circuit.

Solution: $I=\frac{E}{Z}=\frac{E}{\sqrt{R^2+(2\pi f L)^2}}=\frac{110}{\sqrt{5^2+(2\times 3.1416\times 60\times 10)^2}}=.03$ amps. Ans.

Example: What current will flow through an a. c. circuit having an e. m. f. of 110 volts, a resistance of 4 ohms, an inductive reactance of 100 ohms, and a capacitive reactance of 120 ohms? Will the current lead or lag the applied e. m. f.?

Solution: $I=\frac{E}{\sqrt{R^2+(X_c-X_L)^2}}=\frac{110}{\sqrt{4^2+(120-100)^2}}=\frac{110}{20.4}=5.4$ Amperes. Ans.

The current will lead the voltage since the capacitive reactance is largest and therefore the circuit acts as a capacitive circuit.

170. Impedances in series and parallel: When several inductive or capacitive devices are connected in series in an alternating current circuit, the total impedance of the group cannot be determined by simply adding the individual impedances *arithmetically* since this does not take into account the various phase displacements produced. Instead, the impedance of each device must be resolved into its component resistance and reactance, and these are then added separately remembering that the net reactance is equal to the total capacitive reactance subtracted from the total inductive reactance or vice versa. This may be expressed by the following:

$$Z=\sqrt{(R_1+R_2+\text{etc.})^2+(X_{L1}+X_{L2}+\text{etc.}-X_{C1}-X_{C2}-\text{etc.})^2}$$

In a parallel circuit, the current in each branch is found from the applied voltage and the impedance of the branch. To find the resultant current, the currents in the various branches must be combined vectorially with proper regard to their phase relations.

171. Power in a-c circuits: In direct current circuits, the power expended is given by the product of the applied e. m. f. and the current. Thus if an application of 110 volts to a circuit produces a current flow of 5 amperes, the power used is 110×5 or 550 watts. In an a-c circuit containing resistance only, the e. m. f. and current are in phase at every instant and the power in watts is also equal to $E\times I$. When inductance or capacitance are in the circuit, the current lags or leads respectively the applied e. m. f., the current being at times positive when the e. m. f. is negative as shown in Fig. 110. Hence under these conditions the actual true power is less than that given by $E \times I$. When the reactance is very great compared to the resistance, the current is 90° out of phase with the e. m. f. (Figs. 105 and 107) and the actual or true power taken from the line is zero. This is called a *wattless current.* In circuits of this kind, the energy is stored in the device, (either in the form of a magnetic or an electrostatic field), during one part of the cycle, and is returned back to the line during the next part, so that the net power taken from the line is zero.

The electrical power in a circuit at any instant is equal to the product of the instantaneous current and the instantaneous e. m. f. existing at the time. Thus at (A) of Fig. 111, the voltage and current waves for a circuit containing pure resistance are plotted. They are in phase with each other. If we select some instant represented by F on the horizontal or time axis, the power in the circuit at that instant is equal to the height FG of the e. m. f. curve above the axis line at that instant, multiplied by the height FH of the current curve above the axis line at that instant. This power may be represented by point J. If the instantaneous powers at various instants during the cycle are found in this way and plotted we will have the power curve throughout the cycle as shown. The *total* power is represented by the total area of the shaded portions of the curve. Notice that the power curve lies wholly above the axis line, for during the second alternation both the e. m. f. and the current are negative (—). The result of multiplying two negative quantities together gives a positive quantity. All of the power represented by the shaded area is used up to produce heat in the resistor. Looking at this from the physical point of view it means that the power expended in the circuit when the current and voltage are in one direction, is just as much as when they are both in the opposite direction.

When the current and voltage variations are not exactly 90 degrees out of phase, as is the case in an inductive circuit containing some resistance, (B) of Fig. 111, or a capacitive circuit containing some resistance, (A) of Fig. 112, a different power-curve results, although the power at any one instant is still equal to the product of the instantaneous values of current and voltage.

The power curves for the inductive and condensive circuits have been drawn for the same values of e. m. f. and current as that of the pure resistive circuit. The part of the power curve below the axis line is the result of multiplying a positive current by negative instantaneous values of voltage or vice versa. The product is negative; so that the power at that instant must be considered as a negative power. This means that during these intervals, the reactive device was returning power to the line. The power consumed in the device is considered as positive power. A pure resistive circuit consumes all of the power fed to it by the generator. A reactive circuit returns a part of it to the generator. In the case of an inductance, power is returned to the line when the current is falling to zero and the magnetic field collapses. In a condensive circuit power is returned to the line when the applied e. m. f. falls to zero and the negative condenser plates begin to discharge the excessive negative electrons back around through the circuit to the positive plates. Notice that in the case of the inductive and capacitive circuits, the total useful or effective power supplied to the circuit, (represented by the shaded area above the axis

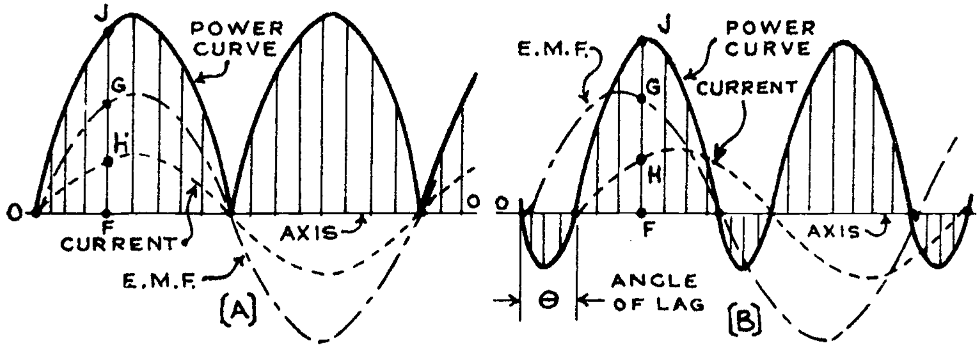


Fig. 111—Curves of e.m.f., current, and power in a circuit containing (a) resistance alone (b) inductance and some resistance.

minus that below the axis), is less than in the case of a similar circuit with pure resistance.

The *true power* in a resistive circuit is equal to the product of the effective volts and effective amperes. In a reactive circuit, the effective power as found by simply multiplying volts times amperes, is reduced by the power returned by the device to the generator, so that the product of effective volts times effective amperes does not give the *true power* but gives what is known as the *apparent power*. The true power is given by:

$$P = E \times I \times \cos \theta$$

Where θ is the angle of lag or lead between the e. m. f. and current variations, and cos θ is the trigonometric cosine function of this angle. The angle θ is represented in the vector diagrams shown in (B) and (C) of Fig. 112. Diagram (B) represents the case of an inductive circuit and that at (C) represents the case of a condensive circuit.

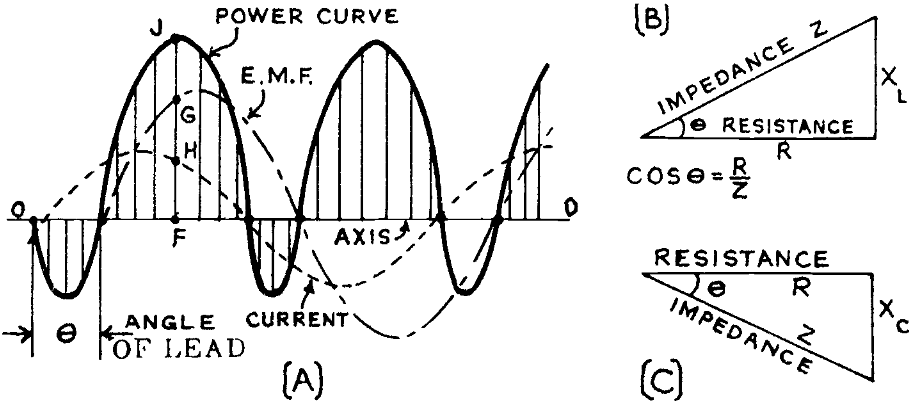


Fig. 112—(a) Curves of e.m.f., current, and power in a circuit containing capacitance and some resistance. (b) Vector diagram showing angle of lag in an inductive circuit. (c) Vector diagram showing angle of lead in a condensive circuit.

By trigonometry in either case, Cos θ is equal to the base divided by the hypotenuse, or

$$\cos \theta = \frac{\text{Resistance}}{\text{Impedance}} = \frac{R}{Z}$$

Therefore: $\text{True Power} = \text{Apparent Power} \times \dfrac{\text{Resistance}}{\text{Impedance}}$

Example: A voltmeter connected across a coil in an a-c circuit reads 110 volts and an ammeter indicates that a current of 10 amperes is flowing through the coil. The angle of lag is 30°, the corresponding Cos θ being equal to 0.866. How many watts of power are being consumed by the coil from the line?

Solution: $P = E \times I \times \cos \theta = 110 \times 10 \times .866 = 952.6$ Watts. Ans.

Example: What is the true power in a coil having a resistance of 200 ohms, a reactance of 100 ohms and an e. m. f. of 110 volts applied to its terminals?

Solution: Impedance, $Z = \sqrt{R^2 + X^2} = \sqrt{200^2 + 100^2} = 223.6$ ohms.

Current, $I = \dfrac{E}{Z} = \dfrac{110}{223.6} = 0.49$ amperes.

$$\text{Power factor, Cos } \theta = \frac{R}{Z} = \frac{200}{223.6} = 0.89$$

$$\text{Power, } P = E \times I \times \text{Cos } \theta = 110 \times 0.49 \times 0.89 = 48 \text{ Watts (approximately). Ans.}$$

The product of the volts and amperes is called the *apparent power.* Since this apparent power must be multiplied by Cos θ to find the *true* or *actual power,* this factor is called the *power factor* of the circuit. When the current and voltage are in phase (resistive circuit), the power factor is equal to 1.0. This is the maximum value it can have, and the circuit is said to have *unity power factor.* If inductance, or capacitance are present, the power factor will be less than 1.

When electrical power is measured by means of the electrical instrument called the "wattmeter", the true power is obtained directly. When power is measured by means of an ammeter and voltmeter in the circuit the product of $E \times I$ gives the apparent watts. This must be multiplied by the power factor, (Cos θ) to obtain the true watts.

172. Resonance: It was mentioned in Article 168 that if the values of inductance and capacitance in an a-c circuit are such that the inductive reactance is equal to the capacitive reactance, then $X_L - X_C = O$ and the formula for impedance becomes:

$$Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{R^2 + O^2} = R.$$

This is the condition of *resonance.* At resonance the total opposition to the current flow is simply equal to the resistance of the circuit, and the maximum current therefore flows through it. At resonance there is neither lag nor lead. The phenomenon of resonance may be illustrated very simply by the following experiment:

Experiment: Connect a 10 or 15 microfarad condenser, a low-resistance variable inductor of at least 0.5 henry, and an incandescent lamp bulb all in series across a 110 volt 60 cycle alternating current electric light line as shown at (A) of Fig. 113. For the condenser, several ordinary 1 or 2 mfd. filter condensers of the type commonly used in radio receivers, may be connected in parallel. For the inductance coil, wind from 750 to 1,000 turns of No. 18 double cotton covered wire on a cardboard tube 3 inches in diameter and about 12 inches long. A core of soft iron or silicon steel which just fits the tube is also used.

When either the inductance coil or the condenser are short-circuited out of the circuit by connecting a short piece of wire across their terminals, the lamp gets brighter showing that both the inductive reactance and the capacitive reactance have been reducing the current. Now with the short-circuiting wire removed, slowly vary the inductance of the coil by moving the iron core in or out of the coil. At a certain position of the iron core the inductance will be such that the lamp will glow brightly, showing that the inductive reactance of the coil and the capacitive reactance of the condenser are equal and neutralizing each other as shown at (B) of Fig. 113, so that the current flowing is determined only by the total ohmic resistance of the coil, lamp and condenser. If it is possible to change the frequency at this time, the lamp will grow dim, showing that resonance exists for this particular value of inductance and capacitance only at one particular frequency. If now the inductance is varied again by adjusting the iron core, the circuit may be brought to resonance at the new frequency.

The foregoing experiment illustrates the application of series electrical resonance in a circuit to adjust it for maximum current when a constant e. m. f. is applied. It is evident that the circuit could be brought to resonance for a given frequency either by varying the inductance or the capacitance or both. The process of making this adjustment is called *tuning.* In radio receivers the radio frequency amplifier stages are tuned to the frequency of the incoming voltage impulses of the station it is desired to hear, by turning the tuning knob or dial. This turns the rotor plates of the variable tuning condensers (see Figs. 86, 100 and 101) so as to adjust the capacitance to the proper value. The inductance is usually made fixed, although some receivers have been marketed in which the tuning capacitance was fixed and the tuning inductance was variable.

173. Series resonance: In a series circuit, resonance occurs when the inductive reactance is equal to the capacitive reactance, and the only

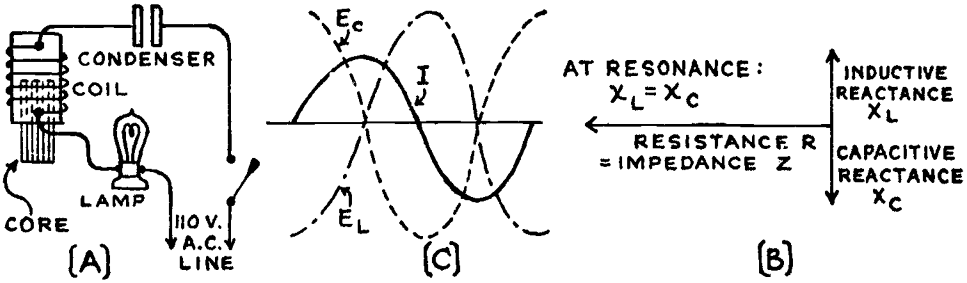


Fig. 113—Effects of resonance in a series circuit.

opposition to the current flow is then the ohmic resistance as shown at (B) of Fig. 113. We then have the condition:

$$X_L = X_C$$

Since $X_L = 2\pi f L$ and $X_C = \frac{1}{2\pi f C}$, substituting these values in the above equation gives

$$2\pi f L = \frac{1}{2\pi f C}$$

multiplying both sides by f we obtain

$$2\pi f^2 L = \frac{1}{2\pi C}$$

dividing both sides through by 2π L gives.

$$f^2 = \frac{1}{4\pi^2 L C}$$

taking the square root of both sides of this equation we obtain

$$f = \frac{1}{2\pi \sqrt{L C}} \quad \text{............} (20)$$

in which f=frequency in cycles per second at resonance.
L=inductance in henries at resonance.
C=capacitance in farads at resonance.

This is one of the most important equations in radio work, for from it are derived the equations used in calculating all tuned circuits, filters, wavemeters, oscillators, etc.

If L is expressed in microhenries and C is in microfarads, equation (20) may be written as

$$f=\frac{159{,}000}{\sqrt{L\ (\text{microhenries}) \times C\ (\text{microfarads})}}$$

In Fig. 113 a current I flows in a circuit consisting of a coil and condenser in series. The counter e. m. f. E_L built up by the inductive action is maximum when current is changing at a maximum rate, for it is then that the magnetic field produced by the windings is changing at the greatest rate. When the current is maximum, this voltage is at zero, for then there is no change in flux, but when the current starts to decrease, this counter-voltage increases from zero, in the same direction as that of a voltage in phase with the current, for the magnetic field is collapsing and tending to keep the current flowing in the same direction.

The counter-voltage built up by the condenser when current I flows through the circuit (charging and discharging the condenser), is shown by Ec. This counter-voltage is maximum when the current is zero, for then the negative plate of the condenser has its maximum number of electrons and its charge is maximum; and is zero when the current is maximum. When the current starts to decrease to zero, this counter-voltage increases from zero, but this time it is in a direction opposite to the line voltage, for the condenser is now charging.

It can be seen that these counter-voltages are opposite in sign (direction in which they would cause a current to travel) at all times, and, if they are of equal magnitude, they will neutralize each other. Thus, if resistance were not present, there would be nothing to block the passage of current through this circuit, so that for even a small impressed voltage the current would be infinite, no matter what size the condensive and inductive elements were, as long as the capacitive reactance was equal to the inductive reactance (dielectric and hysteresis losses neglected).

Looking at the condition of resonance from the physical point of view we can see that at resonance the frequency, capacitance and inductance are all of such values that the time required to charge and discharge the condenser, and that required to build up current and let it die down in the inductor are exactly equal and are timed with each other so that there is a maximum continuous exchange of energy between the collapsing magnetic field of the inductor and the consequent charging of the condenser; the discharging of the condenser and consequent building up of the magnetic field in the inductor. At resonance these impulses are timed exactly so that while the condenser is discharging, the field in the inductor is building up; and while the field is dying down the condenser is being charged so they help each other. At any other frequency they would not take place exactly in step with each other, and so some opposition between the two would result at intervals. Therefore, less current would flow.

174. Voltage relations in a series tuned circuit: Fig. 114 shows a common tuning arrangement employed in radio receivers. We will assume that the passing radio waves from some station cut across the antenna, and induce a voltage in it of a frequency of say 500,000 cycles per second. This voltage sends an alternating current through the circuit which consists of the antenna, the primary P of the radio-frequency coupling coil

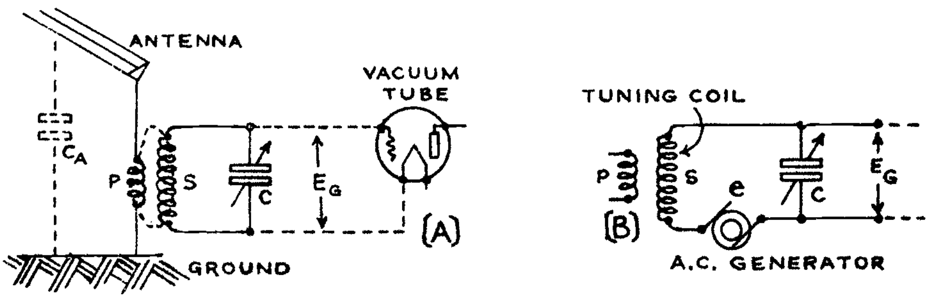


Fig. 114—Series resonance in the tuned circuit of a radio receiver (acceptor circuit).

in the receiver and the capacitance C_A which exists between the antenna wires and the ground. A slightly higher e. m. f. (e) will be induced in the secondary winding "S" of the tuning coil by transformer action. Let us take a practical case and suppose that the e. m. f. (e) induced in S is one millivolt (.001 volt) ; that the secondary winding has an inductance of 405.4 microhenries; that the capacitance of the tuning condenser C, adjusted to produce resonance at this frequency, is .00025 microfarads; and that the total ohmic resistance of the secondary coil and condenser is 10 ohms.

The conditions are shown in (A) of Fig. 114. The secondary coil and condenser circuit are usually connected across the input circuit of a vacuum tube as shown. It might be supposed on first thought that the secondary of the tuning coil and the condenser form a parallel circuit, but this is not so. The voltage in the tuned circuit is induced in the windings of the secondary coil, and therefore is considered to be in series with the windings. The induced voltage (e) may be represented as being supplied by an a-c generator developing an e. m. f. of .001 volt, in series with the secondary coil and tuning condenser as shown at (B).

Note: The question of series and parallel connections is troublesome at times in tuned circuits. Whether the connections are series or parallel depends on the location of the e. m. f. with respect to the impedances. Suppose we connect a resistance across a battery. Is the resistance in series or in parallel with the battery? The e. m. f. in this case is in the battery, and anything that is connected across the terminals of the battery is in series with the e. m. f. This will be evident by actually drawing the circuit diagram of this condition.

If we connect two impedances or resistances across the terminals of the battery, these two are in parallel, but the two of them are in series with the battery.

If we substitute a generator for the battery, the same rule holds. The e. m. f. is in the generator, and anything that is connected across the output terminals of the generator is in series with the e. m. f. of the generator.

If we connect two impedances across the terminals of the generator these two impedances are in parallel but the two are in series with the e. m. f.

In determining whether the connection is series or parallel, it is well to regard the source of the e. m. f. as a pump and the impedances, or rather admittances, as pipe lines. The pump forces a certain amount of water through the system. If the same amount of water is forced through two or more sections of the pipe system (two or more impedances) they are connected in series. If the sections of the pipe system are so connected with respect to the pump that the water can divide, the sections are in parallel.

The electrical pump may consist of a primary battery, a storage battery, a magneto, a generator or dynamo, the secondary of a transformer, a microphone, a phonograph pick-up, a thermo-couple or the plate-filament circuit of a vacuum tube, etc.

At resonance, the current is in phase with the induced e. m. f. in the secondary winding, since the resistance is the only obstacle to the passage of the current under these conditions. An induced e. m. f. (e) of .001 v. in S will therefore send a rapidly surging current of $I=\frac{E}{R}$ or $.001 \div 10 =$ .0001 amperes through the circuit from one condenser plate through the coil to the other plate and back again. From the table in Article 166, we find the capacitive reactance of a .00025 mf. condenser at a frequency of 500,000 cycles to be 1,273.8 ohms. Therefore, since .0001 ampere is flowing into this condenser, the voltage E_G across its terminals is equal to:

$E_G = IX_C = .0001 \times 1{,}273.8 = 0.13$ volts. Since the reactance of the secondary coil must also be equal to 1,273.8 ohms at resonance, the voltage actually existing across its terminals must also be equal to 0.13 volts.

It is thus seen, that by means of resonance, the voltage E_G actually applied to the grid circuit of the vacuum tube is greatly increased over what it would be if the induced voltage (e) developed in the secondary coil by electromagnetic induction from the primary were applied directly to the grid circuit of the vacuum tube. In that case E_G would only be equal to .001 volts. Actually we find it is 0.13 volts, or 130 times as much. This example illustrates the great advantage gained by tuning the secondary winding of the radio frequency transformer in a radio receiver, since the volume of sound depends upon the strength of the voltages applied to the grid circuits of the amplifier tubes. *By tuning, it is possible to have a much higher voltage developed across either the condenser or the inductance, than is impressed on the two in series by the e. m. f. induced from the primary winding by electromagnetic induction.* The ratio of E_G to e is called *the gain* of the tuned circuit. Since E_G is equal to $2\pi f L I$ and e is equal to $I \times R$, the *gain* is equal to:

$$\frac{E_G}{e} = \frac{2\pi f L I}{I R} = \frac{2\pi f L}{R}$$

This expression for the "gain" indicates that, to obtain greatest efficiency from a tuned circuit, it is essential that the ratio of the inductive reactance to the resistance of the coil should be made as large as possible. Thus the tuning coils in radio receivers are designed to have as low resistance as practical, consistent with other controlling factors such as physical size, cost, etc.

175. Resonance curves: If the e. m. f. applied to a series circuit having inductance and capacitance is kept constant, but the frequency is increased, the current in the tuned circuit varies as shown by the *resonance curve* at (A) of Fig. 115. At first the current increases slowly, then as the resonant frequency (400 k. c. in this case) is approached, the current increases very abruptly and after passing through a sharp maximum at

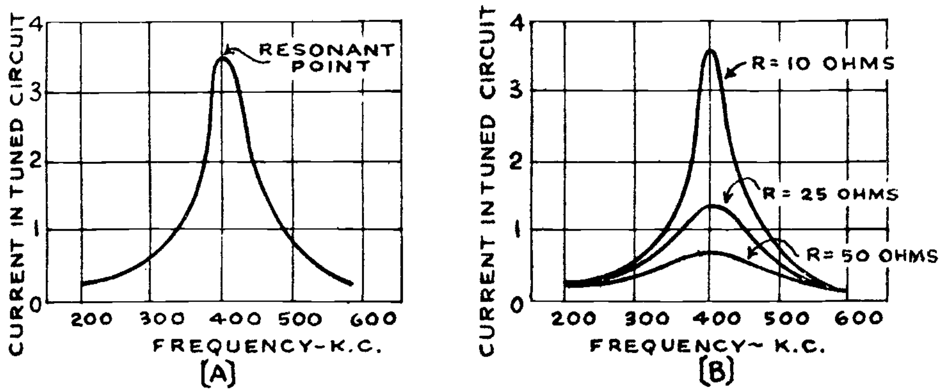


Fig. 115—Resonance curves for series tuned circuit, showing the effect of resistance on the current which will flow, and the sharpness of tuning, when a constant voltage of various frequencies is applied to it.

400 k. c. (peak), falls very rapidly at first and then more slowly. The voltages across the tuning coil and condenser go through similar changes. The phase between the current and the e. m. f. also changes. It is a negative angle (current leads e.m.f.) at frequencies below resonance, since the capacitive reactance predominates; it is zero at resonance, (current and e. m. f. changes are in phase), and becomes a positive angle at frequencies above resonance (current changes lag behind voltage changes), since then the inductive reactance predominates as shown at the right of Fig. 116. At the low frequencies the reactance of the condenser is high, so very little current flows. Likewise, at the high frequencies the reactance of the coil is high, so very little current flows. This principle is used in radio receivers to separate the signal of the station it is desired to receive from those of all other stations which may be induced in the antenna at the same time by the passing radio waves. When the tuned circuits of the receiver are set at resonance for a particular station broadcasting on a certain frequency, the signal currents from this station will build up comparatively large voltages across the inductances and condensers in the tuned circuits and

hence the signal is heard loudly. The tuned circuits offer a much higher impedance to the flow of currents of all other frequencies both above and below this resonant frequency, as shown by the resonance curves. Consequently the incoming voltage impulses from stations of other frequencies cannot set up much current in the tuned circuits, and hence very little voltage is developed across the tuning inductors and condensers and applied to the grid input circuits of the amplifying tubes. If the resonance curve is sharply peaked, the current falls off sharply for all frequencies other than the resonant frequency, and *the receiver is said to "tune sharply."* If the resonance curce is more flattened due to resistance, there is not very much difference between the current set up in the tuned circuit by the wanted station and that set up by other unwanted stations of different frequencies, so they may all be heard at once, causing interference, *and the receiver is said to "tune broadly."*

At resonance, the magnitude of the current in the circuit is controlled entirely by the resistance. Its effect is very important in the tuned circuits of radio receivers. The curves at (B) of Fig. 115 show the effects of adding various resistances to the circuit whose resonance curve was shown at (A). The smaller the resistance of the circuit, the greater are the voltages across the condenser and the inductance coil. This is due to the fact that the voltage across these reactances is equal to the product of the reactance and the current ($E=XI$). The latter, controlled entirely by the resistance at resonance, in turn produces greater voltages across the reactance when less resistance is in the circuit.

It is seen from (B) of Fig. 115, that in the tuned circuits having the higher resistance, the current at resonance is very much less than that in the circuits having low resistance, for the above reasons. These are *broadly tuned* circuits. For frequencies much above or below resonance, the currents are practically the same in each case, for here the ohmic resistance is only a small part of the total impedance of the circuit, since the inductive and capacitive reactances do not equal each other, and therefore the current is determined mainly by the net reactance. The curves are not symmetrical about the resonance frequency line, because below the resonant frequency the *capacitive reactance predominates*, and above the resonant frequency the *inductive reactance predominates*. Therefore, the currents existing at any two frequencies equally above and below the resonant frequency are not equal, since the *net reactance* increases faster below the resonance frequency than it does above the resonance frequency, as shown by the dotted line in Fig. 116. Here the inductive reactance of a 300 microhenry tuning coil employed in a standard broadcast receiver, and the capacitive reactance of the tuning condenser set at .0001 microfarads and connected in series with it, are plotted against the frequency. The net reactance at each frequency is given by the dotted line. Note that there is one point at about 920 kc where the reactances equal each other and the dotted curve of net reactance passes through zero. This is the resonant frequency to which the coil and condenser are tuned for that particular setting of the tuning condenser.

The effects in a series circuit may be summed up as follows:

When a series circuit is in resonance, the current and the e. m. f. are in phase; the current is a maximum; the impedance is a minimum; the voltages across the condenser and inductance are equal and opposite in sign and greater than the total voltage across the combination. In some cases, the voltage built up across the inductance and condenser may become so great at resonance, that the condenser may be punctured. This is especially liable to happen in radio transmitting circuits.

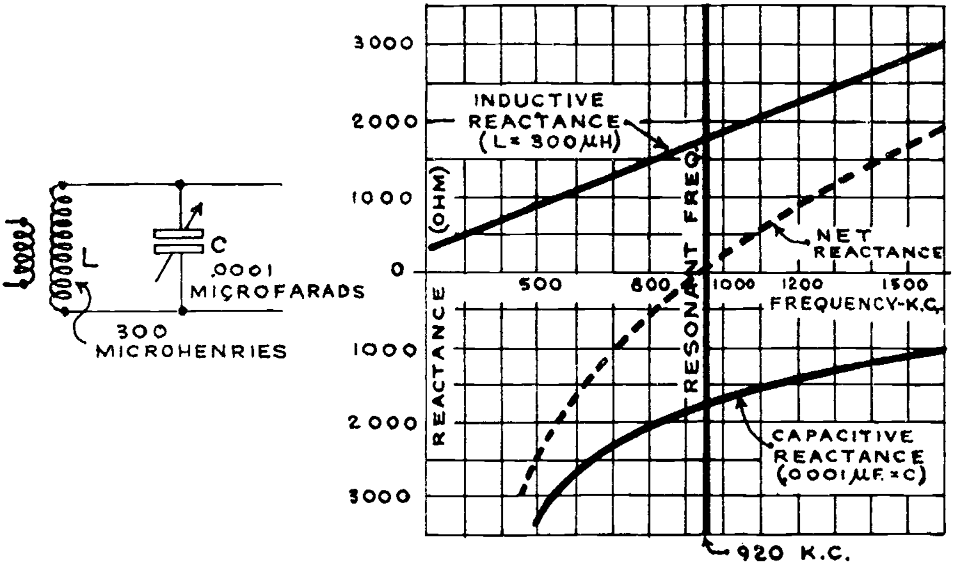


Fig. 116—Curves showing how the inductive, capacitive and net reactances in a variable tuned circuit vary as the resonant frequency is approached, reached, and passed.

If it is desired to keep the circuit in tune as the frequency of the impressed e. m. f. is decreased (wavelength increased), as in the case of the tuned circuits in radio receivers, either the inductance or the capacitance must be increased. If the frequency of the applied e. m. f. is increased (wavelength decreased), either the inductance or capacitance must be decreased. It can be seen that every circuit containing capacitive reactance and inductive reactance will be in tune for some particular frequency. This *resonance frequency* may be determined by using formula (20).

If the inductive element has an iron core, the inductance and consequently the inductive reactance, will vary with the current through it as the strength of the magnetism in the iron core approaches and passes through its saturation value. Thus, with a saturated core condition of this kind, a circuit may be in tune when a certain voltage is impressed and certain current flows, and be out of tune when the applied voltage is above or below this value, even though the frequency remains the same. This principle is applied in the design of some forms of line-voltage stabilizers used with radio receivers.

176. Wavelength and resonance relations: A simple relation exists between the frequency of a circuit and the *wavelength* of the electrical voltage impulses to which it responds. The wavelength is equal to the speed of propagation of the electric waves, divided by the frequency in cycles. As we have already seen in Article 2, this speed is approximately 186,000 miles or 300,000,000 meters per second for electric waves. We usually express wavelengths in meters, so it is necessary to use the velocity of propagation in meters. If f is the frequency in cycles per second then

$$\text{Wavelength in meters} = \frac{300{,}000{,}000}{f} \qquad (21)$$

$$\text{or } f \text{ (cycles)} = \frac{300{,}000{,}000}{\text{wavelength}} \qquad (22)$$

$$\text{or } f \text{ (k. c)} = \frac{300{,}000}{\text{wavelength}} \qquad (23)$$

The customary symbol for wavelength in meters is the Greek letter "lambda" (λ).

If we substitute the value of f from equation (20) into equation (22) we obtain:

$$\frac{1}{2\pi\sqrt{L\,C}} = \frac{300{,}000{,}000}{\text{wavelength}}$$

from which wavelength in meters $= 300{,}000{,}000 \times 2\pi\sqrt{L\,C}$

where L is in henries and C is in farads.

If L is expressed in microhenries and C is in microfarads this expression reduces to:

$$\text{Wavelength (meters)} = 1885\sqrt{L\,C} \qquad (24)$$

These expressions enable us to compute the combination of inductance L and capacitance C necessary to tune a series circuit to resonance at any frequency or wavelength. A table of "LC" products already worked out to simplify the calculations will be found in Appendix I. A graphical chart for quickly finding, without mathematical computations, the L and C for tuning to any desired frequency or wavelength, will be found in the chapter on R. F. Amplifier design, (Art. 402).

Example: What wavelength corresponds to 1,500,000 cycles?

Solution: $\text{Wavelength} = \frac{300{,}000{,}000}{f} = \frac{300{,}000{,}000}{1{,}500{,}000} = 200$ meters. Ans.

Example: What inductance is required to tune to 600 meters with a tuning condenser of .00035 microfarads capacitance?

Solution: $\text{Wavelength} = 1885\sqrt{LC}$ or $L = \dfrac{\text{Wavelength}^2}{1885^2 \times C}$

from which $L = \dfrac{600^2}{1885^2 \times .00035} = 300$ microhenries. Ans.

177. Parallel resonance: In many circuits used in radio work, the inductance and capacitance are connected in parallel with each other *across* the source of e. m. f. as shown in Fig. 117. This arrangement forms a *parallel* tuned or *anti-resonant* circuit. The effects of this circuit are very different from those studied for the series resonant circuit, as will be shown by the following experiment:

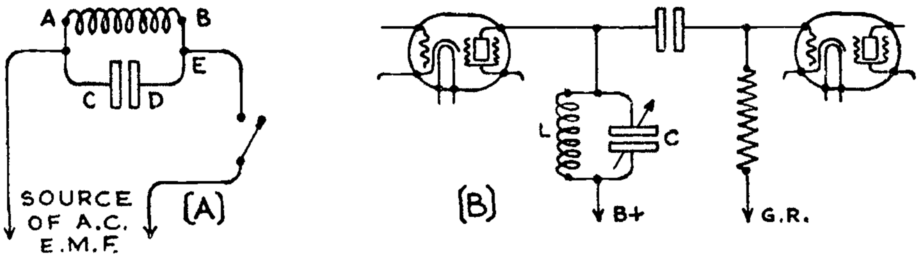


Fig. 117—(a) Parallel tuned circuit (rejector circuit). (b) Application of parallel tuned circuit in the plate circuit of a radio frequency amplifier in a radio receiver.

Experiment: Connect the coil and condenser used in the experiment on series resonance in Article 170, in parallel with each other; and the parallel combination of the two, in series with the incandescent lamp bulb across a 110 volt a-c circuit. The lamp will either burn very dimly or be extinguished entirely when the inductance is adjusted to resonance at the same value employed in the previous experiment. This is a case of parallel resonance. If the frequency is changed, or the position of the iron core is changed, the lamp will light up. The inductance and capacitance form a parallel tuned circuit which offers a high impedance to the flow of current through the external circuit at resonance.

In the series tuned circuit of Fig. 113, a stream of electrons was rapidly surging through the coil and into and out of the plates of the condenser, by way of the line circuit and the lamp. The lamp in this circuit burned brightly because the electrons had to flow through it during their excursions around the circuit. When a coil and condenser are in parallel, as in (A) of Fig. 117, they form a complete circuit CABED. Electrons surge back and forth through the coil, and into and out of the condenser plates, as in the series arrangement, but now the lamp is not in the path of this stream of electrons. At any given instant excepting that of reversal, a stream of electrons is flowing either from B to D or from D to B; let us say from B to D: Then at E some electrons tend to flow from the line *into* the parallel circuit in the direction ED. The result is, that the net flow of electrons or current from the parallel circuit into the line is either zero or is very small, even though the transfer of electrons (current) from the coil to the condenser and vice versa may be quite large.

The line current is especially small the more nearly the reactance of the coil and the reactance of the condenser become equal (approaching resonance). The current in the coil and condenser circuit becomes many times as great as that in the line, the coil discharging into the condenser and vice versa, first one plate and then the other charging up. If the resistance of the resonant circuit were zero, the line current would become zero when the inductive and capacitive reactances are equal at resonance. Of course the resistance cannot be made exactly equal to zero, but in most tuned circuits employed in radio equipment, it can be made very small compared with the reactance.

Thus at resonance, a parallel tuned circuit offers a very large impedance to the external source of applied e. m. f., and the current in the main line is very small, even though the currents flowing between the coil and condenser may be quite large. The same voltage is across each branch, but the currents through them differ as the frequency is changed. With increase of frequency, the reactance of the capacity branch decreases, so a larger proportion of the total current flows through it. At the same time, the reactance of the inductive branch increases, so the current flowing through it gets less.

In a parallel circuit at resonance, the capacitive reactance is equal and opposite to the inductive reactance as in the case of series resonance. Therefore the same equations hold for parallel resonance as for series resonance (Article 171), provided the resistance of the circuit is very small.

Thus for parallel resonance $f = \frac{1}{2\pi\sqrt{LC}}$

and wavelength $= 1885\sqrt{LC}$.

The resistance of a parallel circuit at resonance is the same as that for a similar series circuit at resonance, provided the resistances of the parts are low.

Example: What capacitance is required in parallel with an inductance of 300 microhenries, to produce resonance at a wavelength of 300 meters?

Solution: Wavelength $= 1885\sqrt{LC}$

therefore $300 = 1885\sqrt{300C}$ from which we find that $C = .000085$ microfarads approximately. Ans.

As we shall see later, the fact that the impedance of parallel resonant circuits are very high at resonance, makes them used sometimes in the tuned plate circuits of screen grid radio frequency amplifiers as shown at (B) of Fig. 117, where a high impedance is desirable. They are also used in several types of filters which we will study about. Due to the fact that they offer a very high impedance to the applied e. m. f. at resonance parallel tuned circuits are often called *rejector circuits*, because they reject signals of the frequencies to which they are tuned. They are also sometimes called *wave traps*, when they are used to trap out the currents of unwanted signals.

The series resonance circuit is called an *acceptor circuit* because it offers low impedance to signals of the resonant frequency and therefore accepts them.

178. Alternating current frequencies: Alternating currents of various frequencies are employed in electrical work. For electric lighting, frequencies of 60 and 40 cycles are used, 60 cycles being the more common. Some rural electric power and light lines furnish current at 25 cycles. In the microphone circuit of a radio transmitter, and the loud speaker and audio circuits of radio receivers, we have *audio frequency* currents varying from below 60 cycles to as high as 10,000 cycles per second. The low-frequency notes of an organ may produce currents as low as 32 cycles per second in frequency, in these circuits. The high notes and harmonics of a piccolo may produce currents as high as 10,000 cycles per second in them.

The carrier currents employed in broadcasting stations for producing the radio waves in space, have very high frequency, and are called *radio frequency currents.* Radio frequencies are considered to range from 20,000 cycles to about 300,000,000 cycles, per second. A frequency of 20,000 cycles corresponds to a wavelength of 15,000 meters, while a frequency of 300,000,000 cycles corresponds to one meter. The effects produced by alternating currents varies greatly with the frequency. Thus, a coil of wire exhibits the property of inductance only, at low frequencies, but at high frequencies it may act more like a condenser than an inductance, due to the distributed capacitance which exists between its turns of wire.

The recent development of radically new forms of vacuum tube oscillators designed especially for the purpose, has made it possible to generate currents of higher frequencies than have ever been produced heretofore, (see Articles 570 and 635). When made to flow through the proper apparatus, these ultra-high frequency currents produce effects which are extremely interesting in that they are similar in many respects to the effects produced by light rays. The radiations produced by them are called quasi-optical rays, and promise to open up a very important new field in radio and television work.

REVIEW QUESTIONS

1. Explain in detail the actions occurring in an inductance connected in an alternating current circuit.
2. Explain in detail the actions occurring in a condenser connected in an alternating current circuit.
3. Explain with the aid of diagrams why the current variations in a condenser connected in an a-c circuit lead those of the applied e. m. f.
4. Explain with the aid of diagrams why the current variations in an inductor lag those of the applied e. m. f.

5. Distinguish between (a) ohmic resistance, (b) inductive reactance, (c) capacitive reactance, (d) impedance.
6. What is the reactance of a 20 henry choke coil of negligible resistance at 100 cycles?
7. What is the impedance if a resistor of 500 ohms is connected in series with the choke coil in problem 6? What will be the cosine of the angle of lag between the current and the e. m. f. in this circuit?
8. What is the reactance of a one microfarad by-pass condenser at 100 cycles? If it is connected across a 2,000 ohm C-bias resistor, what proportion of the current goes through the resistor and what proportion is in the condenser circuit at this frequency?
9. Give the physical reason for the fact that a condenser has a lower reactance at high frequencies than at low frequencies.
10. From the values in the table of Article 161, plot a curve showing the variation in reactance of an inductor of 30 henries as the frequency is increased from 60 cycles to 100,000 cycles.
11. From the values in the table of Article 164 plot a curve showing the variation in reactance of a condenser of .001 microfarad capacitance. Plot this on the same sheet and to the same scales as the curve in problem 10.
12. What is the impedance of a circuit having a resistance of 10 ohms in series with a capacitance of 100 microfarads and an inductance of 50 henries, if the frequency is 60 cycles?
13. How much current will flow in the circuit in problem 12 if the e. m. f. is 1000 volts?
14. Explain what happens in a series circuit containing inductance and capacitance when resonance occurs.
15. Under what circuit conditions do voltage and current differ in phase? Under what condition is the voltage and current in phase?
16. Explain the fact that a lamp connected in series with a condenser having sufficient capacitance will light up when connected to a 110 volt source of alternating e. m. f. even though the dielectric separating the plates of the condenser is an insulating material.
17. Find the true power, the apparent power, and the power factor for the conditions in question 12. Draw the vector diagram.
18. What must be the inductance of a coil to form a resonant circuit with a condenser of .0005 microfarad capacitance, at a wavelength of 200 meters? At a wavelength of 600 meters?
19. What is an *audio frequency* current? What is a *radio frequency* current?
20. If a fixed inductance of 300 microhenries is used to form a tuned circuit with a variable tuning condenser, what are the maximum and the minimum values of capacitance needed for a tuning

range over the broadcast band from 200 to 600 meters? (Distributed capacitance of the inductor to be neglected.)

21. Why is the voltage appearing across the inductance or condenser in a series resonant circuit, greater than the applied e. m. f.? Explain in detail.
22. Explain what is meant by "gain" in a tuned circuit.
23. What are two effects of increase of resistance in a tuned circuit?
24. What frequency corresponds to 600 meters? To 200 meters?
25. What wavelength corresponds to a frequency of 550 kc?
26. What is meant by an "acceptor circuit"? Draw the circuit diagram for one. Where would you use it?
27. What is meant by a "rejector circuit"? Draw the circuit diagram for one. Where would you use it?
28. Explain the important characteristics of (a) series tuned circuits, (b) parallel tuned circuits.
29. An inductance of 200 microhenries is connected in parallel with a capacitance of .0005 mf. At what frequency will they be in resonance?
30. What is the frequency at which the circuit of Question 12 will be in resonance?

CHAPTER 12

ELECTRIC FILTERS

FILTERS — LOW-PASS FILTERS — T TYPE LOW-PASS FILTER — THE "PI" TYPE LOW-PASS FILTER — DESIGNING T AND "PI" TYPE LOW-PASS FILTERS — SOME APPLICATIONS OF LOW-PASS FILTERS — HIGH-PASS FILTERS — BAND-PASS FILTERS — DESIGNING OF BAND-PASS FILTERS — THE BAND SUPPRESSION FILTER — GENERAL USES OF FILTERS — REVIEW QUESTIONS.

179. Filters: Generally speaking, a *filter* is a device for separating things of different characteristics from each other. Mechanical filters are commonly used in everyday life. Thus a mechanical filter or screen is used to separate sand from stones, a coffee strainer separates the coffee grounds from the liquid, etc. Similarly, when a circuit contains currents of several frequencies, electrical filters may be used to separate currents of certain frequencies from those of other frequencies. The perfection of the modern a-c electric receivers has resulted in the widespread development and use of electrical filters, both in their power packs and in the radio and audio amplifier systems. Heretofore they were used almost entirely in telephone circuits.

The purpose of the electric filter is not very much different from that of any mechanical filter; it is simply designed to separate currents of different characteristics from each other, i.e., for separating direct from alternating currents, or separating alternating currents of different frequencies from each other. Although the design of some complicated filters involves intricate calculations, the more simple types may be easily understood by the novice.

The action of all types of electrical filters depends upon the following three main principles of alternating current circuits:

(1) *An inductor ("inductance") offers much less resistance or opposition to the passage of direct currents and low frequency currents than it offers to high frequency currents* (see Article 161).

(2) *A condenser ("capacitance") offers much less resistance or opposition to the passage of high frequency currents than to low frequency currents, and stops or "blocks" the flow of direct current altogether* (see Article 166).

(3) *That a "series tuned circuit" offers a low impedance at resonance, and will permit the passage through it of those alternating currents which lie in a narrow band of frequencies near the resonant frequency, and will oppose the flow of currents of all other frequencies* (see Article 173).

(4) *That a "parallel tuned circuit" offers a high impedance at resonance, and opposes the flow of those alternating currents through it which lie in a narrow band of frequencies around the resonant frequency, and will permit the flow of currents of all other frequencies* (see Article 177).

Resistances do not provide any filtering action in themselves, for they impede all currents which pass through them, regardless of frequency. Resistances do have an effect of a different kind upon a filter however. They do not determine which frequencies the filter will pass or impede, but they have an effect upon the sharpness of the filter—they determine whether the dividing line between the frequencies which pass and those which do not is finely drawn, or whether the division between the two is of a more gradual kind. The less the resistance in any filter the sharper will be the dividing line between the frequencies which are let through and those which are blocked, and it is usually desirable to have this division as sharp and clean-cut as possible. There is another factor, also, which affects the sharpness of the "cut-off" of a filter. This will be taken up later.

By proper arrangement of condensers, inductors and tuned circuits therefore, any desired electrical filtering action may be obtained. There are four general classes of filters. The first is the *low-pass filter* (Fig. 118). This is the type designed to pass all frequencies below a pre-determined critical or "cut-off frequency", and substantially reduce or "attenuate" the amplitude of currents of all frequencies above this cut-off frequency. This type of filter will also pass direct current without opposition.

Next comes the *high-pass filter* (Fig. 126). This is the type designed to pass currents of all frequencies above a pre-determined critical or "cut-off" frequency and substantially reduce the amplitude of the currents of all frequencies below this cut-off frequency. In most cases a filter of this type will stop the flow of direct current, as well as that of low-frequency alternating current.

The third is the *band-pass* filter (Fig. 129). This is designed to pass currents of frequencies within a continuous band limited by an upper and lower critical or "cut-off" frequency, and substantially reduce the amplitude of the currents of all frequencies above and below that band. In this case, currents of both the higher and lower frequencies are stopped.

The fourth and last of the general types is the *"band-suppression," "band-elimination"* or *"band-exclusion"* filter (Fig. 131). This is designed to substantially suppress currents of frequencies within a continuous band limited by an upper and lower critical or "cut-off" frequency, and pass currents of all frequencies above and below that band. In this case, currents of frequencies within the band are opposed or stopped. It is just opposite to the band-pass type.

In all these cases, we consider a direct current to be simply a current of zero frequency. We will now study each of these, together with some of their applications in detail.

180. Low-pass filters: Let us consider first the simple low-pass filter shown at the left of Fig. 118. Notice that an inductor is connected

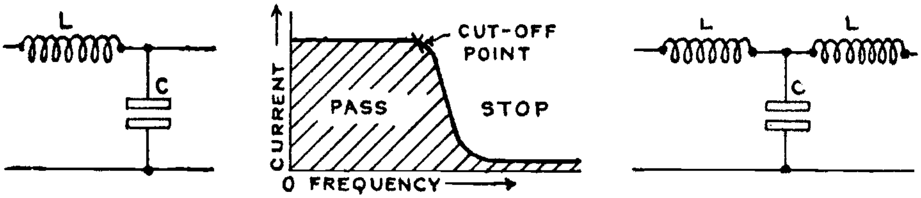


Fig 118—Left: Single section of a low-pass filter. Middle: The frequency-current characteristic of a low-pass filter.
Right: Single section T-type low-pass filter.

in series with the circuit and a condenser is connected across the circuit. If we remember the action of an inductor and a condenser in an a-c circuit, it is easy to understand the action of this arrangement. The low-frequency currents which are to be passed through the circuit find an easy path back and forth through the inductor since the reactance which an inductor offers to low-frequency currents is small ($X_L = 2\pi f L$). These low-frequency currents cannot get in and out of the condenser plates to any great extent since the reactance of a condenser to currents of low frequency is very high $X_C = \frac{1}{2\pi f C}$ Therefore low-frequency currents are not appreciably shunted or short-circuited by the condenser across the line.

The high-frequency currents which may also be in the circuit at the same time, find that the inductor offers a high impedance to their flow through the circuit, but that the shunting condenser allows the current to surge back and forth between the plates, (in the electrical circuit) since it offers a low impedance to currents of high frequency. Thus we see that the action of this filter is to offer very little impedance or opposition to low-frequency currents passing through it, but to offer a high impedance to high-frequency currents passing through it, besides partially short-circuiting them across the line.

The result is shown by the graph in Fig. 118. The frequency is plotted along the horizontal axis, increasing toward the right. The current is plotted vertically. This is sometimes called the *transmission curve* of the filter, for it shows how the filter transmits current through the circuit. Notice that at low frequencies the current is strong since the filter passes it easily. The shaded portion of this graph shows the frequency range over which the filter easily passes current. Above the cut-off point the current is low, because the inductor presents a high impedance to the flow of these currents through it, and the condenser plates act as storage reservoirs for these currents during each cycle, thereby shunting them from the load circuit.

The shunting action of a condenser connected across a source of e. m. f. is usually very puzzling to the novice, especially since many confusing and misleading statements concerning it are to be found in popular radio literature. As this important action occurs in many parts of radio transmitters and receivers, as for instance in by-passing radio or audio-frequency currents around a C-bias resistor, or the B-voltage supply device; in by-passing radio-frequency currents in the plate circuit of the detector tube in radio receivers, etc., it will be well for us to obtain a good mental picture of it at this point.

By-passing by means of a condenser is always associated with either alternating, or pulsating direct current. The action is practically the same in each case. Consider the circuit shown at (B) of Fig. 119 which represents the filter circuit of Fig. 118 with an a-c generator or other source of e. m. f. supply connected at the left and a device at the right into which the current from the source is to flow. This load may

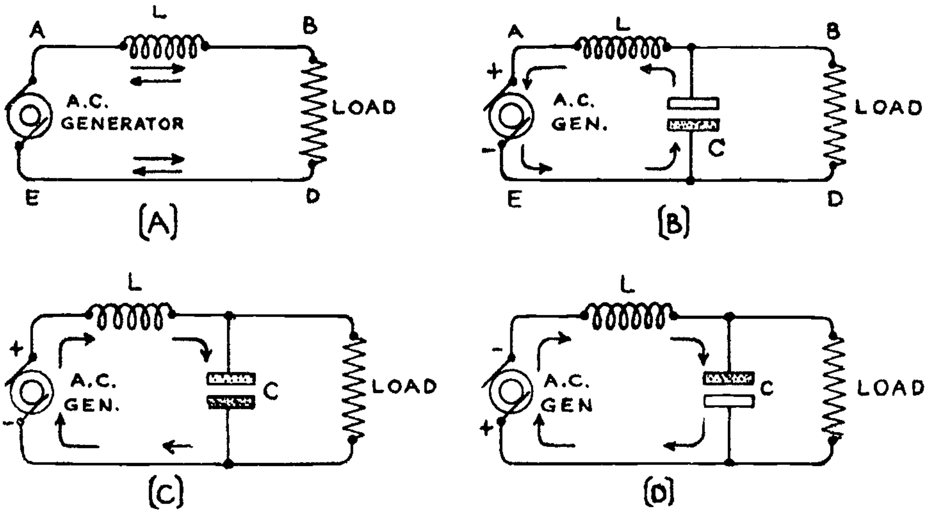


Fig. 119—Illustrating the by-passing action of a condenser across a line.

be simply a resistance as shown. The end of the filter which is connected to the source of e. m. f. is called the "*source*" end. That connected to the load is called the "*load*" end. The e. m. f. of the generator is rapidly alternating, so the current through the circuit is doing likewise as shown by the arrows.

Let us consider the action taking place when the e. m. f. supplied by the generator is at a frequency which is suppressed by the filter. If the condenser were not connected in the circuit, as at (A), the inductor would present a definite impedance or opposition to the flow of current around the circuit, both when it flows in the direction

A-B-D-E and also when in the reverse direction E-D-B-A. At high frequencies this impedance would be high, but some current would always get through the inductor. Therefore the inductor alone would act as a sort of low-pass filter, but imperfectly.

Now if the condenser is connected as shown, during the part of the cycle when terminal A of the generator is positive (as at B) the electrons flow through the circuit in the direction shown by the arrows, (opposite to the direction of current flow). The lower plate of the condenser collects a large portion of the electrons which are being transferred around through the circuit consisting of the upper condenser plate, inductor, and a-c generator (provided the reactance of the load is appreciably larger than that of the condenser so it does not also furnish an appreciable quantity of electrons). If the condenser were not there, as in (A), all of the electrons transferred around the circuit by the e. m. f. of the generator would have to go through the load. Hence it can be seen that the condenser really assists the action of the inductor L, in *reducing* the current flowing through to the load, simply by taking into its plates a large number of the electrons thus *by-passing* them from the load. The larger the capacitance the more electrons it will take in at the high frequencies considered, and hence the greater will be the filtering action. Now when the e. m. f. of the generator has reached its peak value and begins to decrease, the current through the coil tends to decrease, and the collapsing magnetic field induces a self-induced e. m. f. in the coil which tends to keep the electrons flowing into the condenser still in the same direction. When they both die down, the lower plate of the condenser begins to discharge electrons back around through the circuit to the upper plate of the condenser as shown at (C). When the generator e. m. f. reverses, it tends to drive more electrons around to the upper plate as shown at (D) and thus the plate now becomes negatively charged.

When the e. m. f. passes its peak value in this direction the electrons surge around the circuit again in the direction shown at (B). This is repeated over and over again. The inductor of course reduces the number of electrons or current transferred around the circuit in each case, but since the condenser stores some of them each time, less reach the load than would if the condenser were not there. Notice that no electrons or current can actually flow through the condenser, since the dielectric insulates one plate from the other. This is contrary to the misleading statements often made when speaking of this action. Also notice that the condenser will act exactly as described above only when its reactance is very small compared to the reactance of the load it is shunting. If the reactance of the load were equal to that of the condenser at the particular frequency being considered, the latter would only exert half as much filtering action since now half of the transferred electrons would go into the condenser and half would go directly through the load. It is for this reason that the load impedance should preferably bear a definite relation to the impedance of the filter. This will be discussed in Art. 183. The condenser and inductor really form a series circuit across the source of e. m. f.

181. T-type low-pass filter: The single filter section just described (even though it is better than a single coil or single condenser alone) does not give very sharp reduction of current at the cut-off frequency. Another inductance, connected in series with the load side of the circuit as shown at the right of Fig. 118 will improve the filtering action. This additional inductor has the effect of sharpening the cut-off. This circuit is called a "T" section of a filter because it resembles the capital letter T. Two of these sections may be connected as shown at (A) of Fig. 120 to give sharper cut-off. This is sometimes called a Campbell Filter of T sections. When more than one section is used in any filter, different values of L and C are used for the center section and the end branches, as we will see. *The terminal unit of any multi-section filter is always different from the value of the units in the body of the filter.* It is evident from (A) of Fig. 120 that the joining of the two T sections gives us, at the center, a combined inductance which is equal to the sum of the two section inductances joined in series. Therefore this may be simplified as shown at (B) by considering the center inductance L_1 equal to 2 times each outside inductance, which is now called $\frac{1}{2} L_1$ for convenience. This relation should be remembered. In practical filters of this type, the center choke L_1, either consists of two chokes in series as shown at (A), each one having half the

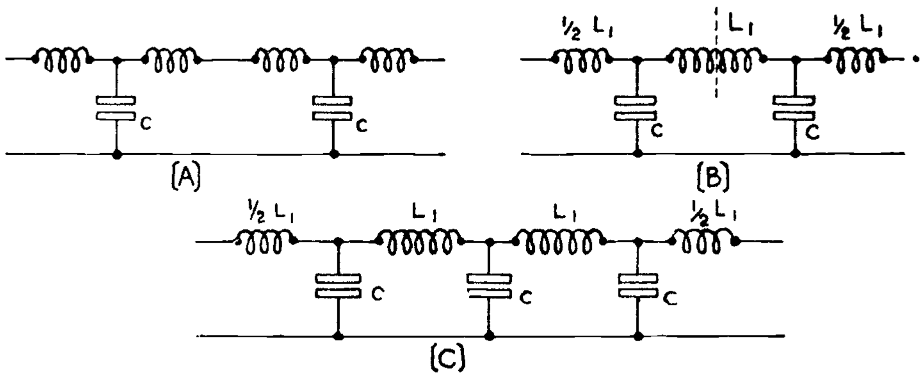


Fig. 120—Method of forming a multi-section T-type filter from several single units. A 2-section filter is shown at the upper right and a 3-section filter is shown at the bottom.

total inductance value L_1, or if a single choke is used, its inductance must be twice as great as that of each outside or end choke as shown at (B). This is the general rule that applies to all T-section filters—the end chokes are always ½ as large as the others. A 3-section T filter would look as shown at (C).

The sharpness of the cut-offs of filters depends upon the number of sections, as well as upon the resistance of the apparatus. A filter composed of only a single section will not give as sharp a division between what is passed and what is blocked as will a filter of several sections. The number of sections which are actually used in any particular case depends, of course, upon how sharp it is desirable to have these cut-offs and upon the cost of the apparatus. In general, two or three-section filters are all that are necessary, and in some cases even one section is sufficient.

If the variation in frequency is plotted horizontally, usually upon a logarithmic scale, while the corresponding *attenuation* or "*reduction*" of the current caused by a high or low-pass filter is plotted vertically on a uniform scale, the so-called *attenuation curve* of the filter is obtained.

If the filters had no resistance or leakage losses, the T-type filter described above would give similar results to the π ("pi") type to be described next. However, under practical operating conditions it may be said that in general, the T-type of filter section is preferable to the "pi" type for *constant voltage* circuits. Of course this is only a general rule, as other factors will often alter the conditions. The calculations for the T type filter will be considered together with those of the "pi" type filter since they are identical.

182. The "pi" type low-pass filter: If the inductance is arranged with a condenser shunting the line at each end, as shown at (A) of Fig. 121 we have what is known as a π ("pi") filter section. (This name originated from the fact that the circuit diagram has the same

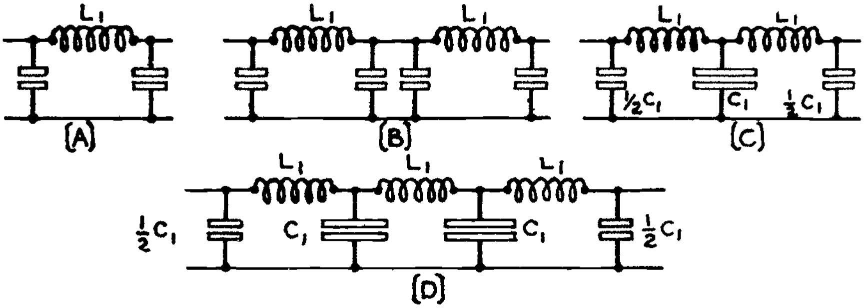


Fig. 121—(A) Single section "Pi" type filter. (B) and (C) 2-section "Pi" filter. (D) 3-section "Pi" type filter.

form as the symbol π. The action of this type is somewhat similar to that explained for the T-section, excepting that now there are 2 condensers across the circuit. If two of these filters are connected together as shown at (B), we have at the junction a total capacitance which is equal to the sum of the two similar capacitances joined in parallel there. This circuit may be re-arranged as shown at (C) where the larger single capacitance C_1 has been put in place of the two smaller ones in parallel, and is equal to two times each outside capacitance. The outside capacitances are now called $\frac{1}{2}C_1$ for convenience. At (D) a three-section filter of the "pi" type is shown. Notice that the end capacitances are ½ the capacitances used in the repeating sections. The "pi" type filter is usually better than the T type for circuits of approximately constant current.

183. Designing T and "pi" type low-pass filters: The point at which a low-pass filter begins to cut-off is known as the *cut-off point,* and the design consists of calculating the inductances and capacitances required to locate this cut-off at the desired frequency. This frequency may be referred to simply as f. Usually the number of sections which the filter must have to make the cut-offs as sharp as desired must also be found.

For a low-pass filter of either the T or "pi" type, the values of capacitance in microfarads, and inductance in henries for a cut-off at *f* cycles per second, are given by:

$$L_1 = \frac{0.3183\ Z}{f} \quad \text{.............}(25) \qquad C_1 = \frac{318{,}300}{f\ Z} \quad \text{.............}(26)$$

$$\text{and } f = \frac{318.3}{\sqrt{L_1 \times C_1}} \quad \text{..}(26A)$$

Notice that these formulas give the values of L_1 and C_1 as shown in Figs. 120 and 121. L_1 is in henries and C_1 is in microfarads. Z is in ohms

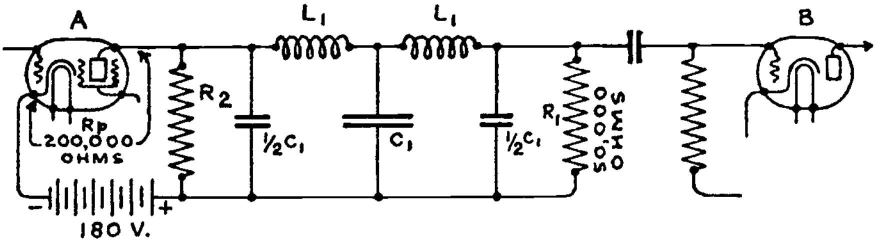


Fig. 122—A practical low-pass filter used to filter high frequency (R-F) currents out of an audio amplifier.

and is called the *characteristic* or *iterative impedance* of the circuit in which the filter is to be placed. The impedance Z is an important factor in the determination of the size of the condensers and coils. In practice it is desirable to terminate a filter externally both at the load and at the source of power (Fig. 122) in an impedance approximately equal to its characteristic impedance, for it is only then that the filter approaches in performance the type after which it was designed. If both the source impedance and the load impedance are known, this value is usually taken for the characteristic impedances in the above formulas. If either the load or the source impedance is known, this is taken as the characteristic impedance in the formulas, and then an impedance is connected at the other end so as to make it of the same combined impedance value. as will be illustrated in the example to follow.

If a certain ready-built fixed filter is to be employed, and it is desired to know what impedance to terminate it in, it may be found from the expression for the "characteristic" impedance *at zero frequency* which is,

$$Z_0 = \sqrt{\frac{L_1}{C_1}} \qquad \text{where: } Z_0 = \textit{ohms},\ L_1 = \textit{henries},\ C_1 = \textit{farads}$$

This is independent of the number of sections and, depends only on the inductance and capacitance used. There is always one best load impedance for a particular filter. The best load is a pure resistance, and loads having reactance or resonant characteristics will upset the filter characteristics very much.

Example: The low-pass filter shown in Fig. 122 is to be connected between two amplifying tubes as shown. Radio and audio frequencies are fed into the amplifier and it is desired to separate them and amplify only the audio frequencies. Assume 20,000 cycles (the limit of audibility) as the cut-off point. The internal plate circuit resistance of tube A is 200,000 ohms. Plate coupling resistor R_1 into which the filter terminates is 50,000 ohms. Design the filter if it is of the type shown.

Solution: Since the terminating impedance R_1 is 50,000 ohms, the input impedance to the filter should also be made equal to this value by connecting resistor R_2 in parallel with the plate resistance R_p of the tube. Then since:

$$\frac{1}{R_{total}}=\frac{1}{R_2}+\frac{1}{R_p} \text{ we have } \frac{1}{50{,}000}=\frac{1}{R_2}+\frac{1}{200{,}000}$$

from which $R_2=66{,}666$ ohms.

The filter therefore should be designed for 50,000 ohms, since it will terminate with this same impedance at both ends,

We now have: $$L_1=\frac{0.3183\ Z}{f}=\frac{0.3183 \times 50{,}000}{20{,}000}=0.8 \text{ henries.}$$ **ans.**

and $$C_1=\frac{318{,}300}{f\ Z}=\frac{318{,}300}{20{,}000 \times 50{,}000}=0.00032 \text{ microfarads.}$$ **(approx)**

The capacitance of the first and last condensers must each be equal to ½ C_1, or .00032÷2, or .00016 microfarads. It is not practical to obtain the exact values of L_1 and C_2 as computed above. In practice, values of commercially available coils and condensers as close as possible to these values should be used and the filter re-computed to see how much f and Z have changed.

In filter construction, the resistance should be kept as low as practicable since the effect of resistance is to introduce some attenuation in the passed band, and to round out the abrupt changes at cut-off.

If the inductors have iron cores and carry much current, they should be provided with an air gap so that their values will not change appreciably with changing current. They may also need to be magnetically shielded from one another, as any coupling between them may change the characteristics of the filter. In radio-frequency circuits, the choke coils should be of low-loss type.

It will be seen from an examination of (B) of Fig. 120, and (C) of Fig. 121, that a two section T filter is quite similar to a two section "pi" filter at the center. Whether to use end sections of the "pi" or T type in any case, depends on the problem in hand and the rules already given are good ones to follow. The "pi" section type of filter ends with a condenser and in some applications advantage may be taken of this fact to use this same condenser to by-pass any radio-frequency currents present. The sum total of capacitance and inductance used in both types is the same, for an equal number of sections. Of course, since every filter has some resistance, the filter always causes some reduction in the strength of the currents passed. Also the current suppressed by the filter is never reduced entirely to zero at any frequency, although the zero value may be approached by using a number of well designed sections.

184. Some applications of low-pass filters: A practical application of the low-pass filter is in the "B" power supply unit in electric radio receivers. In this case, the pulsating "rectified" direct current is passed through the choke coils with some opposition but, since direct current cannot pass through a condenser, the direct current is kept in the correct path. The choke coils tend to oppose any pulsations in the current. The high-capacity condensers in the filter absorb the pulsations in this direct current. This leaves the output current free of all pulsations which would otherwise cause "hum" in the receiver.

In most "B" power units a two-section filter is employed, comprising

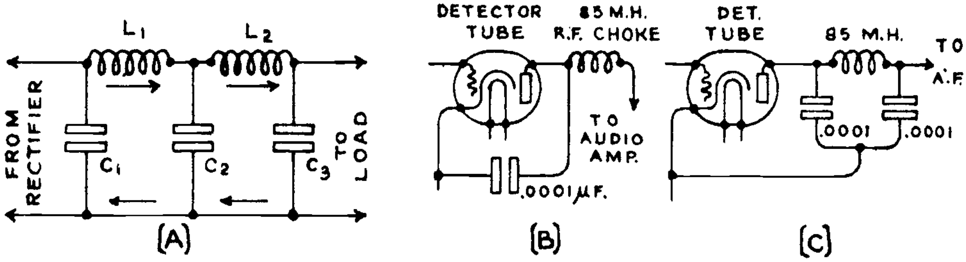
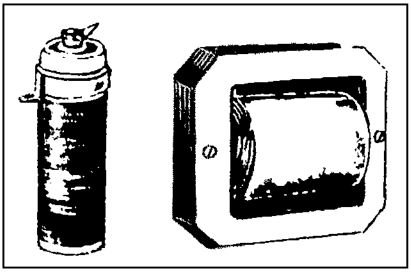


Fig. 123—(A) A type of low-pass filter section commonly used in B-power units of A-C electric radio receivers. (B) Low-pass filter section following the detector tube in a radio receiver to keep the r-f currents out of the audio amplifier, but pass the lower frequency audio currents through. (C) Improved form of the filter at (B).

two choke coils and two or three filter condensers, as shown in (A) of Fig. 123. Assuming that 30-henry chokes and 2-microfarad condensers are used, a filter of this type will pass all currents having a frequency of less than about 20 cycles, including direct current. This filter will block all currents which have frequencies above 20 cycles, however, which includes the 60-cycle hum-current which we wish to eliminate, and also practically all of the "line" noises which are present. Such a filter is ideal for the purpose for which we wish to use it. A 30-henry filter-choke and an electrolytic condenser-unit used in a filter of this kind, are shown at the left of Fig. 124. At (B) of Fig. 123 is shown the simple low-pass filter arrangement commonly used in the plate circuit of the detector tube in a radio receiver. The r-f choke coil is an air-core coil of about 85 millihenries inductance, designed to offer low impedance to the passage of audio-frequency currents from 0 to about 10,000 cycles through it. It does, however, present a high impedance to the flow of radio-frequency currents (about 20,000 cycles—up). The by-pass condenser, usually of from .0001 to .0005 mf. capacitance, acts as a by-pass for all radio-frequency currents which exist in the plate circuit of the detector tube.

At (C) is shown an improved form of detector plate filter which is now being used in many receivers. It has two condensers instead of one. This form a "pi" section filter which is more effective for this purpose than that shown at (B), since the condenser on the right also helps to by-pass the radio-frequency currents. An 85 millihenry r-f choke coil and 0001 mf. by-pass condenser actually used for this purpose are shown at the right of Fig. 124.

Low-pass filters are also used as tone controls for suppressing the high frequency audio currents in audio amplifiers, and in interference eliminators for suppressing extraneous electrical disturbances. In some electro-dynamic loudspeakers, high-pass filters are used to suppress any 60 cycle hum which may be present, but they pass through all audio frequencies above this. These will be considered in detail later at appropriate places.



Courtesy Aerovox Wireless Corp. and Pilot Radio & Tube Corp.

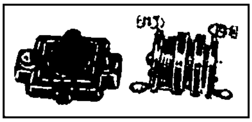


Fig. 124—Left: An electrolytic condenser and a 30 henry choke used in the low-pass filter of a B-power supply unit.
Right: .0001 mf. condenser and 85 mh. choke used in the low-pass filter following a detector tube.

185. High-pass filters: A simple type of high-pass filter is shown in (A) of Fig. 126. The high-frequency current passing through the circuit encounters very little impedance from the series condenser, but encounters a high impedance in the inductance, so not much is shunted. The low-frequency currents attempting to pass through however, encounter high impedance in the condenser and are easily short-circuited out by the inductance—none of them, therefore, getting through. The action of this type of filter is shown at (B). Notice that the low frequencies are cut off and the high frequencies are passed through. At (C) is shown a single section T-type high-pass filter.

At (A) of Fig. 127 we have two single section T-type filters joined to make a 2-section unit. The part of the circuit between the two chokes has two similar condensers in series. They may be replaced by a single condenser C_1 having half the capacitance of either one. To keep our condenser notations in accordance with those used in discussing low-pass filters, the equivalent inside condenser is called C_1. Each outside condenser then has a value of 2 C_1 as shown at (B). Therefore in T type high-pass filters, the end capacitances are *each twice* the capacitance used in the repeating sections, since the latter is the sum of two section-capacitances in series.

At (C) is shown a "pi" type single section high-pass filter. When two or more such sections are joined together as at (D), we have two similar inductances in parallel with each other at the center. These may be considered as being replaced by a single inductor L_1 having half the inductance of either one. Therefore the outside inductors are each equal to $2L_1$. Thus in a multi-section "pi" type high-pass filter, each end inductance is twice the inductance used in the repeating sections, since the latter is the sum of two section-inductances in parallel. Here again, the larger the number of sections, the more perfect is the cut-off.

186. Designing high-pass filters: For a high-pass filter of either the T or "pi" type, the values of capacitance in microfarads, and inductance

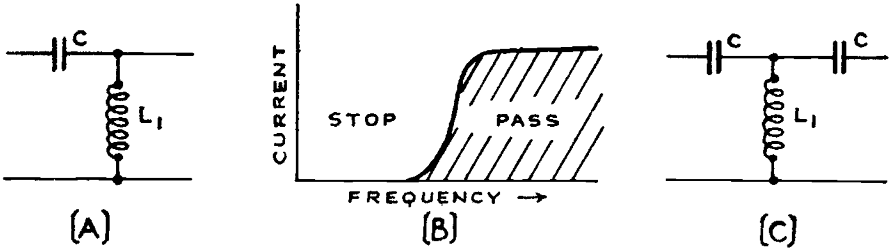


Fig. 126—(A) A single section high-pass filter. (B) Transmission characteristic of a high-pass filter. (C) Single section T-type high-pass filter.

in henries for a cut-off at *f* cycles per second are given by:

$$L_1 = \frac{0.07958\ Z}{f} \quad \text{.........} (27) \qquad C_1 = \frac{79{,}580}{f\ Z} \quad \text{.........} (28)$$

$$\text{and } f = \frac{795.8}{\sqrt{L_1 \times C_1}} \quad \text{..............................} (28A)$$

These formulas give the value of L_1 and C_1 as shown in (B) of Fig. 127. Z is in ohms, and applies exactly in the same way as in the formula for low-pass filters in Article 183. The same precautions regarding source and terminal impedances must be observed. The following example will serve to illustrate the use of the formulas.

Example: The high-pass filter shown in Fig. 128 is to be connected between two vacuum tubes in an r-f amplifier, as shown. Radio and audio frequencies are fed into the amplifier and it is desired to separate them and amplify only the radio frequencies. Assume 20,000 cycles, the upper limit of audio frequencies, as the cut-off point. The internal plate circuit resistance R_p of tube A is 200,000 ohms. The 50,000 ohm plate coupling resistor R_c is in parallel with this at the source of the filter. Assume the input impedance of tube B to be infinitely great.

Solution: Since R_p and R_c are in parallel, their joint resistance R is:

$$\frac{1}{R}=\frac{1}{R_p}+\frac{1}{R_c}=\frac{1}{200{,}000}+\frac{1}{50{,}000}=40{,}000 \text{ ohms.}$$

This is the effective input impedance of the source. The filter therefore should be designed for 40,000 ohms, and the other end should be terminated with resistance R_t of approximately the same value.

From the formulas for high-pass filters we obtain:

$$L_1=\frac{0.07958\ Z}{f}=\frac{0.07958 \times 40{,}000}{20{,}000}=0.16 \text{ henries (approx.)}$$ **ans.**

$$C_1=\frac{79{,}580}{f\ Z}=\frac{79{,}580}{20{,}000 \times 40{,}000}=0.0001 \text{ microfarads (approx.)}$$ **ans.**

The filter is made up of two "T" sections and therefore the capacitances of the two outside condensers must each be equal to 2 x 0.0001, or 0.0002 microfarads.

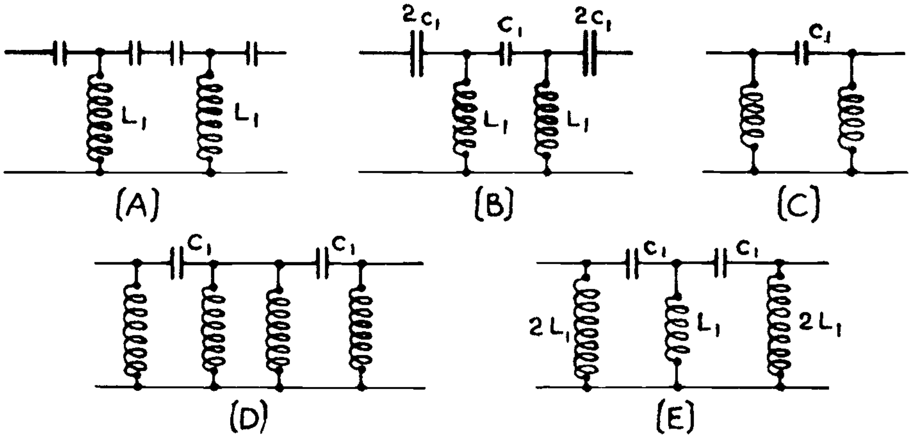


Fig. 127—Various arrangements of T and "Pi" section high-pass filters. (A) and (B) 2-section T-filters; (C) single section "Pi" filter; (D) and (E) 2-section "Pi" filters.

High-pass filters are sometimes used in the audio amplifiers and electro-dynamic loud speakers of radio receivers, to suppress 60 or 120 cycle hum currents, and pass the currents of all higher frequencies.

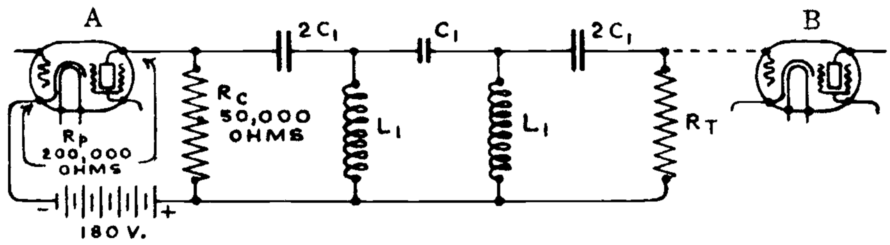


Fig. 128—A practical high-pass filter for keeping low frequency (A-F) current out of a high frequency (R-F) amplifier.

187. Band-pass filters: If a low-pass filter of say 1000 cycle cut-off were connected to a high-pass filter of say 500 cycle cut-off and then to the load, as shown at (A) of Fig. 129, it is evident that below 500 cycles nothing could get through due to the high-pass filter, and above 1,000 cycles nothing could get through due to the low-pass filter. Therefore the frequencies transmitted would be limited to those lying between 500 and 1,000 cycles as shown at (B). This combination is known as a *band-pass* filter, because it passes only a narrow band of some pre-determined frequencies. The circuit at (A) is made up of two "pi" section filters. It is not necessary to make separate filters since the various parts can be

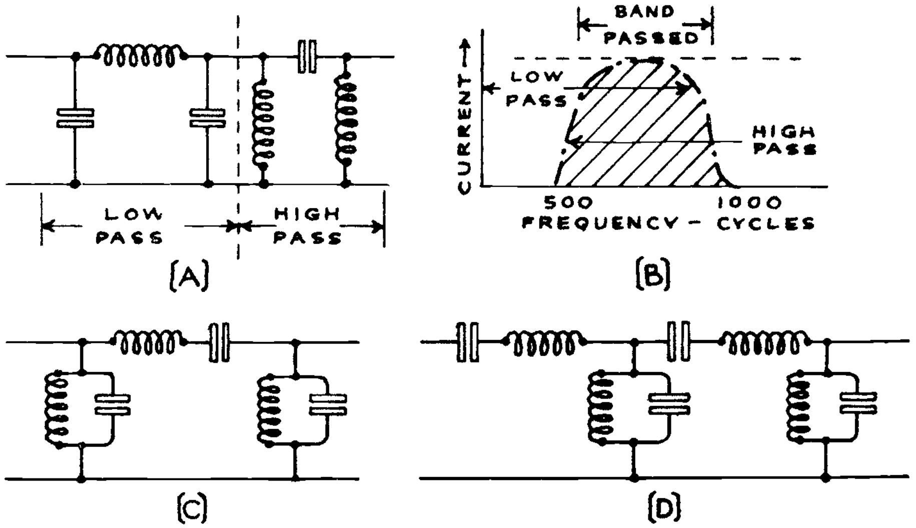


Fig. 129—(A) Combination of single "Pi" low-pass and high-pass filters to give the band-pass effect shown at (B). A practical combined band-pass "Pi" filter is shown at (C). A T-type band-pass filter is shown at (D).

combined into a single filter section as shown at (C), and the same results obtained. This may also be made with two T-section filters in the same way as shown at (D). The type shown at (D) will pass two separate bands of frequencies. This makes it objectionable for use in many applications where only a single band is to be passed. Usually it is necessary and desirable to pass only one band of frequencies rather than two, and since it also takes less apparatus, the filter circuits of Fig. 130 are the ones which are most generally encountered in ordinary band-pass filter work. A little study will show that each of the filter circuits shown here is really nothing more than the general circuit shown in (D) of Fig. 129, but with one or more of the inductances or condensers left out.

A study of (D) shows that the series resonant circuits allow one particular frequency to flow through them more easily than any other. The parallel resonant circuits across the line impede one frequency only, and allow all others to flow right through them, thus by-passing them across. The circuits are so designed that the one frequency which gets through the series resonant circuits is the only one not short-circuited by the parallel resonant circuits.

Every tuned circuit in the ordinary tuned radio-frequency radio receiver is really a one-section filter, but in this case it is a band-pass filter designed to pass currents of one particular small band of frequencies around that to which it is tuned, and block all others. Intermediate fre-

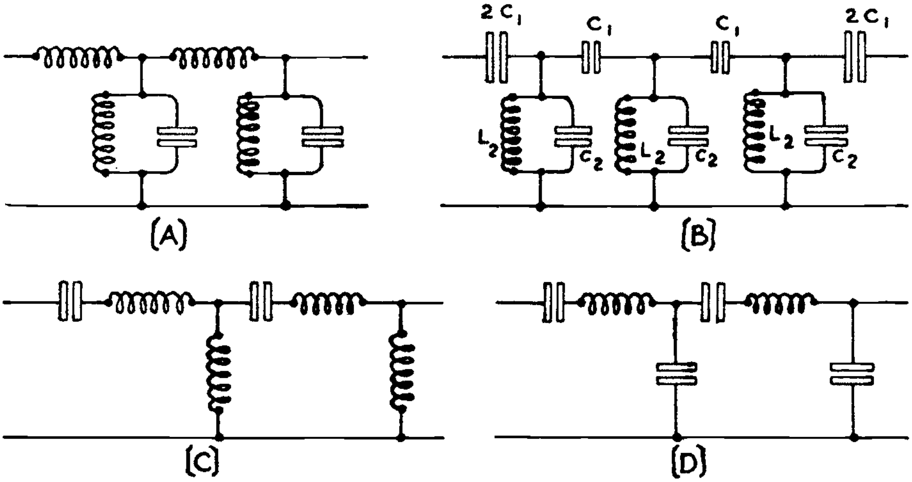


Fig. 130—Four commonly used band-pass filter circuits.

quency transformers in superheterodyne receivers are designed for the same purpose, and in carrier telephone work, filters of all three types are widely used. Various special forms of band filters and band selectors will be studied later in Arts. 360 and 391, in connection with radio receivers.

188. Design of band-pass filters: In designing a band-pass filter three quantities are usually known. These are: the impedance (Z) the filter is to work out of (or into), and the upper and lower cut-off frequencies (f_2 and f_1 respectively). With this data as a basis, the capacitances and inductances required for the filter may be calculated by formulae:

$$C_1 = \frac{f_2 - f_1}{4\pi f_1 f_2 Z} \textit{(farads)} \qquad (29)$$

$$C_2 = \frac{1}{\pi (f_2 - f_1) Z} \textit{(farads)} \qquad (30)$$

$$L_2 = \frac{f_2 - f_1) Z}{4\pi f_1 f_2} \textit{(henries)} \qquad (31)$$

C_1 and C_2 are the capacitances in farads, as indicated in the conventional band-pass filter shown in Fig. 130, L_2 is the inductance of each coil in *henries*, f_2 is the higher cut-off frequency in cycles per second and f_1 is the lower cut-off frequency, Z is the characteristic impedance of the filter. As with the other filters described, Z should be made as nearly equal to the impedance of the source and load, as practical. In practice, the impedance selected is usually that of the line, for some frequency near the middle of the pass-band. The use of these formulas may be illustrated by the following example:

Example: It is desired to make a band-pass filter for a superheterodyne receiver; the filter is to pass a band 10 kc wide and is to have its cut-off frequencies at 100 and 110 kc. It is to be terminated at one end by a resistor of 50,000 ohms which is in the plate circuit of a 227 type vacuum tube having a plate impedance of 10,000 ohms; at the other end it is terminated by a variable grid leak which is adjusted to match the impedance of the filter.

Solution: Impedance R, of the parallel circuit feeding into the filter:

$$\frac{1}{R}=\frac{1}{50,000}+\frac{1}{10,000} \text{ or } R = 8,350 \text{ ohms. (approx.)}$$

$$C_1=\frac{f_2-f_1}{4\pi f_1 f_2 Z}=\frac{110,000-100,000}{4\pi\times 100,000\times 110,000\times 8,350}=.0000087 \text{ microfarads.}$$

$$C_2=\frac{1}{\pi(f_2-f_1)Z}=\frac{1}{3.14\times 10,000\times 8,350}=.0039 \text{ microfarads.}$$

$$L_2=\frac{(f_2-f_1)Z}{4\pi f_1 f_2}=\frac{10,000\times 8,350}{4\pi\times 100,000\times 110,000}=.0006 \text{ henries.}$$

Note: In the above solutions C_1 and C_2 have been converted to microfarads by multiplying the answers given by the formulas by the conversion factor 1,000,000.

189. The band-suppression filter: By inverting the band-pass filter, the filters shown at (A) and (B) of Fig. 131 are obtained. This is called a *band-suppression filter*. The characteristic of this type is shown at (C). Filters of this type are commonly used to suppress electrical disturbances lying within some particular band of frequencies.

The "*wavetrap*" sometimes used in the antenna circuits of radio receivers is a form of band-suppression filter. As shown at (A) of Fig. 132, a series wavetrap consisting of a coil and a variable condenser connected in parallel with each other, are connected in series with the antenna circuit of a radio receiver. When the filter is tuned to resonance for a given frequency, signals of that frequency cannot enter the receiving set since the parallel resonance filter circuit presents a very high impedance to the flow of current of the frequency to which it is tuned. It can be designed to suppress a band of frequencies about 10 kc wide, depending upon the width of its resonance curve. It is a "rejector" wavetrap.

If the filter is shunted across the antenna and ground connections as shown at (B), the signals to which the filter is tuned will go through the receiver while the other signals will be shunted across through the filter since it offers a very high impedance to signals of its resonant frequency and a low impedance to all others. A band of frequencies about 10 kc wide (depending on the resonance curve of the filter) will pass through the receiver coil for any setting of the filter condenser. This is an *acceptor wave trap*. The filter tunes more sharply if it is inductively coupled to the antenna circuit by winding a 5-turn coil over the coil of the filter and connecting it in series with the coil in the antenna circuit.

190. General uses of filters: Electrical filters are used extensively in studying the characteristics of communication equipment and in the transmission of electrical impulses of multiple frequency as exemplified by speech or music. Such filters consist of capacitance and inductance networks so designed that they allow certain frequencies to

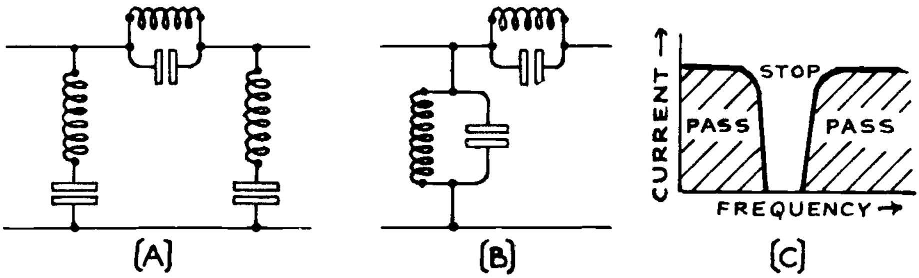


Fig. 131—Two forms of band-suppression filters and the transmission characterstic produced.

pass readily through them while at the same time they attenuate other frequencies strongly. By the use of filters for instance, a composite sound may be divided into several parts, or a fault in telephone apparatus may be remedied by attenuating or placing emphasis on certain ranges of the frequency spectrum.

By means of band filters, it becomes possible to separate in accordance with the frequency. We are thus enabled to transmit a number of messages simultaneously over the same telephone circuit, or through the air, and to separate these messages at the receiving station. For example, in the multiplex telegraph system, known as the carrier current system, there are transmitted over the same pair of wires simultaneously, 10 telegraph messages which are carried by currents of ten different frequencies, all somewhat above those of the voice range; two ordinary telegraph messages, carried by direct currents, i.e., zero frequency currents; and an ordinary telephone conversation. This multiplex telegraph system is in operation between many of the important cities of the country. In every case, the separation of the different messages is accomplished by means of electrical filters which select a single band of frequencies for transmission to the apparatus to which they are connected and fail completely to transmit all the other messages which may be simultaneously received.

Filters are being used more and more in radio receivers in order to obtain certain desired characteristics which are either otherwise unobtainable, or else would be very much more expensive if arrived at by other methods. We will examine these in detail at the proper points during our study of radio receivers.

Resistance-capacity type filters consisting merely of a resistor in series with one side of the line, and one or more condensers across the line, are used extensively in audio amplifiers as we shall see presently. They have one great advantage in this type of work in that they are cheap and do not have any bothersome resonant frequency points which might be objectionable if the ordinary inductance-capacity filters were used.

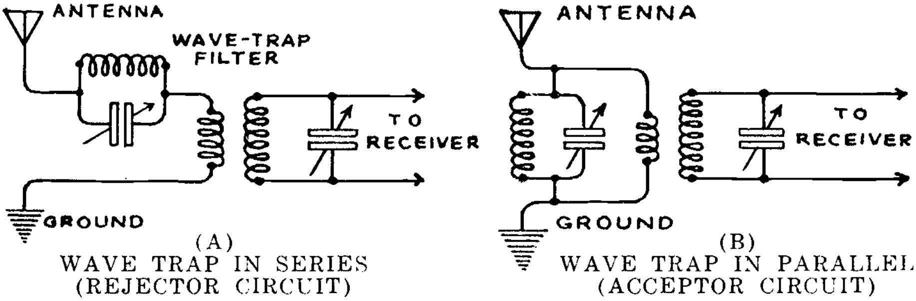


Fig. 132—Band-suppression wave traps or filters connected to the antenna circuit of a radio receiver to eliminate interference from unwanted stations. (A) series wave trap. (B) Shunt or parallel wave trap.

Band-pass filters are being used extensively in radio receivers of both the tuned-radio-frequency (T.R.F.) and the superheterodyne type. They are arranged to pass a band of frequencies approximately 10 kilocycles wide.

In the T.R.F. receivers the 10 k.c. frequency band passed through, can be shifted throughout the entire broadcast band frequency range from 500 to 1500 k.c. by means of the tuning condensers. In the superheterodyne circuit the frequency band-passed is set fixed at some definite value in the intermediate amplifier. At the present time most supers are designed to pass through their intermediate amplifier stages, a 10 k.c.-wide band of frequencies at about 175 or 180 kilocycles. That is, if the intermediate amplifier is designed for, say 175 k.c., then the band-pass filter is arranged to pass the band from 170 to 180 k.c. and sharply cut off all frequencies above and below this value. The simple form of band-pass filter usually employed in circuits of this kind is a bit different from the usual form. In the plate circuit of one amplifier tube we have the primary of an intermediate transformer, forming with its tuning condenser a *parallel* resonant circuit which places a high impedance in the plate circuit of the tube at the particular frequency (or 10 k.c. band of frequencies) to which it is tuned to resonance. This causes maximum amplification of the signals at this band of frequencies. The secondary of the coupling transformer forms a *series* tuned circuit (at the same frequency band) with its tuning condenser, and hence this tends to allow currents of this particular frequency (or band of frequencies) to be passed and to circulate freely and set up comparatively large voltages across the grid input circuit of the following amplifier tube. The net effect then is simply to pass through the band of frequencies to which the primary and secondary tuned circuits of the coupling transformer are resonant, and reduce or completely stop the flow of currents of all other frequencies. The system will be studied in more detail later in connection with superheterodyne receivers. The tuned circuits are made broad enough so they pass a band of frequencies about 10 kc wide, instead of passing only a single frequency as a sharply tuned resonant circuit would do.

REVIEW QUESTIONS

1. Give three examples of mechanical filtering devices and explain their action.
2. What do you understand the term "electrical filter' to mean?
3. What is a low-pass filter? Draw a circuit diagram of (a) a single section T filter of this type (b) a "pi" section.
4. Describe one application of a low-pass filter.
5. What is a high-pass filter? Draw a circuit diagram of (a) a single section T filter of this type, (b) a "pi" section.
6. Describe one application of a high-pass filter.
7. What is a band-pass filter? Draw a circuit diagram of a 2-section filter of this type.
8. Give an application of a band-pass filter.
9. What is a band-rejector filter? Draw a circuit diagram of a 2-section filter of this type.
10. What three principles of alternating currents do the operation of electrical filters depend upon?
11. What is the effect of building a filter with several similar sections rather than a single section?
12. What is meant by the cut-off point of a filter? Draw curves illustrating the point of cut-off for each of the four types of filters.
13. A 2-section low-pass filter connected between the output tube and the loud speaker of a radio receiver is to cut-off at 4000 cycles. The plate impedance of the tube circuit at its source is 2000 ohms. What must be the values of the inductance and capacitance used in the filter? Draw the circuit diagram with all constants marked (a) if the filter is of the "pi" type (b) if it is of the T type.
14. A 2-section high-pass filter connected between the output tube and the loudspeaker of the above radio receiver is to cut off at 100 cycles. What must be the values of the inductance and capacitance used. Draw the circuit diagram with all constants marked, (a) for a "pi" type filter, (b) for a T type filter.
15. What is the effect of resistance in the elements of a filter?
16. It is desired to design a band-pass filter to pass a 10 kc band of frequencies from 170 kc to 180 kc in a 175 kc intermediate amplifier of a superheterodyne receiver. The source and load impedances may be taken as 200,000 ohms. The filter is to be arranged as shown at (B) of Fig. 130. Calculate the values of the circuit constants required.

CHAPTER 13

ELECTRICAL MEASURING INSTRUMENTS

EXTERNAL EFFECTS OF CURRENT FLOW — MAGNETIC TYPE INSTRUMENTS — TANGENT GALVANOMETER — D'ARSONVAL GALVANOMETER — BALLISTIC GALVANOMETER — THE WESTON MOVEMENT — D. C. AMMETER AND SHUNTS — USE OF AMMETERS — EXTENDING RANGE OF D. C. AMMETERS AND MILLIAMMETERS — HOT WIRE AMMETERS — THERMOCOUPLE INSTRUMENTS — DIRECT CURRENT VOLTMETER — INCREASING D. C. VOLTMETER RANGE — MAKING D. C. VOLTMETER FROM MILLIAMMETER — HIGH RESISTANCE VOLTMETER — COMBINED VOLTMETERS AND AMMETERS — WATT METERS — A. C. METERS. — RECORDING WATT-HOUR METER — POWER CONSUMPTION TEST OF RADIO RECEIVER—INCLINED COIL, MOVABLE IRON, AND ELECTRO-DYNAMOMETER TYPE A. C. METERS — DRY PLATE RECTIFIERS AND COPPER-OXIDE TYPE METERS — RESISTANCE MEASUREMENT BY AMMETER & VOLTMETER, VOLTMETER ALONE, OHMMETER — WHEATSTONE BRIDGES FOR MEASURING RESISTANCE, INDUCTANCE OR CAPACITANCE — THE WAVEMETER — MEASURING FREQUENCY AND WAVELENGTH — REVIEW QUESTIONS.

191. External effects of current flow: It must be evident to the student at this time that the two quantities which we deal with most in electrical work are the *current* or rate of flow of electrons through the circuit, and the *voltage* or electrical force which causes the drift of electrons. The *electrical power* in watts may also be considered. It is necessary for us to be able to accurately measure these quantities, in order to design, build and test electrical and radio equipment. Since we cannot see, taste, smell, hear or feel an electric current flowing through a circuit, we must employ one or more of its effects which we can observe, for its measurement.

First, current flowing through a circuit, always produces around it an associated magnetic force or field whose strength is proportional to the rate of current or electron flow (amperes) through it. This is known as the *magnetic effect*, and is illustrated at (A) of Fig. 133. Second, a current flowing against the resistance of a circuit always produces heat, proportional to the square of the current. This is the *heating effect*, as shown at (B). Third, if current is sent through an acid or salt solution between two conducting plates, electrolytic action will take place, the solution will be dissociated chemically and metal will be plated out on one of the plates. This is known as the *electro-chemical effect* and is illustrated at (C).

Theoretically, any of the three effects mentioned and described above could be employed for the measurement of electric current and e. m. f. simply by measuring the intensity of the effect produced by the passage of the current to be measured. Practically however, the magnetic effect is employed most frequently, in what are known as the *magnetic type* electrical measuring instruments, and the heating effect is used in the *hot wire* instruments used for special applications. The electro-chemical effect is not used for current measurement in practical work.

192. Magnetic type instruments: Instruments which depend for their operation on the electromagnetic effect of the electric current are called *galvanometers,* and are the most common types for both d-c and a-c measurement work on account of their ruggedness, high degree of accuracy, simplicity and portability. Since the magnetic field existing around an alternating current carrying wire varies in strength and direction with the current, a-c ammeters and voltmeters are constructed differently than d-c meters. They will be studied later. We will first study the simple forms of galvanometers which led up to the development of the Weston movement which forms the basis of most high grade magnetic type ammeters and voltmeters in use today. Although these galvanometers are not used to any extent at present, a study of them will help the student to easily understand the operation and construction of our present forms of instruments.

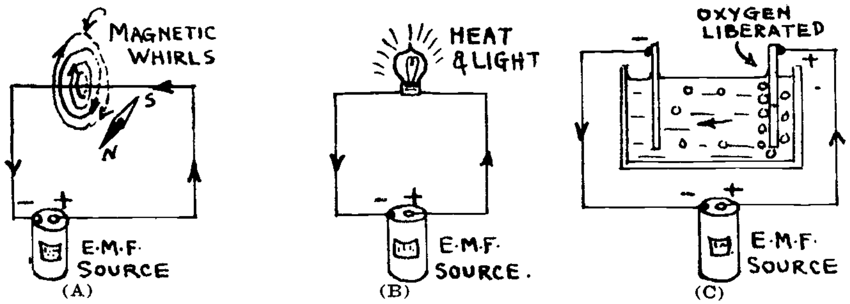


Fig. 133—Magnetic, heating, and electrochemical effects of an electric current.

193. Tangent galvanometer: Probably the simplest type of magnetic current indicating and measuring instrument, is the tangent galvanometer shown at (A) of Fig. 134. A description of the construction and action of this old form of instrument follows:

The tangent galvanometer consists of a vertical coil of insulated copper wire, with a small permanent-magnet compass needle mounted in a horizontal plane at its center, as shown in (A) of Fig. 134. Since this compass needle is free to rotate in a horizontal plane, it will point exactly *north* and *south* in the earth's magnetic field when no current is flowing through the coil. To use the galvanometer, the coil (with no current flowing) is first turned around so its plane lies directly in line with the compass needle, i.e., pointing in a north and south direction. When this is done, the compass needle will be directly over the "zero" mark on the scale mounted underneath it.

Now the current to be measured is sent through the coil of wire. This produces, inside of the coil, a magnetic field whose strength depends upon the number of turns of wire and the current. With the current direction shown at (A) of Fig. 134, a N pole is produced at the front face of the coil and a S pole is produced at the rear, as marked. The S pole of the coil attracts the N pole of the compass needle and makes it tend to move around in a clockwise direction, against the force of attraction of the earth's magnetic field for it. The N pole of the coil will also tend to attract the S pole of the compass needle around in the same direction. The result is that the passage through the coil, of the current to be measured, produces a deflection of the needle around from its "zero position", the tangent of the angle of deflection thus produced being proportional to the strength of the current flowing through the coil. For this reason it is called a "tangent galvanometer". If the galvanometer has been previously calibrated, and the current values are already marked on the scale below the compass needle, the current in amperes flowing when a given angle of deflection is produced can be read directly from the scale. In this way, the instrument can be used as an ammeter, to measure current.

We have here, a device for measuring the flow of electric current by means of the magnetic force of attraction it produces on a movable magnet at the center. This is called a *galvanometer*.

This form of galvanometer has several disadvantages, the most important of which are as follows: (1) it is not readily portable and compact; (2) the readings are affected by any external magnetic fields which may exist around near the instrument; (3) it is not sensitive to small currents since the magnetic field produced by the current must pass through a long air path; (4) the instrument can only be used when the plane of the coil is lined up so it points N and S, and the instrument must be leveled up to permit free rotation of the compass needle every time it is used; (5) it also has the disadvantage that in its simplest form it does not return to the zero point very quickly when the current flow through the coil is stopped, and also, the needle oscillates back and forth for quite a long period of time before it finally comes to rest at any position; (6) the accuracy of its readings are also affected by changes in the earth's magnetism, which as we know may be severe during magnetic storms and times of "sun-spots".

194. D'Arsonval galvanometer: The foregoing objectionable features of the original form of tangent galvanometer, led to its improvement by several men, but perhaps the most important improved form was that of D'Arsonval. This is called the D'Arsonval galvanometer, after its inventor, and is shown in simple form at (B) of Fig. 134. Its construction and operation is as follows:

A permanent horseshoe magnet is placed with its poles as shown and a movable rectangular coil of very fine insulated wire is suspended between the poles at the top by a fine phosphor bronze or steel wire which also serves as one current lead from the coil. The other connection is in the form of a very flexible spiral of soft copper ribbon connected to the bottom of the coil, but exerting no appreciable restraint to its rotation. When the current to be measured flows through the coil, a magnetic field is produced in and around it, the poles being at the back and front faces of the coil as usual. The attraction between the S pole of the coil and the N pole of the permanent magnet, and that between the N pole of the coil and the S pole of the permanent magnet causes the coil to turn around in a clockwise direction (looking down on the top), the amount of deflection being approximately proportional to the current flowing through the coil. The coil will of course move clockwise or counter-clockwise depending on the direction of the current through it. The tendency to rotate is opposed by the twisting or torsion of the suspension wire, and the motion continues until the turning effort (or torque) due to the current is equal to the opposing torque of the suspension wire. A stationary cylindrical soft iron core is placed inside of, and clearing the coil, and is supported from the back. Its purpose is to strengthen the magnetic field between the poles of the permanent magnet, by reducing the reluctance of the flux-path, and hence it makes the instrument more sensitive; that is, a given current sent through the instrument will produce a larger deflection of the coil.

It must be remembered that the coil rotates freely in the small annular space between the magnet poles and the soft iron core. If the coil is wound on a thin non-magnetic metallic frame such as aluminum, the instrument is very "*dead beat*", for the instant the coil moves, eddy currents are induced in the frame in such a direction as to tend to stop its movement. This damps the motion of the coil so it quickly comes to rest when the current flow through the coil is stopped or when it is deflected to any position, instead of oscillating back and forth for several seconds.

A mirror is usually attached to the coil so that a beam of light from an incandescent lamp, directed on it by a system of lenses, will be reflected back on to a semicircular graduated scale placed about one meter from the mirror. When the coil deflects, the mirror deflects with it and the light is reflected back to the scale at an angle as shown at (C). Thus a very small deflection of the coil and mirror will produce a very much enlarged or amplified deflection of the beam of light on the scale so that it can be read accurately by means of a telescope. A complete D'Arsonval galvanometer of this type is shown at the right of Fig. 135. The small lamp which produces the beam of light, and the telescope and scale are supported at the left by an arm. The galvanometer movement and mirror are enclosed in an iron case which shields it from external magnetic fields and is arranged to be mounted on a wall in the position shown. Since the coil and suspensions are exceedingly light, and there are many turns of fine wire on the coil, galvanometers of this type can be made sensitive enough to give a deflection (of the spot of light) of one millimeter on a scale one meter distant from the mirror, for a current of .000000001 amperes. If a resistance of 1,000 megohms is connected in series with the moving coil, an e. m. f. of one volt applied to the meter will produce a deflection of one millimeter division. Therefore it can also be used as a voltmeter by connecting a high resistance in series with it.

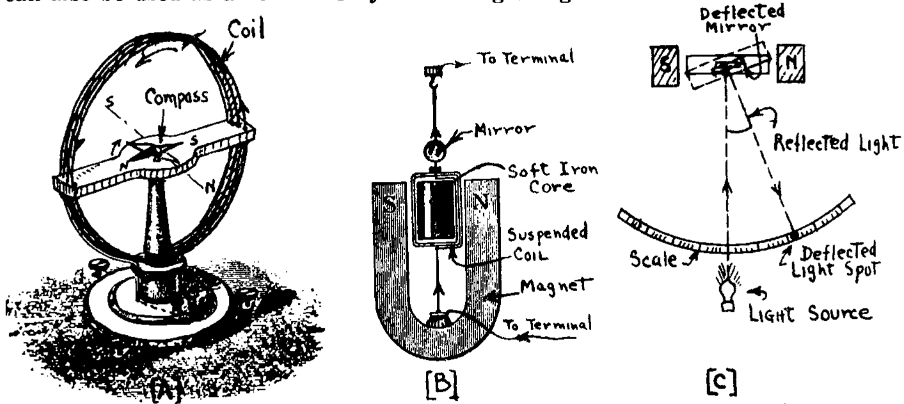


Fig. 134—(A) Simple form of tangent galvanometer. (B) D'arsonval galvanometer movement. (C) Light beam arrangement for amplifying movements of the mirror.

The D'Arsonval galvanometer is quite an improvement over the old tangent galvanometer in that it is not affected by changes in the earth's magnetic field or by external magnetic fields and can therefore be used in close proximity to electrical apparatus. It can also be built very sensitive, but it has several limitations which make it suitable only for use in laboratory work where it is permanently mounted, usually on a wall. It is too large, bulky, and delicate to be conveniently portable, also it must be carefully leveled up so the coil moves freely without touching the pole pieces. This is accomplished by the leveling screws and tension screws provided.

Notice that in the D'Arsonval instrument the permanent magnet is stationary and the coil moves. This construction in refined form is used in most direct-current electrical measuring instruments today.

195. Ballistic galvanometer: A form of D'Arsonval galvanometer which is used for measuring momentary currents (such as currents during discharge of condensers, currents produced by momentary electromagnetic induction etc.) is called a *ballistic galvanometer*.

It is constructed with a wide coil designed to have considerable mass and is arranged so it has very little damping effect. If a momentary current is passed through its coils, the impulse given to the movable coil does not cause appreciable movement at once, owing to the inertia of the heavy moving parts, the result being a slow "swing" of the system. The maximum deflection or "throw" must be noted carefully on the scale, just at the point where the coil and spot of light begin to swing back to zero. The throw is a measure of the *quantity* of electricity sent through the coil. The instrument looks like that shown at the right of Fig. 135. It has a resistance of about 2000 ohms and will produce a deflection of 1 mm. on the scale by a quantity of electricity of about .003 micro-coulomb, the time of the ballistic throw from the position of rest to that of maximum deflection being about 5 seconds.

Ballistic galvanometers are used in many condenser measurements, where the current discharges from the condenser too rapidly to operate the ordinary form of galvanometer or ammeter.

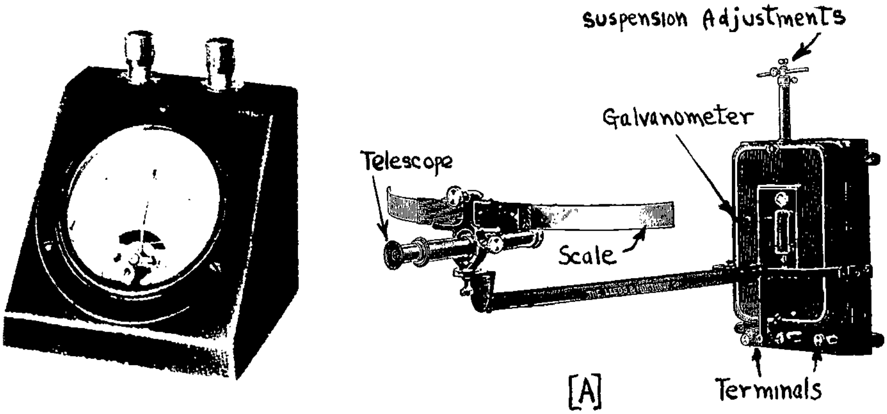


Fig. 135—Left: A modern Weston galvanometer built in portable form with the Weston movement.

Right: A laboratory type of D'arsonval galvanometer used for measurement of small currents or voltages. This same instrument in ballistic form is used to measure momentary currents and voltages.

196. The Weston movement: About 1885 Dr. Weston set about to improve the D'Arsonval galvanometer and reduce it to a form which would meet all conditions of accuracy, ruggedness, portability, compact size, etc., required for electrical measuring instruments which were needed at the time in connection with the development of electric lighting systems and electroplating. The so-called "Weston movement" so widely used today in d-c measuring instruments is the result of his work. He retained the basic idea of the stationary permanent magnet and moving coil, but introduced several refinements of construction which eliminated most of the objections to the old D'Arsonval galvanometer. A description of the Weston movement follows:

A very strong, carefully aged, horseshoe permanent magnet M has two soft iron pole pieces P, fastened to it by screws, as shown at (B) of Fig. 136. The magnet is hoop-shaped at the top in order to obtain a long air gap with consequent reduced magnetic leakage between the pole legs. The stationary soft iron core C, is supported by a screw passing through the brass front cross strip B, extending across the pole pieces. The iron core is smaller in diameter, than the bore of the pole pieces, so a small annular air gap is left between them. In this air gap is a very powerful uniform, radial magnetic field as shown. Since the field is uniform and radial, the instrument has a uniform scale; that is, equal divisions at any point on the scale represent equal changes of current or voltage.

The movable coil shown at (C) consists of a light alumium-alloy rectangular form L, on which is wound many turns of very fine insulated copper wire, W, through which is passed the current (or a definite fractional part of the current) which is to be measured. This coil is provided, above and below, with hardened steel pivots which rest in cup shaped sapphire jewel bearings. It is mounted so it may turn on these pivots, in the unvarying magnetic field existing in the air gaps between the pole pieces and the iron core, as shown at (A). The current is conveyed to and from the coil through two light spiral hair-springs S, (similar to those in a watch) which perform the additional function of always returning the coil to a definite zero position and of exerting a reacting or restoring force whose magnitude is directly proportional to the angular deflection of the coil from the zero position. These two springs are

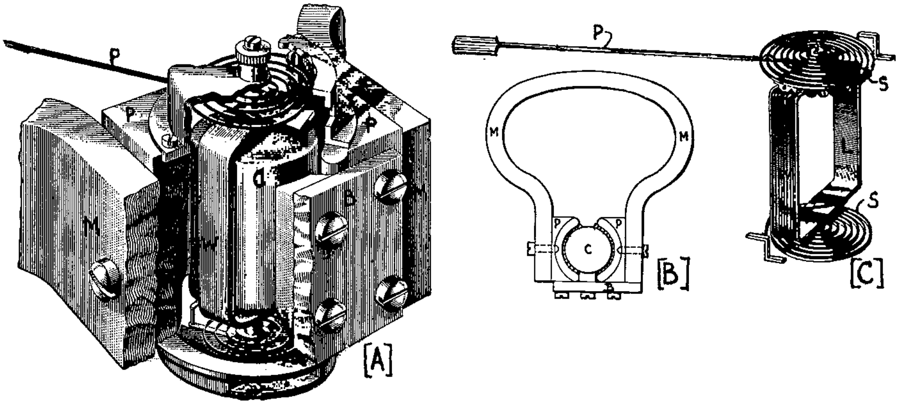


Fig. 136—(A) Assembled Weston d-c meter movement. A portion of the permanent horse-shoe magnet has been cut away at the left, to reveal the interior.
(B) Permanent magnet, pole pieces and core assembled. (C) Movable coil, springs, pivots and pointer assembled.

wound in opposite directions so that any increase or decrease in their length due to changing temperature conditions etc., will affect both an equal amount, and the effect of one in pushing the coil one way or the other is exactly balanced by the equal and opposite effect of the other, so that no change takes place in the position of the movable coil.

Fixed to the coil is a long hollow alumium pointer P, with a flattened knife-like end which moves over a scale which has been graduated during the calibration of the meter at the factory, when its readings were compared with those of a standard precision meter through which the same current was sent. The weight of the pointer is usually balanced by a "balancing nut" which can be moved nearer or further from the pivot. As we shall see, the scale may be calibrated to read amperes, milliamperes, volts, millivolts, etc., depending on what the meter is constructed to measure. The "zero adjuster" is attached to the outer end of the spring, and projects up through the glass in the form of a slotted screw head. When the adjustment is made the spring is rotated slightly either clockwise or counter-clockwise until the pointer is directly over the zero mark.

The entire movable coil assembly is made extremely light and the jewelled bearing have very little friction, so that it requires very little current through the coil to deflect it and the pointer around to full scale position. The number of amperes through the coil required to deflect it around to "full scale" or end position is a measure of the "sensitivity" of the meter. The less current required to do this, the more sensitive is the meter. A meter is made sensitive by using a very strong permanent magnet, a small air gap, a very light coil, and a large number of turns of fine wire on the coil. Instruments of this type usually require between 5 and 20 milliamperes, usually averaging around 15 milliamperes, for full scale deflection of the pointer.

The thin aluminum coil frame makes the instrument "dead beat" due to the opposing eddy currents set up in it when the coil is moving. Since the eddy currents are set up only when the coil and frame are moving, the eddy currents have the effect of damping or retarding any motion of the coil and needle, thus bringing it quickly to rest at the proper point when the current is turned on, and permitting the reading to be taken immediately.

A small portable galvanometer of this type used for measuring very small currents or voltages is shown at the left of Fig. 135. The two terminals are at the top and the instrument is arranged to read currents flowing through in either direction. In instruments designed for great accuracy, a mirror is often set in the scale card as shown in the meters in Fig. 139. Thus if the observer stands directly over the instrument in such a position that the pointer either completely covers its image in the mirror, or appears to be midway in the image, error due to *parallax* or reading of the deflection sidewise, is avoided because the line of vision then coincides with the pointer and its image in the mirror. When reading meters which do not have this mirror, the observer should be careful to keep his eye *directly over* the needle.

The Weston movement just described eliminates all of the objectionable features which are present in the old form of D'Arsonval movement. The rigid mounting of the coil in jewelled bearings makes the instrument rugged, compact, easily portable and very accurate. Of course the permanent magnet in any instrument of this type must not weaken even over a period of years, for any such change will weaken the attractive force for the movable coil and thus make the instrument read low. The permanent magnets of high grade instruments of this type are carefully aged to prevent this. Instruments should be handled carefully, for shocks or jars will tend to weaken the magnet and cause inaccuracy in the readings. Modern electrical instruments represent the finest skill in precision manufacturing. They are built as delicately and as accurately as a watch and should be handled just as carefully. The student is urged to carefully examine the working parts of a high-grade galvanometer, ammeter, or voltmeter. When properly cared for, the readings of instruments of this type may be relied upon to be correct to within a few tenths of one per cent.

197. D-C Ammeters and shunts: We have mentioned several times that the moving element consisting of the coil frame, coil winding, pivots, springs and pointer must be very light to reduce friction in the bearings. An idea of the remarkable lightness achieved in these units may be gained from the fact that in one type of portable Weston combined voltmeter and ammeter, the entire movable system (see C of Fig. 136) weighs less than .007 ounces although consisting of 16 separate little parts. Since the wire wound on such a moving element must be fine and light, it is evident that the movable coil cannot carry very much current without undue heating. The movable element in this form of meter is rarely allowed to carry more than about 0.05 ampere. Thus for ammeters or milliammeters designed to measure currents up to about this value the moving coil is connected directly in the circuit, and carries the full circuit current as shown at (A) of Fig. 137. The reading of the meter is of course directly proportional to the current or (number of electrons per second) flowing through the circuit and the moving coil. An actual Weston meter movement is shown in Fig. 141.

If the meter is to be connected into circuits carrying more current than this, it is evident that we must either increase the size of the wire on the movable coil proportionally to take care of the larger current with-

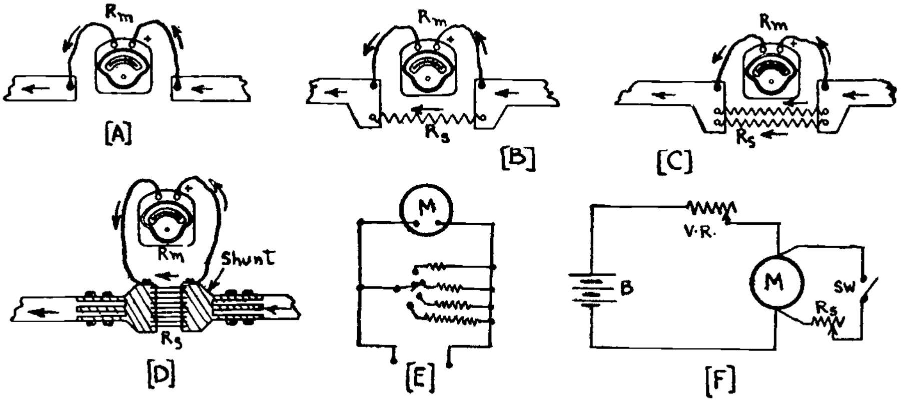


Fig. 137—How shunts are connected to carry a definite fraction of the total current in a circuit, permitting the use of an ordinary galvanometer movement as an ammeter to measure large currents.

out undue heating, or else we must allow only a definite fraction of the total current of the circuit to go through the meter coil, as shown at (B). The former method is impractical for it would result in a clumsy, heavy, movable coil and greatly increased inertia and bearing friction. The latter method is the one used in ammeters. The current is divided, a certain definite part of it flowing through the movable coil and the rest "shunted" around the coil by means of a low resistance "shunt" connected across it. The action of the meter with the shunt may be explained as follows:

At (A) of Fig. 137, the only path for the current is through the moving coil of the instrument. If the current to be measured is greater than the wire on the moving coil can safely carry, part of the current can be "shunted" or allowed to flow through the parallel *shunt* resistor R_s as shown at (B). Suppose the resistance R_s of this shunt is just equal to the resistance R_m of the moving coil of the meter; then, of course, just half of the total current will go through this shunt and half will go through the meter coil, and all we have to do is multiply any reading of the instrument by 2 to determine the total current. If we carried this further and added another similar shunt as at (C) the instrument reading would represent ⅓ of the total current. We might continue this indefinitely, adding any number of equal shunt resistors in parallel and thereby making the current actually flowing through the coil less and less.

In practice, a single shunt resistor of the proper resistance value and current carrying capacity is connected across the moving coil for each particular current range of the ammeter. The shunts are usually made of Manganin alloy since this has a very low temperature coefficient of resistance and therefore the heat developed by the flow of current through the shunt will not change its resistance appreciably. Where the instrument is to be used to measure large currents, the shunt is constructed in multiple blade form with several strips firmly soldered into a block at each end, and having air spaces in between them for cooling, as shown at (D) of Fig. 137. The current which a shunt is to carry chiefly determines its physical size, because enough metal and surface area must be provided to prevent overheating, and at the same time the resistance must be high enough to allow a suitable portion of the current to flow through the movable coil of the instrument. When the current is greater than about 30 amperes, it is not practical to construct an instrument with a self-contained shunt, because the instrument itself would become so large as to be unwieldy, the heat developed in the shunt is not readily dissipated, and besides, the path of the current conductors would have to be more or less indirect in order to reach the instrument. It is much more convenient, therefore, to construct the shunt separately, provide it with suitable terminals and connections, and insert it by cutting the main circuit conductors (or bus bars as they are called) at any convenient point. The indicating instrument is then connected across the shunt by means of a set of flexible leads whose resistances are measured and adjusted exactly so as to form part of the instrument. These should never be cut or lengthened, as their resistance would then be changed.

For ammeters of medium range up to about 30 amperes, the manufacturer puts the shunt inside of the instrument and calibrates the scale so that it correctly indicates the *total current* without any need for further calculations. Most ammeters used in radio work have the shunts enclosed within the instrument case.

198. Use of ammeters: From the foregoing it is evident that a d-c ammeter really consists of a portable type of D'Arsonval galvanometer with a suitable shunt connected across it, and a scale calibrated in amperes. The fine wire on the movable coil only carries a definite small fraction of the total current, which is being measured.

Ammeters are used in all branches of electrical work and are designed to measure small currents of a few thousandths of an ampere (milliampere) as well as currents of thousands of amperes. In radio work, low reading ammeters are commonly used to measure the currents in the filament circuits of the vacuum tubes. Ammeters used to measure the plate currents of these tubes are called *milliammeters* (one milliampere equals 1/1000 ampere), because their scales are marked to read the current in milli-amperes. The only difference between a d-c ammeter and d-c milliammeter is in the size of the shunt employed.

The ammeter or milliammeter must *always* be connected in *series* with *either* side of the line, as shown at (A) of Fig. 137. When connecting an ammeter in a circuit, it is necessary to open one side of the line and connect the ammeter so the current flows *through* it. The instrument should have a range sufficiently high to carry the current flowing. Remember that the ammeter must always be connected in *SERIES* with *one side* of the line. Never connect an ammeter *across* the line, for since it has a very low resistance, the e.m.f. across the line would send a heavy rush of current through it and burn it out.

199. Extending the range of d-c ammeters and milliammeters: It is often desired to increase the range of a d.c. ammeter or milliammeter on hand, in order to save the cost of a new instrument of larger range This may be done by connecting an additional shunt resistor across the terminals of the meter to shunt a portion of the total current around it. Thus consider in (A) of Fig. 137, that the meter on hand (whether it already has a self-contained shunt in it or not does not make any difference) has a range of 0-1 milliamperes. Suppose we want to extend its range to 10 m.a. Then a shunt R_s must be connected across it such that the moving coil of the *meter* will carry 1/10 of the total current and the *shunt* 9/10, or the shunt resistance will be 1/9 of the meter resistance. If the meter resistance is 27 ohms for instance, the shunt resistance required to make a 0-10 milliammeter of it would be, $1/9 \times 27 = 3$ ohms.

In general let us suppose the meter considered has a resistance of R_m ohms and let R_s be the resistance of the additional shunt to be connected across it to increase its range. Let I_m be the original maximum scale reading (in amperes or milliamperes) of the instrument. Let I, be the desired new maximum reading (correspondingly in amperes or milliamperes). Then:

$$\frac{I}{I_m} = N = \text{multiplying factor.}$$

$$\text{and } R_s = \frac{R_m}{N-1}$$

Example: A milliammeter having a range from 0-50 milliamperes and an internal resistance of 2 ohms, is to be converted into an ammeter having a maximum range of 10 amperes. What value of shunt resistor must be connected across its terminals?

Solution: 10 amperes = 10,000 milliamperes.

$$\text{therefore } N = \frac{I}{I_m} = \frac{10{,}000}{50} = 200$$

$$\text{and } R_s = \frac{R_m}{N-1} = \frac{2}{200-1} = .01 \text{ ohm (approximately)} \quad \text{Ans.}$$

Thus a shunt resistor of .01 ohm must be connected across the meter. This should be of a size able to carry the current without undue heating. All readings as read on the old scale of the meter must now be multiplied by the multiplying factor N, (200 in this case) to obtain the correct reading in milliamperes.

A number of shunts may be connected across a meter and controlled by a low resistance contact switch, so that any one of them may be put in the circuit at a time. This arrangement is shown at (E) of Fig. 137.

It is evident from the above problem, that in order to calculate the value of R_s by this method, the exact value of the internal resistance of the meter must be known. This information can be obtained from the manufacturer of the meter. The resistance of most small 2 inch and 3 inch diameter type milliammeters is in the neighborhood of 20 to 50 ohms.

The approximate resistance values of the Model 301 Weston microammeters and milliammeters, and corresponding Jewell meters, are given in the table below to aid in calculating the proper resistance values to be used for extending their ranges. The model 301 type instruments are probably the most popular ones used in radio work on account of their small size, low cost, and general usefulness.

TABLE OF COMMON MILLIAMMETER CHARACTERISTICS

Weston (Model 301)			Corresp. Jewell Meters	
Range Micro-Amp.	Resistance Ohms	Number of Divisions on Scale	Resistance Ohms	Number of Divisions on Scale
200	55	40	140	40
300			140	60
500	55	50	140	50
Milli-Amp.				
1.	27	50	30	50
1.5	18	75	30	75
2.	18	40	25	40
3.	18	60	20	60
5.	12	50	12	50
10.	8.5	50	7	50
15.	3.2	75	5	75
20.	1.5	40		
25.	1.2	50	3	50
30.	1.2	60		
50.	2.0	50	1.5	50
100.	1.0	50	.75	50
150.	.66	75	.5	75
200.	.5	40	.37	40
250.	.4	50		
300.	.33	60	.25	60
500.	.2	50	.15	50
800.	.125	40		
1000.	.1	50		

Courtesy Aerovox Research Worker

If the meter resistance is not accurately known, the exact value of shunt resistance required may be found in another way as shown at (F) of Fig. 137.

Suppose we desire to calibrate a 10-milliampere meter so that it will read up to 50 milliamperes. We would connect a battery, B, as indicated on the diagram, in series with a variable resistance, V.R., so as to limit the current passing through the meter (without a shunt) to 10 milliamperes. The resistance would be varied until the meter read exactly 10 milliamperes and then the resistor R_s (the shunt) would be switched across the meter and its resistance altered until the meter read 2 milliamperes. Under such conditions (with the shunt connected), a reading of 2 milliamperes on the meter would mean that 10 milliamperes were actually flowing through the circuit. Likewise, full scale deflection would indicate a 50-milliampere flow although the needle pointed only to 10 milliamperes. The same procedure would be followed in shunting any instrument, i.e., setting up a circuit which will pass sufficient current to give a maximum deflection on the meter, then shunt the meter and reduce it a definite amount such as one half, one third, or one fifth, then, in order to determine the actual current flowing in the circuit with the shunt connected, it is merely necessary to multiply the meter reading by 2, 3, or 5, depending upon how much the original deflection of the meter was reduced by the shunt.

Resistances selected as shunt multipliers (or as series multipliers for voltmeters) should be of the precision type manufactured especially for the purpose (see Fig. 143) and should be constructed to maintain their resistance unchanged over a long period of time. They should be accurate in value, and should be wound with wire such as Manganin, Chromel, Nichrome, or Constantin, which have very low temperature coefficient of resistance, so that the resistance does not change appreciably with change of temperature. They must be of a wattage rating sufficient to insure cool operation. Also in connecting a new shunt resistor of a certain value, care should be taken to have the connecting wires of low resistance so that no appreciable resistance will be added by them. This means that short thick copper wires should be used for connection of the shunt to the meter and that all connections should be well made. In commercial meters, the connecting cables have already been considered as forming a part of the shunt resistance, so they should never be altered in any way.

200. Hot wire ammeters: The heating effect of electric current is employed in another form of ammeter called the *hot wire* ammeter. This type of meter is frequently used in radio work, since it will operate equally well on direct current, or alternating current of any frequency (the heating effect of an electric current being independent of the frequency). The fundamental arrangement in this form of meter is shown at (A) of Fig. 138.

The platinum wire D C passes around pulley K and is held taut by spring S acting on insulating block B. The current to be measured flows only up through the

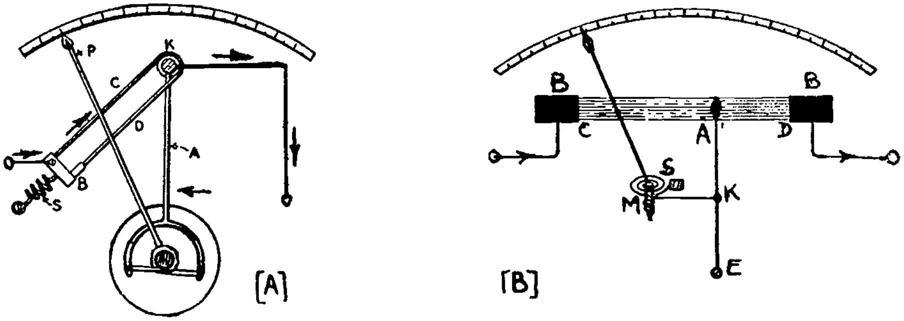
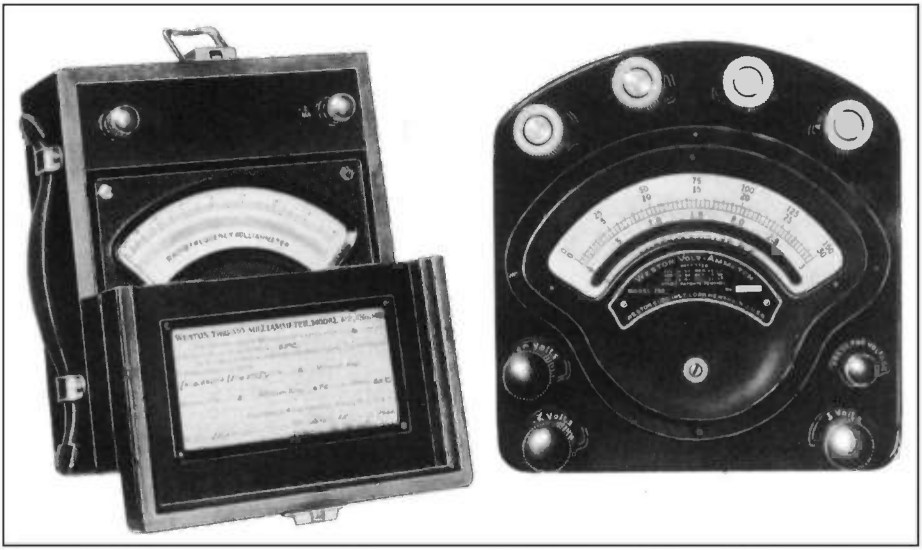


Fig. 138—(A) A form of hot-wire ammeter used for measuring small current.
(B) A hot-wire ammeter used for measuring larger currents.

branch C of the wire as shown, and consequently that branch heats up due to the passage of current, and lengthens. The slack is taken up by the pull of spring S, causing a slight clockwise rotation of the pulley K, which causes arm A (pivoted at K) to swing to the left. This arm has two prongs at its lower end, between which a silk thread is stretched after looping itself around shaft at the lower end of the pointer P. The slight expansion of the wire is thus magnified by the mechanism, to that a large scale reading is obtained.

When large values of current are to be measured, a shunt is provided to divide the current flow. An inductive shunt with even one-half turn of wire cannot be employed because if the meter is used to measure current at *radio frequencies* (above 20,000 cycles per second), the impedance of the shunt would vary with each change of frequency since $X_L = 2\pi fL$. Consequently, hot wire meters for large currents are constructed as shown at (B) of Fig. 138. Several resistance wires C D, are stretched in parallel between large copper blocks B B. The wire A E is attached to wires C D. A silk thread is attached to A E at point K and then wound around shaft M, in such a direction that it will work against spring S, which would normally cause the pointer to move to the full scale position. However, by means of the thread it is normally held in the zero position. When current is flowing through C D it expands, releasing the pull of the thread and allowing the pointer to move across the scale. The stronger the current, the more the wire expands and the further the pointer moves over the scale.

The type of hot wire ammeter described above is relatively slow in its operation and the wire is affected by changes in room temperature and



Courtesy Weston Elect. Inst. Co.

Fig. 139—A portable 0-2 thermo-milliammeter is shown at the left. At the right is a portable precision type d-c volt-ammeter having three current ranges and three voltage ranges. Its circuit diagram is shown in Fig. 145.

has a tendency to stretch when no current is passing through it. This makes it necessary to reset the needle to zero almost every time the instrument is to be used. The divisions on the scale of a hot wire ammeter are not uniformly spaced, since the heating effect and movement of the needle depends on the square of the current (I^2R) flowing through the hot wire. The divisions near the zero end are crowded more than at the high end, as shown in the meter at the left of Fig. 139. This type of instrument is being largely superseded by instruments operating on the thermo-electric principle. This type will now be described.

201. Thermo-couple instruments: In the *thermo-couple* ammeter or galvanometer, the sensitive element is a junction of two dissimilar metals. When two dissimilar metals are joined together and the junction heated, a voltage is generated which is proportional to the difference in temperature between the heated junction and the other ends of the wires.

Experiment: The principle of the thermo-couple can be illustrated by twisting together one end of an iron or German-silver wire and one end of a copper wire. The other ends of the two wires are connected to a low reading d-c milliammeter and the twisted joint held over a gas flame. The milliammeter needle will move, showing that an e.m.f. and resulting current is produced by heating the junction of the two dissimilar metals. If the flame is removed and the junction is allowed to cool slowly, the milliammeter reading will drop slowly.

It is also true that when a current flows across the junction of two different metals, some heat is produced. With some combinations of metals, this effect is noticeable even with very weak currents.

Parts (A) and (B) of Fig. 140 show two methods of using the principle of generating an e.m.f. by a thermo-couple, in connection with a

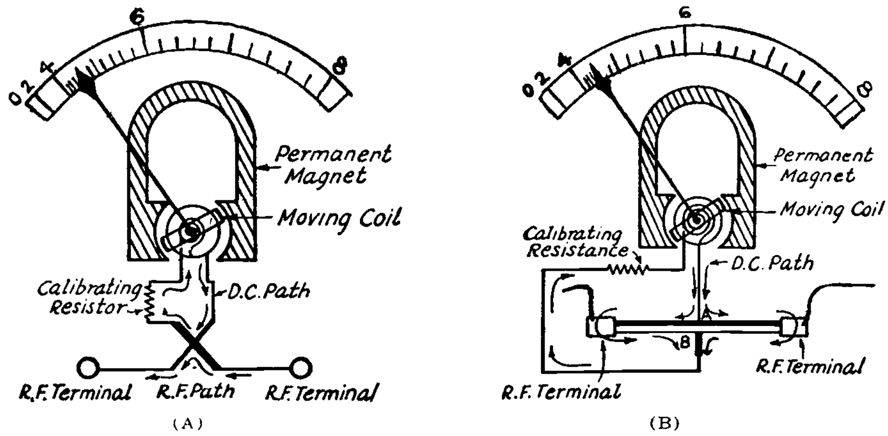


Fig. 140—The principle of operation of thermo-couple instruments.
(A) Single thermo-couple instrument for measuring small currents.
(B) Compound thermo-couple instrument for measuring larger currents.

D'Arsonval movement to measure current of any frequency. These instruments are used more particularly for measuring radio-frequency currents.

The construction shown at (A) is employed where the amount of current to be measured is relatively small, usually not to exceed one half ampere. Two small wires of dissimilar metals are electrically welded together at the center. The radio-frequency current to be measured, passes in through one wire and out through the other, heating the wires and the junction. The remaining ends of the wires are connected through a calibrating resistor to the terminals of the moving coil of the instrument. The heating effect of the radio-frequency current passing through the junction of the dissimilar wires causes a direct current e.m.f. to be generated, which in turn results in a flow of direct current through the movable-coil circuit of the instrument, as shown in the illustration.

The heating effect is proportional to the square of the radio frequency current being measured, whereas the voltage generated across the junction is proportional to the temperature. Therefore, the motion of the pointer over the scale will increase approximately proportionally to the square of the radio-frequency current passed through the thermo-couple. Because of these factors, the instrument has a scale which is crowded at the lower end and more open at the upper end. This makes it necessary to purchase instruments of such a capacity that the average current to be measured will cause a deflection over the "open part" of the scale. Radio-frequency ammeters of this type are not especially accurate below a quarter of the full scale range, because the divisions are crowded at the lower end.

Where the radio frequency current to be measured exceeds approximately one half ampere, it is customary to use two dissimilar wires connected in parallel as far as the radio-frequency is concerned, but connected in series as far as the thermo-electric effect is concerned. This system of connections is shown at (B) of Fig. 140. The heavy line represents one type of metal and the thin line another. Manganin and "Advance" wire are used. It will be noted that the voltage produced at the junction "A" is in the same direction as the voltage produced by junction "B", and they are in series so far as the d-c path is concerned, so they add together. This results in not only a higher thermo-electric voltage, but also much greater current-carrying capacity.

Most thermo-couple instruments are designed for a d-c voltage across the moving coil at full scale, of between 15 and 25 millivolts. In all cases they are calibrated by adjusting a small calibrating resistor connected in series with the moving coil.

This permits of re-calibration of the meter without any need for the adjustment of the thermo-couple or moving coil.

The usual difficulty encountered with thermo-couple radio-frequency instruments is the burning up of the thermo-couples by current overload. This seldom results in any damage being done to the movement and the trouble can be corrected simply by replacing the damaged thermo-couple with a new one. Most manufacturers of instruments of this type will sell the thermo-couples separately so that the customer can make his own replacements. They are usually sealed in a vacuum in a glass tube.

When replacing the thermo-couples, it will usually be necessary to adjust the resistor connected in series with the moving coil in order to re-calibrate the instrument. Calibration can be made with 60-cycle current, as the reading of the instrument is the same on radio frequencies as it is at 60 cycles.

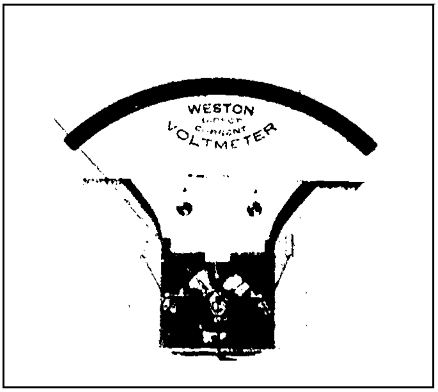
The range of a thermo-couple instrument can be changed by soldering a shunt made of a short piece of copper wire across the thermo-couple lugs. If it is necessary to double the capacity of the instrument, the pointer should be brought to full-scale reading by means of 60-cycle a-c. A shunt should then be soldered between the brass block carrying the thermo-couple, and adjusted so that the instrument reads one-half the full scale value. The current passing through the instrument then will be represented by the reading of the instrument multiplied by 2.

Shunts on radio frequency instruments always should be as short as possible, and placed parallel and close to the thermo-couple. If they are placed outside the instrument case, the instrument will not read exactly the same on radio frequencies as it does on low frequencies.

Thermo-couple instruments can be used in d-c circuits as well as in a-c circuits of any frequency. The reading is not altered by the frequency of the current.

202. Direct current voltmeter: A voltmeter is used to measure the difference of electric pressure between two points in an electric circuit. This difference of electric pressure or potential is commonly called "voltage" or "voltage drop". Voltmeters are used extensively in all kinds of electrical work, and are always connected "across," or "in parallel with," the source of voltage.

If a milliammeter were connected directly across the line, the e.m.f. would send a strong current through the fine wire, low resistance, moving coil and burn it out. To prevent this, a *high fixed resistance* is connected in series with the moving coil, as shown at (A) of Fig. 142. The milliammeter movement can then be connected across the line in series with this resistance and be used to measure voltage, since the current flowing through the coil, and therefore the turning force at any instant, is proportional to the voltage applied across the terminals of the instrument, $(I=\frac{E}{R})$. A voltmeter is simply a galvanometer or milliammeter movement (Fig 141) connected this way and having its scale graduated in volts instead of milliamperes. Whenever space is available the series resistor is contained within the case of the instrument. The series resistor is considered to be part of the voltmeter. Most voltmeters have a relatively high resistance, so they take a very small current from the line.



Courtesy Weston Elect. Inst. Co.

Fig. 141—A typical Weston d-c movable-coil system. When a series resistor is added to this unit, it becomes a voltmeter (as marked). When a shunt is connected across its terminals, it becomes a milliammeter or ammeter.

Suppose the galvanometer movement in the voltmeter of (A) in Fig. 142 is so constructed that its pointer deflects over the full scale when 1 milliampere flows through the coil. Let us assume this is to be built in the form of a voltmeter having a range of 150 volts. Then enough resistance R, must be connected in series with the coil so that when the voltage across the terminals of the meter is 150, exactly 1 milliampere will be flowing through the resistor and coil, and the pointer will be deflected to the end of the scale.

By Ohm's law. $E=I\times R$.

1 milliampere equals .001 ampere; therefore since $E=I\times R$, $150=.001\times R$

$$\text{from which } R=\frac{150}{.001}=150{,}000 \text{ ohms.}$$

The symbol R_m is usually emplyed to designate the *total resistance* of the meter, but since the resistance of the moving coil is very small compared to the series resistance R, R_m is taken as being the same as the series resistance in most practical problems. The scale of the above instrument would be graduated uniformly in volts, with the maximum at 150 volts.

The high resistance is usually placed inside the voltmeter case, and connected in series with the coil. It is called a *multiplier resistance*. When space is not available, external resistors or "multipliers" are used.

D'Arsonval voltmeters sometimes cause trouble due to open circuits in the multiplier or series resistor. These resistors are wound of the thinnest resistance wire to be had, and are easily damaged by mechanical abuse or by allowing the multiplier to get wet. If the multiplier is made

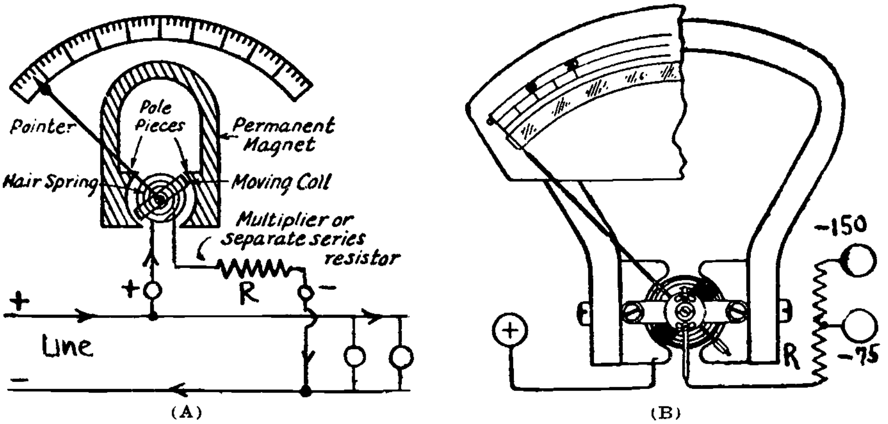
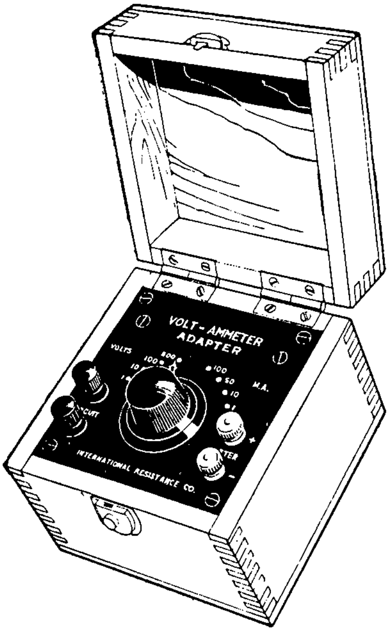


Fig. 142—The general arrangement of a d-c volmeter. In addition to the basic moving coil assembly there is a resistor connected in series with the coil. This "multiplier" resistor determines the range of the meter. At (B) is shown the use of a tapped multiplier resistor to obtain a voltmeter having two ranges, 75 volts and 150 volts.

up of sections and becomes open-circuited, the open section can usually be located and bridged, without the necessity of sending the instrument back to the manufacturer.

It is common to build voltmeters so they have more than one range. This is done by simply tapping the series resistor at suitable points for the low voltage ranges. Thus in the voltmeter considered above, the total series resistor is 150,000 ohms. If a tap were made at the center of this and brought out as shown at (B) of Fig. 142, a voltage of only 75 volts applied between the common terminal and the tap at this 75,000 ohm section, would send a current of $I = \frac{E}{R} = \frac{75}{75{,}000} = .001$ ampere through it, and would produce full-scale deflection. Thus, this would provide a 75-volt range for the instrument in addition to the 150-volt range. Three binding posts would be arranged on the instrument as shown. In order to have the current flow through the coil in the proper direction, the binding post marked + is connected to the positive wire of the line, and either of the other posts are connected to the — side of the line. A small push-button switch is often provided in portable instruments so that the voltmeter circuit may be closed only when the measurement is being taken.

When using a double-range voltmeter or ammeter, care should be taken not to accidentally apply too much voltage or current to the low-scale terminals, since burn-out of the moving coil may result. If the voltage or current in the circuit are not known, the high-reading range should



Courtesy International Resistor Co.

Fig. 143—**Left**: A multiplier and shunt box which enables one to make either a 4-range milliammeter or a 4-range voltmeter from a single low-reading milliammeter.

Right: A precision wire-wound multiplier resistor for increasing the ranges of voltmeters or making oltmeters of any desired ranges from milliammeters.

always be tried first. Then if the reading is less than the highest value of the lower reading range, that range should be used for the final test.

203. Increasing d-c voltmeter ranges: The range of any voltmeter may be increased to any practical limit by inserting a "multiplier" resistance in series with the voltmeter. The resistances should be of the precision type, and permanent in value, as in the case of the resistors used for ammeter shunts. A resistor made especially for this purpose is shown at the right of Fig. 143. At the left of Fig. 143 is shown a combined shunt and multiplier box having precision adjustable resistors which enable one to make either a milliammeter having four current ranges, or a voltmeter having four voltage ranges, from a single low-reading milliammeter. A multiplier of this type is of considerable value in radio test work, in that it does away with the necessity of having a number of milliammeters and voltmeters of different ranges for various tests and measurements.

The customary method of increasing the range of a d-c voltmeter is to connect a high resistance in series with it.

Let R_v=resistance of voltmeter in ohms, or, if ohms-per-volt is given, then

R_v=ohms-per-volt $\times$ original full-scale range of meter, in volts.

V_1=original full-scale range of meter, in volts.

V_2=desired new maximum range, in volts.

then $\frac{V_2}{V_1}$=N=multiplying factor.

R_m=resistance of multiplier to be connected in series with the meter, in ohms.

$$\text{Then} \quad R_m = (N-1) \times R_v$$

The ratio $\frac{V_2}{V_1}=N$ is the "multiplying factor" by which any reading on the old voltmeter scale is to be multiplied in order to determine the true voltage being measured.

Problem: The range of a voltmeter having a range of 150 volts and having a resistance of 150,000 ohms is to be increased to 750 volts. What multiplier resistance must be connected in series with it?

Solution: $N=\frac{V_2}{V_1}=\frac{750}{150}=5$=multiplying factor.

and $R_m=(N\text{-}1)\times R_v=(5\text{-}1)\times 150{,}000=600{,}000$ ohms. Ans.

Each reading taken on the voltmeter according to its old scale, must be multiplied by 5 to get the true voltage.

A series resistor properly tapped can be used to provide a number of voltage ranges, as shown at (B) of Fig. 142. If the resistance of the voltmeter R_v is not known, it can be found by connecting it across a source of potential, within the range of its scale, with a milliammeter connected in series with it to indicate the current drawn by the meter from the line. The resistance of the voltmeter is then equal to

$$R=\frac{\text{Reading of the voltmeter (volts)}}{\text{Reading of the milliammeter (M.A.)}}\times 1{,}000.$$

204. Making d-c voltmeter from milliammeter: A voltmeter is simply a galvanometer in which a coil of high resistance is connected in series with the moving coil. Therefore it is a simple matter to convert a d-c milliammeter into a voltmeter by connecting a resistor of the proper value in series with it. To make a d-c milliammeter into a d-c voltmeter:

Let I=original maximum full-scale range of meter, in milliamperes.

V=desired full-scale range of meter, in volts.

R_m=resistance of multiplier required, in ohms.

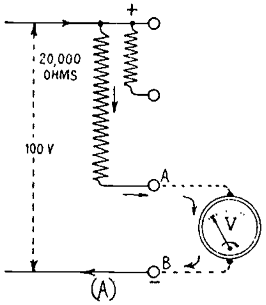
$$\text{Then}\quad R_m = \frac{1{,}000 \times V}{I}$$

Example: A milliammeter having a current range of one milliampere and a resistance of 25 ohms is to be converted into a voltmeter having a range of 750 volts, by connecting a "multiplier" resistor in series with it. What must be the value of this resistor?

Solution: $R_m = \frac{1000 \times 750}{1} = 750{,}000$ ohms. Ans.

It will be noticed that the formula above neglects the resistance of the moving coil, since this is usually very small compared to that of the series resistor when high voltage ranges are to be obtained. If the voltmeter range is to be below about 10 yolts, R_m in the above formula should be considered to be equal to the actual resistance of the meter plus that of the added multiplier resistance.

205. High-resistance voltmeter. The function of a voltmeter is to measure the difference of potential existing between two points in a circuit. It should not influence in any way, the circuit or device across



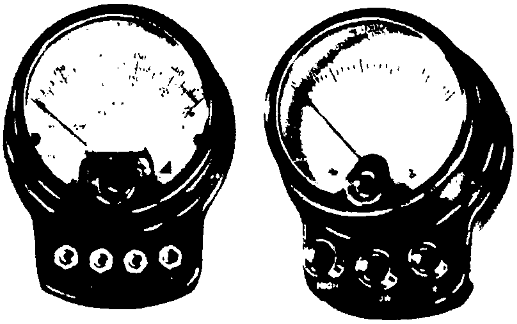


Fig. 144—(A) Connection of a voltmeter to the output circuit of a B-eliminator.
Middle: A 3-range d-c high resistance voltmeter having a resistance of 1000 ohms per volt.
Right: A 2-range a-c voltmeter. These instruments are very useful in radio tests and service work.

which the difference of potential exists. Since every voltmeter will draw some current from the circuit across which it is connected, this current really puts a load on the circuit or device being measured. If the circuit or device has quite some resistance, the meter current flowing through it may produce an additional appreciable fall of potential through it. In this case, the voltage indicated by the meter, is really *lower* than the actual voltage which exists across the circuit normally when the meter is not connected to it.

Thus in (A) of Fig. 144, suppose we are to measure the output voltage across the B battery eliminator circuit at A - B. An e.m.f. of say 100 volts is applied to the circuit by the rectifier tube, and a resistor of 20,000 ohms is in series with the voltage tap we are connecting the voltmeter across. Suppose the voltmeter has a range of 150 volts and a total resistance of 1,000 ohms. The current actually flowing through the resistor and the voltmeter may be found by Ohm's law. Since the 20,000 ohm resistor and the voltmeter resistance are now in series we have:

$$I = \frac{E}{R} = 100 \div (20{,}000 + 1{,}000) = .0048 \text{ amperes, or } 4.8 \text{ milliamperes.}$$

This current flowing through the 20,000 ohm resistance causes a voltage drop across it of $E = I \times R = .0048 \times 20{,}000 = 96$ volts.

The voltage actually recorded on the meter then, is the difference between the applied circuit voltage and the drop across the 20,000 ohm resistor or,

$$\text{Voltage at A B} = E - (I \times R) = 100 - 96 = 4 \text{ volts.}$$

Thus the meter is not indicating the true voltage of the circuit, since it is drawing so much current from the circuit that the circuit voltage drops when it is connected. The meter reads 4 volts, whereas the voltage of this circuit when the meter is not connected, is 100 volts. Of course this is an exaggerated case.

The remedy for this condition is to use a *high-resistance* voltmeter, that is, one having a high resistance connected in series with its moving coil. Suppose the meter has a resistance of 1,000 ohms for each volt range of its scale (1000 ohms per-volt), then its total resistance is $150 \times 1000 = 150{,}000$ ohms. The current drawn by such a meter from the circuit just considered would be,

$$I = \frac{E}{R} = 100 \div (20{,}000 + 150{,}000) = .0006 \text{ amperes, or } .6 \text{ milliamperes.}$$

and the $I \times R$ drop across the circuit resistor is,

$$E = I \times R = .0006 \times 20{,}000 = 12 \text{ volts}$$

and the voltage read at A B would be $100 - 12 = 88$ volts.

This shows that the high resistance voltmeter gives a reading of 88 volts which is much nearer the true open-circuit or no-load voltage of 100 volts than before.

Since a voltmeter having a high resistance takes very little current from the line, the meter itself must be very sensitive, that is, it must require very little current to move its coil and pointer over full scale deflection. This means that either the permanent magnet must be stronger than in the usual meter, or else more turns of wire must be wound on the moving coil to obtain the same ampere-turn effect at a smaller value of amperes. The latter method is used in the construction of high resistance voltmeters used in radio work. The moving coil has several layers of exceedingly thin copper wire in order to produce the necessary magnetic field strength. Such meters have a resistance as high as 1000 ohms-per-volt. The term *ohms-per-volt* may be understood by considering the specific case of a 1000 ohms-per-volt meter having three ranges, 7.5, 150, and 750 volts. Then the resistance in series with the 7.5-volt terminal is 7.5×1000 or 7,500 ohms; that in series with the 150-volt terminal is $150 \times 1000 = 150{,}000$ ohms; that in series with the 750-volt terminal is $750 \times 1000 = 750{,}000$ ohms.

The "ohms-per-volt" value or R_{pv} is equal to the total resistance R_t of the meter divided by the maximum voltage E_t marked upon the scale considered, or

$$R_{pv} = \frac{R_t}{E_t}$$

Voltmeters having a resistance of 1000 ohms-per-volt are used extensively for voltage measurements in radio receiver power packs. A

3-scale voltmeter for this purpose is shown at the middle of Fig. 144. Voltmeters having an ohms-per-volt value as low as 100 are used in ordinary electrical work, since the few milliamperes of current taken by the meter is not objectionable here.

It should be remembered that it is not possible to make a high-resistance voltmeter of the same range from an ordinary low resistance voltmeter by simply connecting a resistance in series with it, for this would reduce the current which flows through the meter, and would therefore reduce the deflections of the pointer. High-resistance voltmeters are built especially for the purpose, more sensitive than the ordinary low-resistance type.

206. Combined voltmeters and ammeters: For certain applications, instruments of the movable-coil type are arranged so that the same instrument may be used either as a voltmeter or as an ammeter, and successive readings of voltage and current may be made with great rapidity. Such instruments are called volt-ammeters.

The instrument shown at the right of Fig. 139 is of triple range for both voltage and current, usually designed for a maximum voltage of 150 volts, with sub-ranges for 15 and 3 volts. The ampere ranges are usually 30, 15 and 3, or 15, 3 and 1.5 as preferred. Many other combinations are obtainable.

In order to obtain a clear idea of the general layout of one of these instruments, a connection diagram is shown in Fig. 145. The shunts are in series with each other, and are connected in multiple with the movable coil through a resistor and a push-button. When connected in the line, only a small part of the current flows through the movable coil, but the pointer indicates the *total current,* because the current flowing through the movable coil is always an exact fraction of the total current, and therefore, the scale is calibrated to indicate this total current which is being measured.

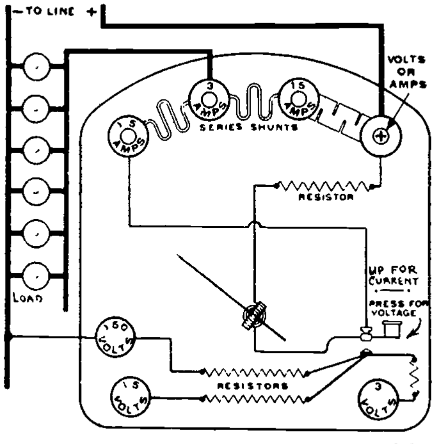


Fig. 145—Circuit arrangement of the Weston model 280 volt-ammeter shown at the right of Fig. 139. Three voltage ranges and three current ranges are provided.

If the proper voltage range is connected across the line and the button is pressed, the main current continues to flow through the shunts, but the pointer no longer indicates amperes because the movable coil circuit to the shunts is opened; and when the button is fully depressed the movable coil will form part of the voltage circuit.

Since a correctly adjusted non-inductive resistor is connected with each voltage range, the one in use will indicate volts, because the current which will flow depends upon the voltage of the circuit. This instrument may, therefore, be used to give volt and ampere indications in practically instantaneous succession as the button is pressed and released.

Instead of having a single hundred and fifty volt resistor tapped at the proper resistances for each of the lower ranges, as previously explained, there are three separate resistors each capable of taking care of the voltage designated on their respective terminals. With this arrangement, if one of the resistors should become damaged, it will not affect the operation of the instrument on the other ranges.

When a separate shunt or series multiplier resistor is used to extend the range of a meter it is important to use accurate seasoned resistors designed for the purpose. The maximum per cent error in any case, is the sum of the per cent error of the moving element and the per cent error in the resistance used. A moving element that is accurate to say 2 per cent would never be more accurate than this no matter how accurate the multiplier is made. On the other hand, if the meter is of an expensive type having a moving element with a high degree of accuracy, a very accurate multiplier should be used. If closer accuracies than one per cent are required, it should be specified that the resistors which are provided, should be accurate to better than ½ per cent.

Fortunately, special wire-wound resistors of an accuracy of one per cent and less are now available commercially, as contrasted with the wider tolerances of ten per cent and more of ordinary commercial resistors. Furthermore, these resistors are thoroughly seasoned. That is, they have been aged so that no resistance changes over a period of time due to easing up of the molecular strains caused in the wire by the tension applied during winding will occur. A wire-wound resistor of this type is shown at the right of Fig. 143.

These perfected wire-wound resistors now make it possible to convert meters into multi-range instruments with every assurance of accurate reading, on all the ranges.

207. Wattmeters: In a direct current circuit, the electrical power in watts expended in the circuit, is equal to the voltage multiplied by the current in amperes. These factors can be determined simply by connecting an ammeter in series with, and a voltmeter across, a d-c circuit and taking the readings. Thus, suppose the ammeter reads 5 amperes and the voltmeter reads 110 volts; the power in watts will equal $W=E\times I=110\times 5=550$ watts.

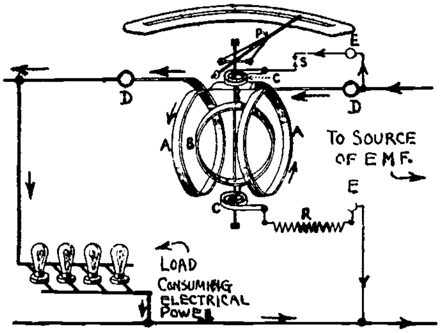
In an alternating current circuit, the power is given by $E\times I$ only if the apparatus connected in the circuit is purely resistive in character. If the apparatus is inductive or capacitive (excepting in the case of resonance) the power factor ($\cos\theta$) must be considered, and the *true power* in watts will be equal to $E \times I \times \text{Cos}\ \theta$, where $E \times I$ gives the *apparent power.*

The power in either an alternating current circuit or a direct current circuit can be measured directly by a *wattmeter.* This automatically multiplies the volts and amperes together and indicates directly the instantaneous value of the *true power* in either kind of circuit, regardless of the power factor. The wattmeter is really a combination of two instruments in one, a voltmeter and an ammeter.

As shown at the left of Fig. 146, two coils are used; one is called the *voltage* or *potential* coil, and the other the *current* or *series* coil. The current coil is fixed in position since it is wound with heavy wire, and is connected in series with one side of the line just as an ammeter would be connected. The voltage or potential coil is connected across the circuit just as a voltmeter would be connected, and is mounted inside the current coil on jewelled bearings, so it can move freely. The pointer P which moves over a suitably calibrated scale for reading, is fastened to the movable-coil.

The current coil A-A is wound with heavy wire, so as to offer very low resistance to the passage of the line current through it. The ends of this coil are brought out to two large binding posts D D. The movable coil B is the voltage coil, and is connected across the line through the high non-inductive series resistance R, and out to the two small, voltage binding posts, E E. The winding of coil B consists of a few turns of very fine insulated wire. The control springs C C serve as conductors for current to and from the moving coil, they also keep the pointer at zero when there is no current flowing, and oppose the movement of the coil when there is current. The pointer is provided with a threaded extension at the non-indicating end and is fitted with a balancing nut which counter-balances its weight.

The magnetic field or force produced by the stationary current coils is proportional to the current flowing through these coils and the main circuit. The magnetic



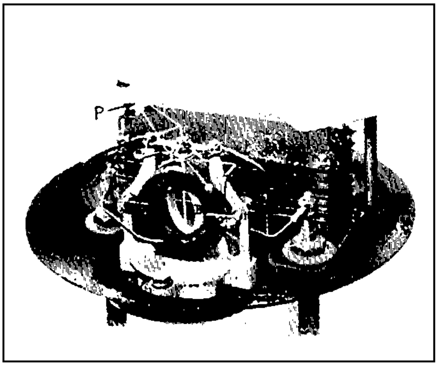


Fig. 146—Left: Construction features of an indicating wattmeter and method of connecting it in a circuit.
Right: An interior view of a wattmeter with enclosing case removed. The various main parts are labeled to correspond with the diagram at the left.

field or force produced by the moving voltage coil is proportional to the difference of potential applied to the potential-coil terminals of the instrument; this is the voltage of the circuit to which the meter is connected. The combined action of the poles of these two magnetic fluxes, one proportional to the current in the circuit, and the other proportional to the voltage, tends to turn the movable coil clockwise; the total turning effort at every instant being proportional to the product of the *instantaneous* current and voltage, or to the watts. At the point of reading, the torque due to the magnetic action is balanced by the counter torque of the control springs, and the pointer and scale indicate the watts corresponding to the load on the circuit. The instrument may be used either on alternating or direct current circuits, since on a.c. the current in both the current and the voltage coils reverses at every alternation so the resultant direction of attraction between the poles of the coils remains the same. The student should prove this for himself by drawing the two coils and working out the direction of attraction first when the current flows through them one way and then when the currents in both are reversed. A wattmeter with enclosing case removed is shown at the right of Fig. 146.

Care must be taken to see that a wattmeter is not connected in a circuit carrying either a current or a voltage value above the maximum current and voltage rating of the wattmeter, for overheating or possible burnout of the coils will result. For example, on a particular 1500-watt instrument the maximum current rating is say 10 amperes and the maximum voltage rating is 150 volts. If this instrument were connected in a circuit in which 20 amperes were flowing and an e.m.f. of 50 volts existed, the current-coil of the meter would be overloaded even though the meter would be indicating only $50 \times 20 = 1{,}000$ watts.

Also, since the voltage-coil takes some current and power from the circuit, in order that the instrument will not indicate these watts in addition to the circuit load, the voltage-coil should be connected to the circuit on the *incoming side* of the current-coil connections, as shown at (A). Then the current in the voltage coil will not pass through the current coil as may be seen by tracing the arrows indicating the current flow in these two coils Wattmeters of the type mentioned above are sometimes called *indicating wattmeters.*

208. Recording watt-hour meter: The consumption of electrical energy is paid for and based upon the *kilowatts* (1 kilowatt=1,000 watts) multiplied by the number of hours. To measure by means of a wattmeter, the electrical energy in watt-hours supplied to a device, it would be necessary to multiply the average of a number of watt readings taken during a given time, by that time expressed in hours. As its name implies, the *recording watt-hour* meter gives the total watt-hour consumption of energy directly, since it automatically multiplies the average of the instantaneous wattage indications by the time.

The recording watt-hour meter really consists of a simple type of electric motor driven by the electric energy which it is to measure (which is arranged to flow through it); its speed of rotation at any instant is proportional to the power in watts flowing through it and delivered to the power consuming device at that instant. By means of a train of gears and suitable dials, the total revolutions made by the motor over a period of time are added up and recorded, so that the total watts or kilowatts which have passed through the meter on the way to the device consuming the electrical power during that time, is recorded. Usually four dials are arranged to give the readings, one dial giving the units, the next one the tens, etc., just as on an ordinary gas-meter. The unit upon which the measurement is based and made, is usually marked on the dial-face, and would be watt-hours or kilowatt-hours.

Watt-hour meter readings are additive, so to find the amount of electrical power consumed during any interval of time, it is necessary to subtract the reading at the beginning of the period from that indicated at the end.

209. Power consumption test of radio receivers: If the power consumed by a device is to be ascertained by a short test during which the dials of the watt-hour meter would not move much, it may be found by accurately measuring with a watch, the time in minutes it takes for the aluminum disc in the meter (watching the black line on the disc) to make say 100 revolutions, then multiply the number of revolutions found, by the "constant" of the meter and by 60 and divide by the number of minutes during which the test was run. This will give the watt-hour consumption of the device for each hour. The *meter constant "K"* is the multiplying factor by which each revolution of the disc must be multiplied to find the corresponding average watts which have passed through the watt-hour meter during the revolution. The "constant" is usually marked on the aluminum disc of the meter or on the name plate, and varies for different types and sizes of meters.

This method is often used to check the watt-hour consumption of radio receivers installed in homes, in order to find out the cost of the electrical power consumed by the receiver for each hour of operation. As the watt-hour meter already installed in the home by the electric light company may be used, no additional meter is necessary. The same method may be used for checking the power consumption of household electrical devices.

Example: A power consumption test is run on a radio receiver. The watt-hour meter disc makes 30 revolutions in 10 minutes, and the constant K, of the meter used is 0.6 watts. If power is supplied by the electric light company for 10 cents per K.W.-hour, how much does it cost to run the radio receiver for one hour?

Solution: $$\text{K. W. hours} = \left(\frac{30 \times 0.6 \times 60}{10}\right) \div 1000 = 0.108 \text{ K.W. hours.}$$

Therefore, $0.108 \times \$0.10 = \$0.01$ per hour. Ans.

Watt-hour meters are often used to measure the total amount of electric power sent into storage batteries during charging. Of course they are also used by electric light and power companies to record the total amount of electric power used by each customer during the month.

210. A-C meters: The D'Arsonval ammeters and voltmeters thus far discussed have been of the magnetic type which are employed in direct current circuits. This type of meter will not function when connected in an alternating current circuit, because during one alternation the current would flow through the coil in one direction and the poles produced would tend to deflect the coil in one direction, and on the following alternation the current and poles would be reversed and would therefore tend to deflect it in the opposite direction. These alternations follow one another so rapidly that the moving element in tending to obey one impulse is almost immediately caused to move in the opposite direction by the next impulse, with the result that the indicating needle remains practically stationary, trembling slightly at the zero position. Since permanent magnet instruments cannot be used to measure alternating currents, they are generally called *direct current instruments.*

We have already seen that hot-wire and thermo-couple ammeters and milliammeters can be used to measure a-c as well as d-c but they are used mostly in circuits carrying radio-frequency currents. There are two main types of meters used in ordinary commercial low-frequency measurements. They are, the Thompson inclined-coil type and the Weston movable-iron type.

211. Thompson A-C ammeter: The Thompson *inclined coil* meter manufactured by the General Electric Company is shown at (A) of Fig. 147.

The inclined coil C through which the current passes, is shown in cross-section. It is mounted with the axis inclined to the horizontal. In the center of the coil is a vertical shaft mounted in jewel bearings and controlled by fine flat hair-springs S S. The shaft carries a light pointer at its upper end. At the center of the shaft is a vane of soft iron A, obliquely mounted.

When no current flows through coil C, the hair-springs keep it at the zero position, and the iron vane lies nearly at right angles to the axis of the coil at position "A". When current is passed through the coil the iron vane tends to turn so that the lines of force passing through it are parallel to the lines of force passing through the center of the coil as shown by the dotted line position "B". This turning of the vane and shaft against the action of the hair-springs, causes the pointer P, to move across the graduated scale from which the reading is obtained.

The coils for large sizes of instruments are generally wound with a few turns of flat insulated copper ribbon having a very low resistance.

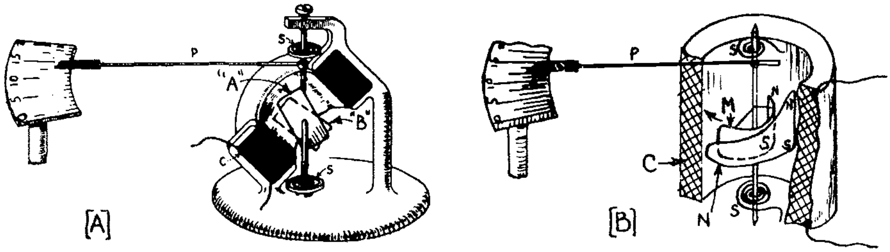


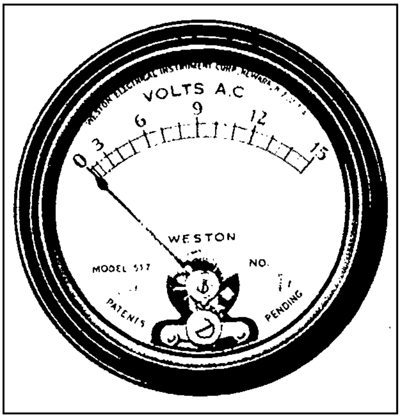
Fig. 147—(A) Thompson inclined coil a-c instrument. The iron vane position marked "A" is slanting toward the back from top to bottom.
(B) Weston movable iron a-c instrument.

When alternating current flows through the coil, the lines of force through it will be rapidly changing in direction. Since the vane is of soft iron, and will tend to line itself up with the lines of force of the coil whether they go up through the coil or down through it, this type of instrument can be used for either direct or low-frequency (60 cycles or so) alternating current. This type of instrument does not have a uniform scale, the divisions at the lower end being more crowded than at the upper end.

212. Weston movable-iron a-c meters: The instruments made by the Weston Electrical Instrument Company primarily for measuring alternating currents and alternating e.m.f.'s, are also of the "moving-iron" type, but are so constructed that many of the defects of other solenoidal types have been eliminated.

The stationary coil of these instruments is wound with a few turns of heavy copper wire or strip when the instrument is to be used as an ammeter. In this case the coil is merely connected in series with the circuit. When the meter is to be used as a voltmeter, the coil consists of a large number of turns of fine wire, and connected in series with this coil, is an accurately a justed high resistance. As shown at (B) of Fig. 147, the moving armature M, which lies in the center of the coil C, consists of a small piece of soft iron, semi-circular in shape, secured to a vertical shaft which rest in accurately fitted jewel bearings. A pointer P of truss construction and of very light weight is secured to the upper end of the shaft. A small, loose fitting, thin vane (not shown) is attached to the pointer and moves in a small air compartment. The vane, as it moves in the closed air compartment like a piston in a pump, provides the damping required to prevent the pointer from oscillating, and thus makes the instrument "dead beat". An adjustable balancing weight at the non-indicating end of the pointer enables it to be accurately balanced. Situated close to the movable iron sleeve, is secured a stationary piece of curved soft iron N, triangular in shape, with the small end of the triangle rounded off as shown. This piece of iron is securely held in place, does not move, and has no physical connection to the movable iron piece on the shaft.

When the coil is connected in the circuit, the current through it sets up a magnetic field through the center and both soft iron vanes become magnetized. The upper edges of each will always have a like magnetic polarity and the lower edges will always have a like magnetic polarity, but when the upper edges are north poles the

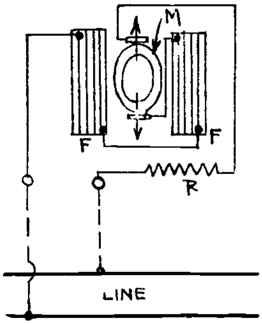


Courtesy Weston Elect. Inst. Co.

Fig. 148—**Left:** Phantom view of the movement of a Weston movable-iron type of a-c instrument.
Right: 2-inch diameter a-c movable-iron voltmeter used in radio work. Notice the crowding of the scale at the low end.

lower edges are south poles and vice versa. Therefore, there will always be a repulsion between the two upper edges, and also between the two lower edges of the soft iron strips, no matter in which direction the current is flowing through the coil, so the instrument can be used either in d-c or in a-c circuits. This sidewise repulsion tends to make the movable vane M, slide around from the fixed one N, and in doing so it rotates the shaft against the action of the hair springs. The pointer then moves over the graduated scale and indicates the volts or amperes depending on whether the instrument is constructed and connected as an ammeter or as a voltmeter. A phantom view of an a-c ammeter of this type is shown at the left of Fig. 148. A small 2-inch diameter alternating current voltmeter used in radio work for measuring the vacuum tube filament voltages in a-c electric receivers is shown at the right. Most of the a-c filament ammeters and voltmeters are of this type.

This type of instrument can be used for direct current measurement with a precision of one or two per cent. When carefully calibrated, a precision of 0.5 per cent and better can be obtained on commercial frequency alternating current. Its advantages are its simplicity, cheapness and the fact that there is no current carried to the movable element. In many of the moving-iron type instruments, the coils are surrounded by iron laminations to shield them from stray external magnetic fields which would cause an appreciable change in their readings, since the iron armature moves in a comparitively weak field inside the coil. Movable-iron type voltmeters are not as sensitive as d-c voltmeters, that is, they require more current in the field coil to produce movement of the pointer, since the magnetic field is practically all in air. Consequently, they draw more current from the line. Movable-iron type instruments have a non-uniform scale which is closely spaced near the bottom and much more open near the upper end as shown on the meter at the right of Fig. 148. When instruments of this type are being purchased, care should be taken that their range is such that the values to be measured come in



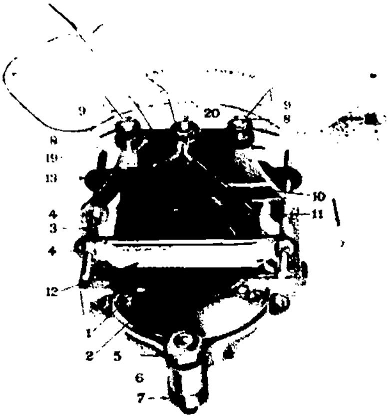


Fig. 149—**Left:** Principle of the electro-dynamometer type of an a-c instrument.

Right: Weston electro-dynamometer type of a-c instrument with fixed and movable coils.

the open part of the scale rather than near the lower end where it is difficult to read the instrument accurately.

213. Electro-dynamometer a-c voltmeter: Some types of alternating current voltmeters operate on the electro-dynamometer principle.

The fixed coils F F at the left of Fig. 149 are wound with fine wire and are connected in series with the movable coil M. The magnetic poles produced on coils F F attract those produced on movable coil M and tend to turn it around, carrying the pointer with it. A high non-inductive resistance R is connected in series with the dynamometer to limit the current when the instrument is connected across the line. The current passing through the instrument is therefore proportional to the voltage of the line it is connected across. As the deflections are nearly proportional to the square of the current flowing through, the scale is non-uniform, being crowded at the lower end. The main parts of an actual meter of this type together with the assembled unit are shown at the right of Fig. 149.

The dynamometer-type of voltmeter takes about 5 times as much current from the line as a d-c voltmeter of similar rating and consumes a comparitively appreciable amount of power. As the moving coil moves in a comparitively weak field due to the fact that the magnetic field is entirely in air, this type of instrument is very susceptible to stray magnetic fields and should not be brought too near current-carrying wires, magnetic apparatus, etc. The instrument may of course be used for measuring direct current as well as for measuring alternating current.

Owing to the difficulty of leading a heavy current into a moving coil, dynamometer ammeters are not commonly made. It is not practical to use a shunt as in the case of the D'Arsonval type d-c ammeter, because alternating currents divide inversely as the circuit *impedances.* Unless the ratio of inductance to resistance were the same in the shunt as in the moving coil, the instrument would be correct at only one frequency, since the impedances of the shunt and moving coil would vary differently with change of frequency. It is for this reason that multiplier resistances are seldom used for increasing the range of alternating current voltmeters or ammeters unless they are to be used only in circuits of a single definite frequency. Dynamometer type instruments in which these difficulties are partly overcome are available, but the movable-iron type of instrument is so much simpler and less expensive, that the dynamometer type is used very little.

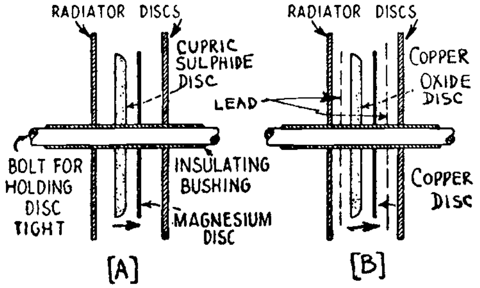
214. Dry plate rectifiers, and copper-oxide rectifier type meters: In many alternating current measurements commonly made in radio work it is of utmost importance that the measuring instrument used require very little current or power for its operation. An instance of this is in the measurement of the ouput signal-voltages of a radio receiver. If an ordinary a-c voltmeter were connected across the output terminals of the set, it would absorb a comparitively large proportion of the power available and the reading obtained would be far from accurate. The measurement of the alternating voltages and currents in these circuits is not always readily accomplished, as the necessary instruments are too sluggish in their movement, or require too much power for their operation. Thermocouple instruments have the first two disadvantages, moving-iron instruments have the last two, and dynamometer instruments have the first and last drawbacks.

In general, a-c meters are more sluggish than d-c meters and require a great deal more power to operate them. This last drawback is a very serious one in radio measurements, for it often happens that more power is required to swing the meter's needle than is available in the circuit being studied. We are accustomed to d-c voltmeters requiring only 1 milliampere to produce a full-scale deflection (sensitivity of 1000 ohms per volt) and know that a voltmeter consuming 10 milliamperes has a limited usefulness in most radio measurements. On the other hand, a-c voltmeters of the moving-iron and dynamometer types generally require from 15 to 100 ma. in the higher ranges and from 100 to 500 ma. in the lower ranges. The power consumption is usually several watts! Even the expensive and fragile thermocouple instruments require 10 ma. to produce a full-scale deflection.

The advantages of the low current drain of sensitive d-c instruments can be retained for measuring low a-c voltages and currents by using a suitable sensitive D'Arsonval type d-c instrument in connection with a copper-oxide type rectifier.

A rectifier is a device which offers a high resistance to the flow of current through it in one direction, and a comparitively low resistance to the flow of current through it in the opposite direction. Thus if an alternating voltage is applied to the terminals of a rectifier, current can flow through it only in one direction, so the current is a pulsating direct current. Hence we say the a-c is rectified to d-c. Several forms of rectifiers have been developed, but the most suitable, simple and inexpensive one yet found for use in rectifier instruments is known as the *copper-oxide* dry-contact rectifier. We must digress from our study of meters at this point to take up the study of dry plate rectifiers so that we may understand their operation and connections in these meters.

Types of Rectifiers: Dry-contact rectifiers include a wide assortment of devices which, though similar in structure, operate on various principles. All of them comprise a junction between two dissimilar substances, generally a metal and a crystalline



Courtesy Benwood Linze Co.

Fig. 150—(A) A single element of a cupric sulphide type of dry-plate rectifier. (B) A single element of a copper oxide type dry-plate rectifier.

Right: A cupric sulphide type rectifier arranged for full-wave rectification and designed for an output capacity of 1 to 9 amps at 8 to 12 volts. This is employed in electro-dynamic loud speakers, to furnish d-c current for the field coils from the 110 v. a-c electric light line.

metallic salt which is electrically conductive. The junction offers a low resistance to the flow of current from the crystalline metallic salt to the other metal and a high resistance to the flow of current in the reverse direction. The detailed modes of operation of these devices are complex and are not thoroughly understood, but in general they involve the formation of thin films at the junction of the surfaces, in which the molecules are so oriented or "polarized" that the transfer of electrons in one direction requires much less work than a similar transfer in the opposite direction. In some cases the conduction is metallic in nature, i.e., no decomposition of the conductor occurs (such as in the copper-oxide unit) whereas in other cases electrolytic conduction occurs, i.e., the conductor itself is decomposed by the passage of current and new chemical products appear at the electrodes (such as in the cupric sulphide unit).

Probably the oldest dry-contact rectifier is the humble crystal detector. Although this device can handle only very minute currents and voltages, its efficiency is high and its output wave-form good. Operating in much the same fashion, commercial devices are now available which will handle considerable power. Two main types are popular at present, the aluminum (or magnesium) copper sulphide valve, such as the Elkon and Benwood-Linze devices, and the copper-cuprous oxide valve, such as the Rectox and Kuprox units.

In the former, each element consists of a disc of cupric sulphide held in contact with a disc of magnesium-aluminum alloy under a pressure of about 200 pounds per square inch as shown at (A) of Fig. 150. Current can flow easily only from the cupric sulphide disc to the magnesium disc. In the copper oxide type shown in

(B), each element consists of a disc of copper oxide held in contact with one of copper. Lead washers between the brass terminal plates serve to produce uniform pressure over the entire surface of the copper oxide and copper discs. Current flows easily from the copper oxide to the copper, but not in the reverse direction.

In general, contact rectifiers are simple in construction and have a high efficiency. All contact rectifiers, however, suffer from the fact that their characteristics vary with the condition of the contact surfaces and with the pressure upon these surfaces. In the cupric sulphide type of rectifier this fact is most noticeable, inasmuch as the rectifying junction is at the contact between two separate bodies of material. A change in pressure will change the area of contact between these dissimilar bodies and will also affect the nature of any absorbed gas film on the surfaces. In the case of the copper oxide device, the rectifying action takes place in the interior of a disc, at the interface between the mother copper and the cuprous oxide formed chemically thereon. Thus a complete rectifying element is made up of only one physical body and the active junction that is formed during the manufacturing process is not altered subsequently by pressure, abrasion, corrosion or the like. Pressure does affect the copper oxide rectifier, however, insofar as it determines the resistance of the contact made between the external conductor and the crystalline copper oxide surface. Insufficient pressure will cause a high resistance joint between the rectifying element itself and the connection thereto, thus increasing the resistance in the current flow direction and decreasing output and efficiency. The Kuprox unit is a riveted assembly and no adjustment of pressure can be made, but the other units are of bolted construction and their outputs can often be improved by tightening up the bolts and thus increasing the pressure on the elements.

Contact rectifiers resemble electrolytic rectifiers in possessing a definite breakdown voltage and breakdown temperature. If either critical value be exceeded, the rectifier will pass current freely in both directions. After the unit cools down, or after the high voltage is removed, it will immediately function again much as if it had never been overloaded. Rectox rectifiers have been broken down in this way ten times in succession without showing any permanent ill effects.

Contact rectifiers, furthermore, all show leakage. Like the electrolytic rectifier, this leakage increases rapidly with temperature and to a certain extent with the age of the unit. For this reason it is extremely important that such devices be adequately ventilated; the unit itself should not operate appreciably above 90°-100° F. The leakage current in a Rectox full-wave unit charging a 6-volt storage battery will be 2-6 milliamperes at 70° F., 15-25 milliamperes at 90° F., and 60-100 milliamperes at 140° F. A peculiar leakage phenomenon is demonstrated by some copper sulphide rectifiers which show markedly increasing leakage current in both directions. If the rectifier output be short-circuited for a time, the threads will burn off, the leakage will be greatly reduced and the output and efficiency will be improved.

Contact rectifiers have one other pecularity in common with electrolytic rectifiers, namely, that the completeness of rectification is affected strongly by current density or, what is similar, by the voltage applied to a given unit. In the contact rectifier this does not come about as a result of capacity effects but rather because the ratio of "closed" and "open" resistances depends upon the voltage applied. This means that any given design of rectifier requires a certain minimum current to cause the rectifier to function properly. For a copper-oxide rectifier the minimum density is about 50 ma. per square inch and the normal density 200-500 ma. per square inch. The Rectox rectifier unit has an efficiency of 60%. The breakdown voltage is about 11 volts a-c per disc and the critical temperature about 160° F. The life is probably the greatest of any commercial low-power rectifier and is measured in years. When higher voltages of alternating current are to be rectified or converted into pulsating direct current it is necessary to connect a number of units in series, as shown in the dry-plate rectifier unit at the right of Fig. 150. A suitable clamp or bolt supplies the pressure for the discs. The metal radiating discs serve to separate the various cells and to conduct away the excess heat.

The copper-oxide unit is claimed to have a rectifying ratio of 10,000 in one direction to 1 in the other, as compared to a 75-to-one ratio which is ascribed to the copper sulphide unit.

Connection of rectifiers for half-wave rectification: There are several different methods of connecting rectifiers, the choice of method being governed by the characteristics of the rectifier and the load.

The simplest form of rectifier circuit is the single-phase, or half-wave circuit shown in (A) of Fig. 151. In this circuit, the rectifier is merely connected in series with the supply transformer and the load. The flow of current through the rectifier unit itself is in the direction indicated by the arrow-head which symbolizes the copper oxide (or the cupric sulphide) plate of one of the elements; the direction of the direct current through the load is shown by the arrow adjacent to the load resistance in the sketch. When the top of the transformer secondary is positive, current flows through the rectifier and load and back to the bottom of the winding. When the bottom is positive no current flows until the polarity of the transformer secondary again reverses. The load current is therefore a series of intermittent current pulses.

In this circuit the rectifier unit must carry the entire load current, and during the no-current part of each cycle it must withstand the peak voltage of the transformer plus the voltage across the load. Since current gets through the rectifier only during one alternation for each wave or cycle, this arrangement is called a *half-wave rectifier.* The rectified wave is shown at (D) of Fig. 151.

Connection for full-wave rectifier: If it is desired to have a more "smooth" output current than is produced by the above arrangement, or if better regulation of output

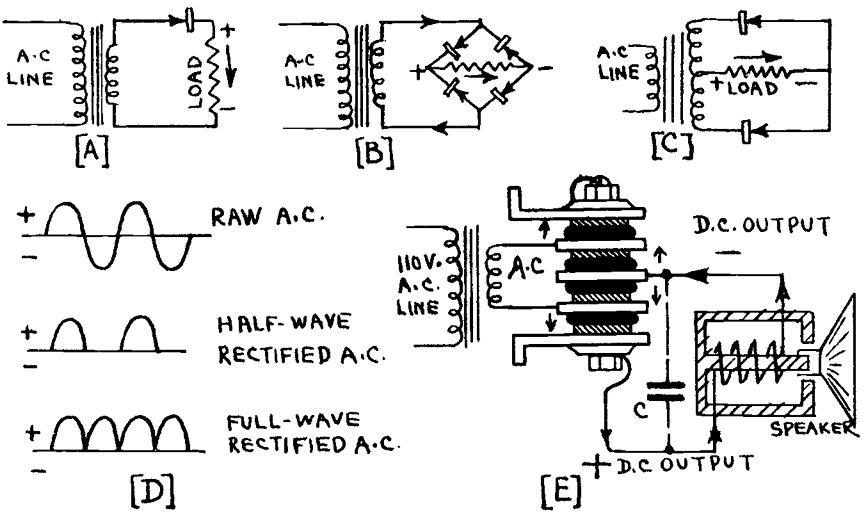


Fig. 151—Various rectifier and circuit arrangements employed for half-wave and full-wave rectification of a-c current to pulsating d-c current. A practical full-wave dry-plate rectifier arrangement designed to furnish the d-c current to the field magnet coil of an electro-dynamic type loud speaker is shown at (E).

voltage with load current is necessary, then two or more rectifiers may be connected so that both halves of the a-c wave are utilized, one rectifier filling in the gaps in the output of the other. One of the oldest of such full-wave circuits is the "Graetz Bridge" or "4-cell bridge" shown in (B). Here, four rectifiers are connected in series in a closed loop. Each half of the loop is made up of two units connected in the same direction, but the two halves of the loop are opposed to one another. The two junctions of unlike elements form the a-c input terminals, while the two junctions of like elements form the d-c output terminals. In the sketch, when the top of the transformer secondary is positive, the current flows through the upper left unit, through the load, and thence through the lower right unit to the bottom of the secondary. Current is prevented from flowing in the opposite direction by the upper right-hand unit. When the polarity reverses and the bottom of the secondary becomes positive, the current flows through the lower left unit, through the load, and thence through the upper right unit back to the transformer. The output of such a rectifier will resemble the output of two of the half-wave rectifiers described in the preceding paragraph, one being shifted a half cycle relative to the other as shown at (D). In this circuit any given unit carries only one-half of the total load current, although this current must pass through two units in series. In the closed valve position, one unit must withstand the peak transformer voltage plus half the load voltage. This arrangement is the one commonly used in full-wave rectifiers of this type employed in radio receivers. At (E) is shown the actual connections of such a rectifier arrangement designed to furnish d-c current to the field coil of an electro-dynamic type loudspeaker from the 110 volt a-c electric light lines. An electrolytic condenser C of from 12 to 2000 mfd. (low voltage dry type) is usually connected across the field to form a filter which effectively smooths out the ripples in the rectifier current.

Another full-wave connection is the bi-phase or "split-secondary" circuit shown in (C). In this common hookup, the transformer is wound for twice the desired voltage and a rectifier is placed in each leg of the transformer output, the two rectifiers facing in the same direction. The load is connected between the center-tap of the transformer secondary and the common connection of the two rectifiers. In the sketch, when the top of the secondary is positive, no current can flow because the upper unit is closed. However, the center of the secondary is also positive with respect to the bottom of the secondary, so current flows through the load, through the lower unit and back to the bottom of the transformer, only the lower half of the winding being active. Similarly, when the bottom of the secondary becomes positive it is rendered inactive by the lower unit, while the upper half becomes active, current flowing through the load and upper unit. Thus this connection achieves with two units the same output wave that was obtained by the circuit of "B" from four units, though with different conditions prevailing in the rectifier circuit. In this circuit each unit carries one-half of the load current and that load current flows through only one unit at a time. In the closed valve position, however, each unit must withstand the peak of the total transformer voltage plus the load voltage. The total transformer voltage is twice the voltage which is useful at any given instant in the circuit. Since the peak voltage of one side of the transformer is nearly one and one-half times the "effective" or "r.m.s." voltage, and since twice this voltage is applied to the unit plus the load voltage (which is generally nearly equal to the effective voltage of one side of the transformer), it follows that each rectifier unit must withstand approximately four times the output load voltage. This consideration is very important and limits the use of this circuit to rectifiers whose breakdown voltage is sufficiently high to permit safe operation under such conditions. The thermionic tube and the mercury arc are in general best suited for use in this circuit.

Having studied the action and connections of dry-plate rectifiers, we can now proceed with our study of the copper oxide rectifier type of electrical measuring instruments which have lately come into popular use. In these instruments, a small copper oxide rectifier is built into the instrument case and is employed to rectify the alternating current applied to the instrument. The resulting pulsating unidirectional current is sent to a sensitive moving-coil type of d-c milliammeter, (see Art. 196), as shown in the detailed connection diagram at (C) of Fig. 152. A simple full-wave copper oxide rectifier is employed. If *current* is to be measured with this arrangement, the terminals of the complete instrument are connected in series with one side of the line (the usual connection for ammeters), as shown at (A). If *voltage* is to be measured instead of current, the milliammeter used is of very low range and a multiplier resistor R, (see Arts. 202 and 204), is connected in series with the a-c terminals of the rectifier, as shown at (B). This type of meter is very useful since it can be used for measurements on both a-c and d-c circuits if suitable switching arrangements are provided for switching the rectifier in or out of the circuit at will.

A 3-inch diameter rectifier type a-c voltmeter with a range of 0-3 volts is shown at the right of Fig. 153. This has a resistance of 1000 ohms-per-volt. Notice its typical d-c movable-coil type movement.

Since the output of the rectifier is a pulsating direct current, as shown at the bottom of (D) of Fig. 151, the d-c meter will read the *average value* of the pulsating rectified current applied to it. A dry rectifier used in this service is so nearly ideal that the maximum and average values of the rectified current are the same as those of the a-c current. Therefore the meter will read the average value of the a-c current or voltage, which is equivalent to the effective value $\times$ .901. If a meter of this type is made up by the student, he should remember that the d-c meter reads 90% of the true alternating current flowing in the external circuit, and therefore he must multiply all readings by $\frac{1}{.901}$ or 1.11 to obtain the true effective value of the a-c. In meters sold commercially, the scale is already calibrated to read the true effective value of the a-c. Meters of this type are shown in Fig. 153.

Due to the fact that this constant proportionality exists between the reading of the d-c meter and the a-c input, the scale of the resultant

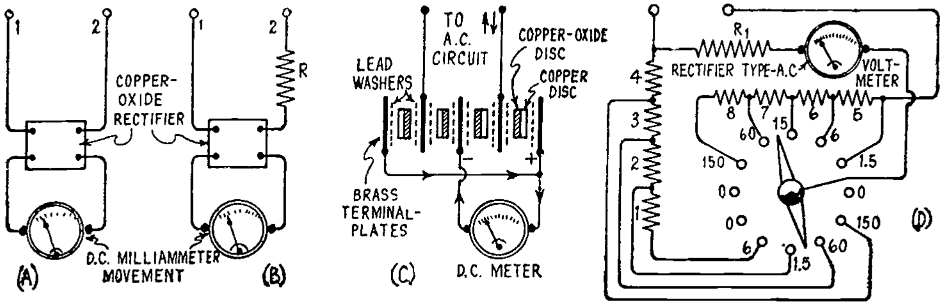


Fig. 152—(A) The connection of the rectifier unit to the d-c meter movement, in a rectifier type a-c milliammeter.
(B) The connection of the rectifier, multiplier resistor, and d-c meter movement in a rectifier type a-c voltmeter.
(C) The detailed connections of the parts of the full-wave rectifier unit to the d-c meter movement in a rectifier type instrument.
(D) Interior connections of all the parts of the copper oxide rectifier-type output meter shown at the left of Fig. 153. The shunt and series resistors are so arranged that the overall impedance of the entire instrument is constant at 4000 ohms, for all ranges.

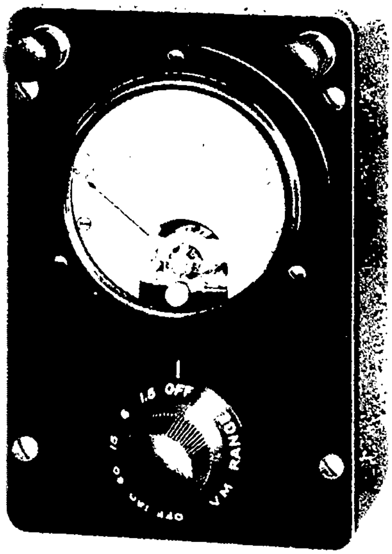
meter is practically uniform rather than being of the inconvenient "square law" type (crowded at the lower end) found in other types of a-c meters.

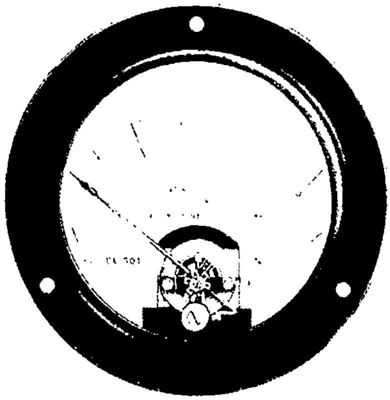
Up to 35,000 cycles per second the instrument indications of the usual type of copper oxide rectifier meter decrease at a substantially uniform rate of approximately ½ of 1 per cent for each 1000 cycle increase in frequency. For example, at 4000 cycles per second the instrument would indicate $4 \times \frac{1}{2} = 2$ per cent low. This correction may be applied when very accurate measurements are to be made.

Since the commercial rectifier instruments are calibrated with currents or voltages having a sinusoidal wave-form, the scale reads r.m.s. or effective values. It is obvious, therefore, that the instrument indicates correctly only if the currents or voltages measured have sine-wave shapes. For other wave-shapes, errors of varying magnitudes will result, the amount of error depends upon the variation from the true sine-wave shape.

A useful adaption of the rectifier instrument principle is shown at (D) of Fig. 152 and at the left of Fig. 153. This is a so-called "output meter" for measuring the signal output voltages of radio receivers and public-address amplifiers. The method of measurement is to feed the output of the set to a load resistance and measure the voltage drop produced across this resistor. The scale is calibrated in volts.

This complete instrument consists of a 5-range copper oxide rectifier type voltmeter enclosed in a Bakelite case. Voltage ranges of 1.5, 6, 15, 60 and 150 volts are obtained by the dual selector switch. When one side connects more and more resistance (sections 1, 2, 3, 4) in *shunt* with the entire meter for the lower ranges, the other side automatically connects proper values of resistance (sections 5, 6, 7, 8) in *series* with the entire meter at the same time. These resistances are so proportioned





Courtesy Weston Elect. Inst. Co.

Fig. 153—**Left**: Copper-oxide rectifier type output meter with 4000 ohm input impedance arranged for radio receiver testing.

Right: Copper-oxide rectifier type 0-3 a-c voltmeter having a resistance of 1000 ohms-per-volt.

that the instrument presents a constant non-inductive load of 4000 ohms to any circuit to which it may be connected, regardless of which voltage range is being used. It is arranged in this way, since the standard loud speaker or output transformer primary impedance which is across the radio receiver output during normal operation is also approximately 4,000 ohms. The power output in "milliwatts," of the receiver being tested, can be calculated from the voltmeter readings and the known resistance (4000 ohms), since $W = \frac{E^2}{R}$.

This meter may also be used for the following purposes: To measure voltage output and compute power output of radio sets; to determine the maximum gain when lining up r-f and i-f stages of radio sets; to compare the gain of radio tubes; to determine gain when a calibrated input voltage is applied to a radio set or audio amplifier; to measure comparative selectivity of r-f tuners; to observe period and per cent of fading; to set or keep volume of sound amplifier equipment at an approximately constant value.

If it is desired to have the input impedance of the meter adjustable between certain limits, as is the case with an output meter used to test various radio equipment directly from the low impedance (10 to 100 ohm) windings of the loudspeaker output transformers, a tapped resistor or auto-transformer arrangement may be employed.

Note: For measuring the output of a radio receiver under test, an output meter may be connected directly in place of a magnetic (cone type) loud speaker, or of a dynamic speaker having a self-contained transformer. If, however, the instrument is to be substituted for the voice-coil of a dynamic speaker, it must be shunted by a resistance approximating that of the voice-coil. If the speaker is left in the circuit, the meter may be connected directly across the voice-coil or across the primary of the transformer (see Fig. 481A).

215. Resistance measurement by ammeter-voltmeter method: One of the simplest and most common methods of measuring resistances is by use of a d.c. voltmeter and ammeter, or milliammeter, connected to a source of steady e.m.f. as shown at (B) of Fig. 154. The method consists in measuring the voltage drop produced across the device due to its resistance, when the measured current flows through it. Then from Ohm's law, we have: $R = \frac{E}{I}$.

Where R is the resistance in ohms; E is the voltmeter reading in volts and I is the current in amperes. A value of applied e.m.f. should be selected for the measurement such that the current flowing through the resistance of the device being measured will not overheat it.

When measuring very high resistances by this method, the current will be small and the voltmeter should always be connected across both the resistor and ammeter as shown at (A). If it is connected simply across the resistor only, as shown at (B), the milliammeter which must be employed to measure the current indicates the sum of the current through the resistor plus that through the voltmeter. Since the current through the resistor is small under these conditions, the voltmeter current may be almost as great (unless a high resistance voltmeter is used) and adding these together for the milliammeter reading causes an appreciable error. It is true that at (A) the voltmeter measures the sum of the voltage drop across both the resistor and the milliammeter, but since the resistance of the average ammeter is only from 20 to 50 ohms adding this to the high resistance to be measured results in only a small error. For low resistances, the connection of (B) should be employed, for this case the current through the resistance will be comparitively large and adding a few milliamperes of voltmeter current to the ammeter reading does not cause appreciable error.

Example: Consider the circuit shown at (A) of Fig. 154. A voltmeter across the device whose resistance is unknown reads 100 volts and the ammeter reads 5 amperes. What is the unknown resistance?

Solution: $R = \frac{E}{I} = \frac{100}{5} = 20$ ohms. Ans.

216. Voltmeter method of measuring resistance: A simple method of measuring resistances by means of a voltmeter alone (whose exact resistance is known) is shown at (C) of Fig. 154. The proceedure is to measure the d-c supply voltage first with the voltmeter, by closing

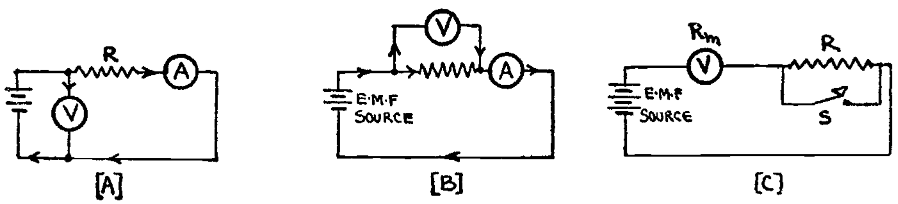


Fig. 154—(A) and (B): Methods of measuring resistance with an ammeter and voltmeter. (C) Measuring high resistance with only a voltmeter of known resistance.

the short-circuiting switch S which short-circuits the resistance to be measured. This is sometimes called the "line reading". Then the switch S is opened, thus putting the unknown resistor R in series with the voltmeter, and the reading of the meter is noted again. This is called the "drop reading". With these readings the value of the unknown resistor may be obtained from the formula.

$$R = \frac{E_L - E_D}{E_D} \times R_m, \text{ or } R = \left(\frac{E_L}{E_D} - 1\right) \times R_m$$

Where R=unknown resistance in ohms.

E_L=the voltage of the line or source, i.e., the voltage indicated by the meter when switch S is closed.

E_D=The "drop reading," i.e., the reading on the voltmeter when switch S is open and R is in series with the voltmeter.

R_m=the resistance of the voltmeter in ohms.

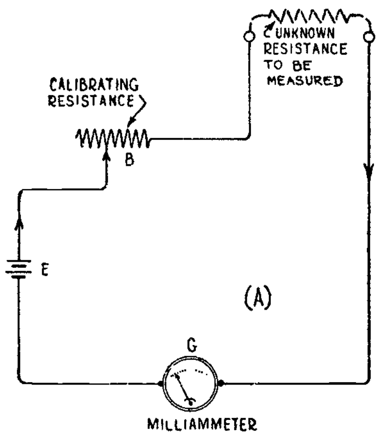
Example: A 250 volt meter having a resistance of 1000 ohms per volt is to be used to measure the value of an unknown resistor. The voltmeter is connected directly across three B batteries in series and the potential is found to be 135 volts. The unknown resistor is then connected in series with the meter and the batteries and the meter now reads 35 volts. What is the value in ohms of the resistance.

(Solution on next page)

Solution: Since the voltmeter has a resistance of 1000 ohms per volt, the total resistance, R_m, is 1000 times 250 or 250,000 ohms. E_L as measured is 135 volts. E_D is 35 volts. Therefore:

$$R = \left(\frac{135}{35} - 1\right) \times 250{,}000 = 715{,}000 \text{ ohms. Ans.}$$

Therefore, the only data needed to measure resistance by this method is the resistance of the voltmeter. This information may be marked on the meter or, if not, it can be obtained from the manufacturer. Weston models 301 and 280 meters each have a resistance of 62 ohms per volt, so that a meter having a range of 150 volts for instance, would have a resistance of 62 × 150 = 9,300 ohms etc. This method is only adapted to the measurement of high resistances, for if the unknown resistance is low there will be no noticeable difference in the voltmeter reading when it is connected directly across the e.m.f. supply line and when it is connected in series with the unknown resistor and therefore accurate readings cannot be taken.



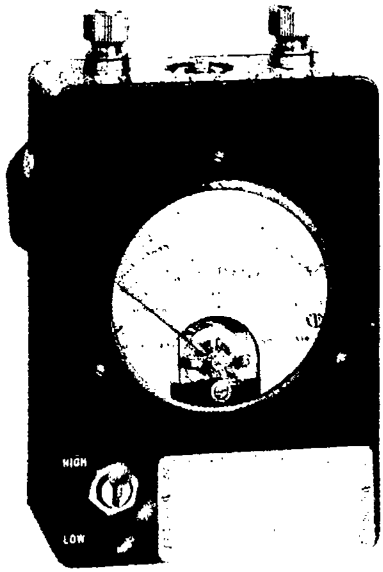


Fig. 155—Left: Circuit of a simple ohmmeter.

Right: A commercial type of ohmmeter used for testing coils, resistors, circuits, condensers, etc. It has two ranges 0-5,000 and 0-50,000 ohms. The switch at the lower left selects the range. The single dry cell is contained inside the case.

Courtesy Weston Elect. Inst. Co.

217. Measuring resistance with the ohmmeter: An ohmmeter is an instrument that indicates the resistance of a circuit or device directly in ohms without need for any calculations. A commercial type of this instrument is shown at the right of Fig. 155. The device whose resistance is to be measured is connected directly across the ohmmeter terminals as in (A) of Fig. 155. The pointer indicates directly, the resistance of the device.

The principle of the ohmmeter is best understood by referring to (A) of Fig. 155. A dry cell E sends current through an adjustable calibrating resistor B, and a milliammeter G, the scale of which is marked directly in ohms. If the unknown resistor to be measured is connected directly across the terminals of the instrument, the meter deflection will be proportional to the current, but since the applied voltage is constant, the current depends upon the value of the unknown resistance. Therefore the deflection depends upon the value of the unknown resistance and the scale of the instrument may therefore be calibrated directly to read the value of the resistance in ohms.

As the dry cell voltage diminishes with age of the cell, the setting of resistance B must be varied. In practice this is accomplished as follows: The ohmmeter terminals are short-circuited by means of a short wire. Since the circuit resistance is now zero, the pointer should stand at zero. If it does not, resistor B is adjusted (usually by means of a slotted shaft) until the pointer stands at zero. When the pointer can no longer be brought back to the zero position by the means, the dry cell inside of the meter case should be replaced by a new one.

The ohmmeter shown at the right of Fig. 155 has two ranges obtained by using two separate series resistors which can be selected by the switch at the lower left-hand corner. One range covers from 0 to 5000 ohms and the other covers from 0 to 50,000 ohms. Ohmmeters can be used to find out if coil windings, circuits, resistors, or condensers are short-circuited or open, as well as for resistance measurements. If the device being tested has a short-circuit the ohmmeter reading will be "zero". If the circuit is open, or above the range of the meter the pointer will go off the scale.

Some meters of this type are made with several series multiplier resistors which can be put in series with the milliammeter movement to make a multi-range voltmeter out of it. Meters of this kind are called *Volt-ohmmeters*. One such instrument used extensively in radio circuit test work has ranges of 3, 30, 300 and 600 volts (all 1,000 ohms per volt) and two ohmmeter ranges, 0-10,000 and 0-100,000 ohms. Two toggle switches connect the various ranges of the meter in the circuit. The single dry cell flashlight-type battery for the ohmmeter is self-contained inside the meter case.

218. Measuring resistance—the Wheatstone bridge: The methods of resistance measurement described in Arts. 215, 216 and 217 are simple methods useful when no great precision is required. When resistance is to be measured accurately, some form of Wheatstone bridge is used.

The ordinary Wheatstone bridge consists of four resistors connected as shown, in the form of a diamond, with a resistor in each side of the diamond as shown at (A) of Fig. 156. Resistor X is the one whose value is unknown, and is to be measured; R is a resistor of known value; S and T are also known. A low voltage battery connected as shown to points A and C will cause current to flow in the resistors when the battery switch is closed. The current from the battery divides at A, one part flowing through path A B C, the other along path A D C., the two branches uniting at C and flowing back to the battery. Resistors S and T are so adjusted that when the galvanometer switch is closed, the galvanometer pointer stays at zero, indicating that no current is flowing through the galvanometer. This is called "balancing the bridge". Under these conditions the points B and D must be at the same electrical potential, for if any difference of potential existed between them it would send current through the galvanometer circuit and a deflection would result, when the galvanometer key was closed.

Let I_1 be the current flowing through the path ABC and I_2 the current through ADC. By Ohm's Law, the voltage drop in any part of a circuit equals the current multiplied by the resistance of that part of the circuit. The voltage drop from A to B, therefore, equals $I_1 X$; that from B to C equals $I_1 R$; that from A to D equals $I_2 S$; that from D to C equals $I_2 T$. Now if points B and D are at the same electrical potential, the voltage drop from A to B must equal that from A to D or,

$$I_1 X = I_2 S$$

and also the voltage drop from B to C equals that from D to C, or

$$I_1 R = I_2 T$$

Dividing the first equation by the second, we have

$$\frac{I_1 X}{I_1 R} = \frac{I_2 S}{I_2 T}$$

Cancelling I_1 and I_2 we have, $\frac{X}{R} = \frac{S}{T}$ or $XT = RS$. From this we obtain, $X = \frac{RS}{T}$.

This is the fundamental equation of the Wheatstone bridge. S and T are called the ratio arms of the bridge. The formula for the Wheatstone

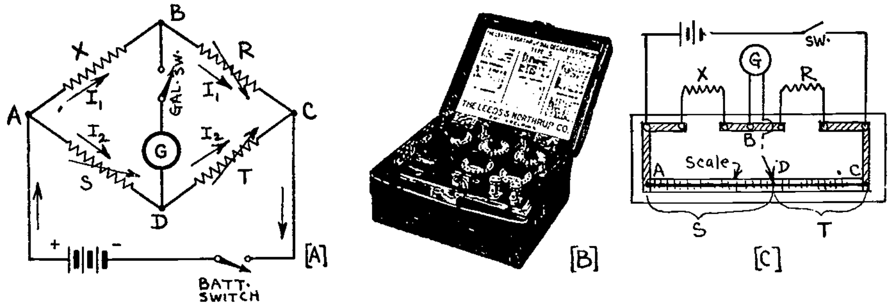


Fig. 156: (A) Simple Wheatstone bridge circuit. (B) Dial type bridge for field test work. (C) Simple slide wire form of Wheatstone bridge.

bridge may easily be remembered by remembering from $XT = RS$ that *the products of the resistances of the opposite arms in the bridge are equal.* Thus, X times its opposite arm T is equal to R times its opposite arm S.

In actual practice it is not necessary to know the exact value of the resistances S and T as long as their ratio is known. With the ratio of S to T or T to S and the resistance of R known, it is a simple matter to determine the value of the resistance of X from the above formula. Notice that the formula contains the ratio of S to T. In practical Wheatstone bridges, the ratio arms, S and T are arranged so that the ratio between T and S can be varied progressively in multiples and sub-multiples of 10 while the variable standard resistor S is variable in small steps. A "decade resistance box" usually serves as the variable resistor R.

The accuracy of the determination of resistance X depends on the accuracy of the ratio arms S and T, the accuracy of the standard resistance S, the sensitivity of the galvanometer G and the relative resistances of all four arms of the bridge. Most accurate determinations are made when all the arms of the bridge are equal, or at least approximately equal.

In practice the Wheatstone bridge is never constructed in the form of the diamond-shape of the diagrams. A much used form of the Wheatstone bridge is shown at (B) and (C) of Fig. 157. It consists of a number of different non-inductively wound coils of resistance wire each hav-

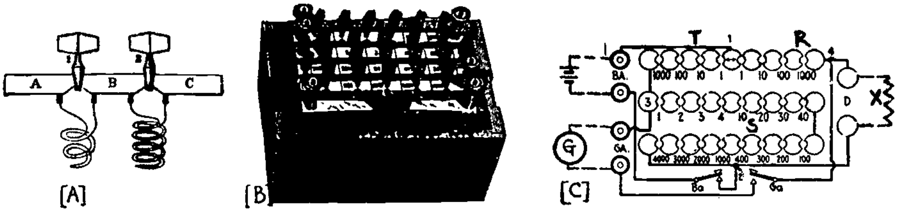


Fig. 157—(A) Arrangement of non-inductive resistor coils and short-circuiting plugs. (B) Post-office type Wheatstone bridge with coil plugs. (C) Circuit of Post-office type bridge.

ing a known marked resistance. The coils are connected to the short heavy brass bars on the top of the box. The individual bars may be connected by inserting round tapered brass plugs which can be easily removed. Each plug shorts the resistance coil connected between the two bars when it is put in place between the two bars, as shown at (A). Removing the plug puts the resistance coil into the circuit. The total resistance can be adjusted to any value by removing different plugs. This is sometimes called the *post office pattern* Wheatstone bridge. The complete bridge is shown at (B). In the Wheatstone bridge shown at (B) of Fig. 156, the resistances are varied by means of switches controlled by dials. These can be manipulated very easily and quickly. The galvanometer is built into the instrument.

Probably the simplest form of Wheatstone bridge is the *slide wire bridge* shown at (C) of Fig. 156. Point D is a sliding contact which is moved along the resistance wire A D C until a point is found for which there is no deflection of the milliammeter or galvanometer, G. The ratio S/T is then the ratio of the length of the two parts of the resistance wire. This is true because since the wire A C is uniform, the resistances of pieces of it are proportional to the lengths of the pieces. A rule or scale mounted under the side wire A C makes it easy to read off lengths S and T when the bridge is balanced. The same formula derived above is used for calculating the value of resistance X, only instead of using the resistance in ohms for S and T, the lengths of the slide wire are used instead. The slide wire bridge is very simple and inexpensive, and is capable of quite accurate measurements if care is taken in its construction and use. The resistance wire and resistors R and X are connected together by heavy solid brass rods as shown. This keeps the resistance of these connections purposely low, since any resistance in either of these connecting strips will be added to the corresponding resistance arms of the bridge.

A *dial* type Wheatstone bridge (B of Fig. 156) has the two ratio arms controlled by a single dial. Turning this dial corresponds to moving the siding contact in a slide wire bridge. Thus accurate and rapid work are possible with this form of bridge. The ratios in the usual form of dial bridge are 1:1, 1:10, 1:100, 1:1,000, 1,000:1, 100:1,10:1. The known resistor R is adjusted by means of four dials. If R is one ohm, X may be as small as .001 ohm. R may be as high as 1111 ohms and X may be 1000 times R. With this bridge any value of resistance from .001 to 1,110,000 ohms may be measured.

Problem: Referring to (C) of Fig. 156, R=10 ohms, S=40 centimeters and T=60 centimeters. What is the value of X?

Solution: $X=\frac{RS}{T}=\frac{10\times 40}{60}=6.67$ ohms. Ans.

The Wheatstone bridge can also be used for measuring inductances or capacitances as we shall now see.

219. Measuring inductance with a Wheatstone bridge: Inductance can be measured by means of a simple Wheatstone bridge arranged as shown at (A) of Fig. 158. This is usually called an *inductance bridge.*

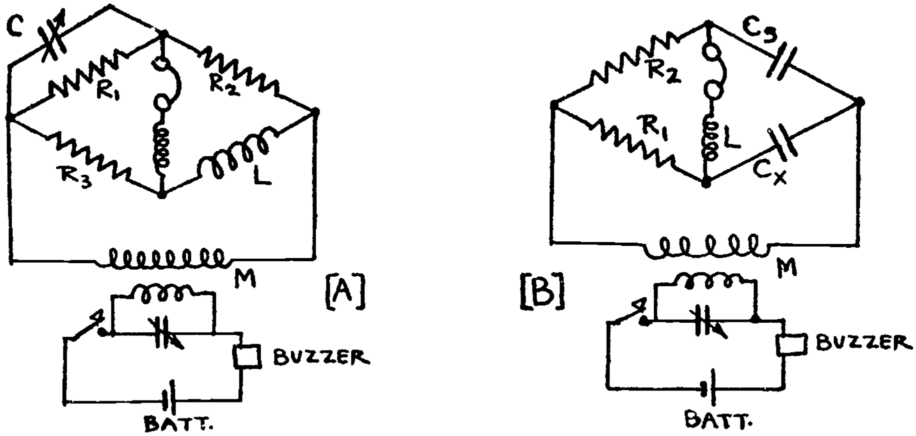


Fig. 158—(A) Wheatstone bridge arrangement for measuring inductance.
(B) Wheatstone bridge arrangement for measuring capacitance.

The four arms of the bridge consist of three resistance boxes, R_1, R_2 and R_3, and the inductor L to be measured.

The resistance of the inductor L, is first found by means of the Wheatstone bridge, using direct current. The bridge is now balanced for direct current resistance, and all three resistors and the inductor must be left as they are for the remainder of the test. The battery connected to the bridge is now replaced by a source of alternating current. Usually a 1000 cycle buzzer or oscillator is used for this purpose, for since the ear is most sensitive to frequencies around 1000 cycles, the point when minimum sound is heard in the earphones may be judged accurately. A buzzer is usually objectionable in that its sound is heard for quite a distance and interferes with accurately determining the minimum sound point in the sensitive earphones. Coil M, couples the bridge to the buzzer or oscillator circuit. This may consist simply of two coils wound on a cardboard tube, or a telephone induction coil with its secondary in the bridge circuit. A variable condenser which has been calibrated is shunted across R_1 as shown. The small inductance coil shown is sometimes connected in series with the earphones to permit sharper adjustment for even the faintest sound. Sometimes a telephone transformer with a primary impedance of about 200,000 ohms and a secondary impedance of 20,000 ohms is connected here instead. The secondary is connected to the earphones. A grounded shield is used between the primary and secondary windings to prevent objectionable capacity effects. Now condenser C is varied until the sound is as faint as it is possible to get it. When this is done, the bridge is balanced for a-c. The resistance of L may be left out of the computations for it has been already been balanced out by the other three resistances. The junction of the two resistance arms should be connected to ground to prevent errors due to the capacitance between the earphones and the observer.

The four arms of the bridge, so far as a-c is concerned, are L, C, R_2 and R_3. L may be found from the equation:

$$\frac{L}{R_2} = \frac{R_3}{1/C}, \text{ or } L = CR_2 R_3$$

The quantity 1/C comes in due to the fact that if the resistance is increased the current is *reduced*, while, if the capacitance is increased the current is *increased*. Thus capacitance and resistance act oppositely so far as affecting the strength of the current is concerned. The resistances chosen for R_2 and R_3 must always be such that with the particular range of condenser employed the product $CR_2 R_3$ may be made numerically equal to the inductance L. For example, if C has a capacitance range from 0.00001 to 250 mfd., and R_2 and R_3 are 200 ohms each, the smallest inductance the bridge will measure accurately is about

$$L = .00001 \times 200 \times 200 = 0.4 \text{ microhenry.}$$

The resistors employed in the bridge must be of the non-inductive type and all wires should be kept as short as possible to prevent induction effects. Commercial forms of inductance bridges are used extensively in laboratories and in production work for checking the inductance values of coils of all kinds.

220. Measuring capacitance with a Wheatstone bridge: Capacitance may also be measured by means of a Wheatstone bridge as shown at (B) of Fig. 158. This is usually called a *capacity bridge*.

The four arms of the bridge consist of non-inductive resistors R_1 and R_2, an accurate standard condenser C_s, and the condenser C_x to be tested. Alternating current (1000 cycles preferable) is supplied to the bridge through the coil M, as in the case of Article 219. An earphone with a small inductance L, (or a telephone transformer as described in Art. 219) in series with it is used as a current detector. The resistances R_1 and R_2 are adjusted until the sound disappears or is as faint as possible.

The capacitance C_x is then found from the proportion

$$\frac{C_x}{C_s} = \frac{R_2}{R_1}$$

This is an inverse proportion, since if the resistance is increased the current is reduced, while if the capacitance is increased the current is also increased. The capacitance and resistance act oppositely in their effect on the strength of the current. The junction of the resistors should be connected to ground for the same reason given in Art. 219.

If a variable condenser is being tested, the capacitance should be tested for a number of settings and a graph plotted with dial readings as abscissae (horizontal) and capacitance as ordinates (vertical).

The same precaution regarding short wires etc., which were set forth in Art. 219 must be observed in this test also. The room in which the test is made must be quiet, for noises will interfere with the accurate determination of the minimum sound point in the earphones. Commercial forms of capacity bridges are used extensively in laboratory and production work for quickly and accurately checking the capacitance of condensers.

221. Measuring frequency, the simple wavemeters: The property of frequency discrimination of a series resonant circuit may be used in an instrument for measuring the wavelength or frequency of the current in a circuit. If the instrument is calibrated in wavelength (in meters) it is called a *wavemeter.* If the instrument is calibrated in frequency (in cycles or in kilocycles), it is called a *frequency meter.* The construction and operation of the wavemeter and frequency meter are identically the same. The operation of the wavemeter depends on the principle of series resonance whereby the capacitive reactance is made equal to, and is neutralized by, the inductive reactance at the resonance frequency, and the impedance of the tuned circuit is then simply equal to its resistance. Under this condition the maximum current flows through the circuit (see articles 172 and 173). Therefore if a simple series tuned circuit is arranged as shown at (A) of Fig. 159, and is coupled either inductively or capacitively with the circuit M whose frequency or wavelength it is desired to measure, such that M induces a voltage of the same frequency into the tuned circuit, then the tuning condenser in the wavemeter may be adjusted until it is in resonance at the same frequency as that of M, and maximum current will be set up in the tuned circuit. (Of course the inductance of the coil and the capacitance of the tuning condenser in the wavemeter must be so chosen as to give the range of wavelength or frequency required for the test.) At this condition of resonance, if L is in henries and C is in farads, the resonance frequency in cycles: $f = \dfrac{1}{2\pi\sqrt{L\,C}}$

If L is in the more convenient unit, microhenries and C is in microfarads, it is necessary to multiply the above fraction by 1,000,000. This gives finally: $f = \dfrac{159{,}000}{\sqrt{L\,C}}$

also the wavelength in meters will be: $\lambda = 1885\sqrt{L\,C}$ ....(24)

Example: A wavemeter has an inductance coil of 200 microhenries and is in resonance with another circuit when its tuning condenser is set at .0002 microfarads. What is the wavelength and the frequency of the tuned circuit?

Solution: $\text{Wavelength} = 1885\sqrt{LC} = 1885\sqrt{200 \times .0002} = 377$ meters.

$$\text{frequency} = \frac{159{,}000}{\sqrt{L\,C}} = \frac{159{,}000}{\sqrt{200 \times .0002}} = 795{,}000 \text{ cycles. Ans.}$$

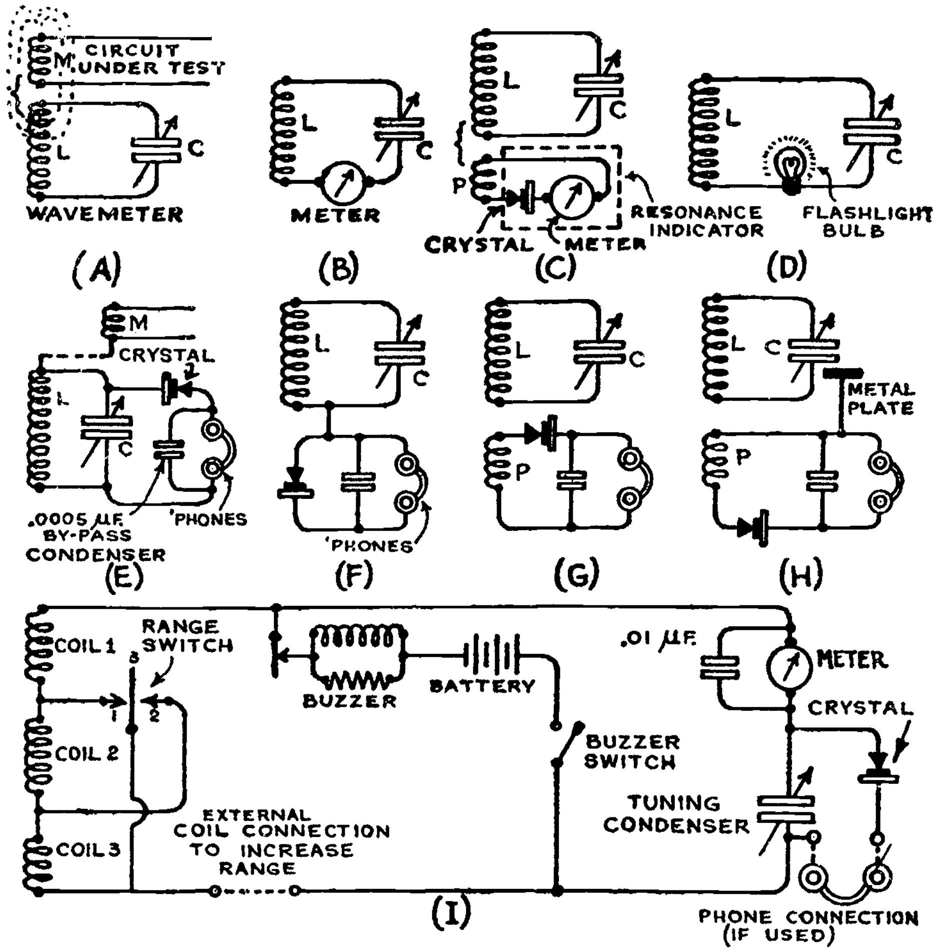


Fig. 159—Various wavemeter and frequency meter circuits. These enable one to measure the wavelength or the frequency of an a-c circuit.

Therefore if the value of the inductance and capacitance of the wavemeter at resonance are known, either the frequency or the wavelength can be calculated. In practical wavemeters, the tuning condenser scale is usually calibrated to read directly in frequency or wavelength.

In order to determine just when the tuned circuit of the wavemeter has been adjusted to resonance, it is necessary to have some device to indicate when maximum current is flowing through it. This is called the indicator. The indicator may be an a-c current meter, a small neon tube or flashlight lamp which will light up when maximum current is flowing in the tuned circuit, or a d-c milliammeter or pair of earphones with a crystal detector to rectify the current (this really forms a rectifier type meter). It may be connected directly in the tuned circuit as shown at (B), or, preferably coupled loosely to it by a coupling coil P consisting of a few turns of wire wound either around the main tuning coil or placed in inductive relation with it as shown at (C). The method at (C) is usually preferable to that at (B), because in the latter, the resistance of the indicating device is placed directly in the tuned circuit. This will tend to reduce the current flowing at resonance (since the current at resonance is equal to the voltage induced in the tuning coil, by the circuit under test, divided by the *total* resistance of the tuned circuit), and will also tend to broaden the tuning of the wavemeter (see (B) of Fig. 115). If the indicator is coupled loosely to the tuned circuit, its resistance will not appreciably broaden the tuning of the wavemeter.

The characteristics of the various resonance indicators which can be used, determine their selection for any particular case, depending on the use to which the wavemeter or frequency meter is to be put. In some cases, it is merely desired to have the indicator tell when the wavemeter is tuned to resonance with the circuit under test, in others it may also be desired to obtain a measurement of the strength or energy of the signal being tested, in which case a meter of some kind must be used to measure the current set up in the tuned circuit at resonance.

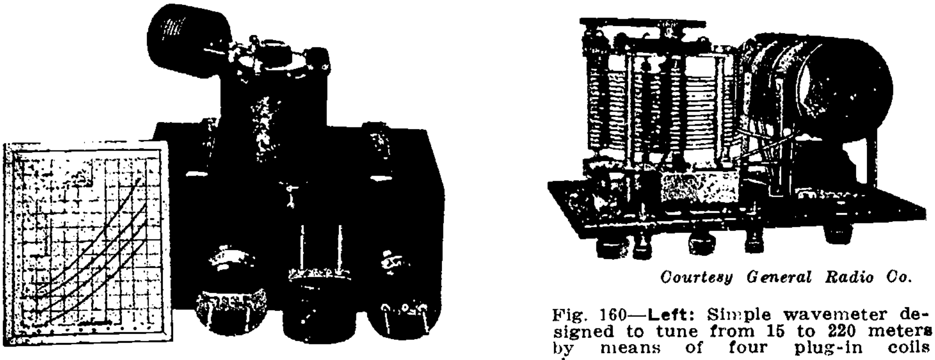
Where the power in the circuit being tested is considerable, as in the case of radio transmitter circuits, test oscillators, etc., the voltage induced in the wavemeter coil is comparatively large and the resonance indicator generally consists of a small flashlight bulb in series with the coil and condenser as shown at (D) of Fig. 159. At resonance the bulb burns brightest since the maximum current is flowing through it. A sensitive hot wire milliammeter (about 0 to 3 m. a.) may be used in place of the lamp bulb. In this case a .01 mfd. condenser should be shunted around its rather high resistance as shown at I of Fig. 159. Thermo-milliammeters are also used extensively for resonance indicators in these circuits. A small neon gas filled bulb connected across the tuning condenser may also be used as the resonance indicator.

When the power in the tested circuit is very small, as in the case of radio receiver circuits, etc., a pair of earphones in series with a crystal detector rectifier may be shunted across the tuning condenser as shown at (E), or connected through a single wire as at (F). This makes a more sensitive resonance indicator since the earphones will respond to the slightest current through them. The arrangement at (E) depends for its action on the fact that at resonance the voltage across the terminals of either the tuning condenser or coil is at maximum and therefore the sound in the earphones is also maximum. When earphones are used, the current in the circuit under test must be modulated at an audio frequency in order to be heard in the earphones, since earphones will not respond to a steady high frequency current. Otherwise, modulation may be accomplished by a buzzer connected in the wavemeter circuit. The crystal detector rectifies the a-c current so that the earphones will operate. The wavemeter circuit is considered as being tuned exactly to resonance with the current in the circuit under test, when the sound in the earphones is at a maximum.

When the resonance indicator is placed in a separate circuit loosely coupled to the wavemeter circuit, as at (C) and (G) of Fig. 159, the energy in the indicating device is of course less than when it is directly in the tuned circuit as at (B). There are various ways of coupling the indicator circuit to the tuned circuit. A small coupling coil P, containing from 1 to 20 turns (depending on the amount of coupling desired) of magnet wire (about No. 18) wound on a 2 inch diameter bakelite tube may be placed several inches from the tuning coil in the wavemeter as shown at (G); both usually being mounted in the same box. The coupling coil should not have too many turns or be placed too close to the wavemeter coil for then it will absorb so much energy from the tuned circuit, that the calibration of the wavemeter will be affected, and its tuning will be broadened. If the coupling coil has too few turns or is placed too far away, the indication of the resonance indicator will be too feeble. The coil should be so designed and placed that it gives the best reading for the purpose used, without causing any change in calibration of the tuning condenser. The fixed Carborundum type of crystal detector is probably the best type of rectifier for this type of circuit, since it need not be adjusted.

If the sound in the earphones is too weak, more energy may be introduced into the indicator circuit by a simple method devised at the Bureau of Standards. A metal plate or piece of tinfoil about 2x3 inches or 2 inches square is mounted near the stator plates of the tuning condenser and is connected to a point in the indicator circuit as shown at (H). This adds some capacitive coupling between the two circuits.

The coupling between the wavemeter and the circuit which is under test should always be made as loose as possible, that is, the meter coil should be kept as far from



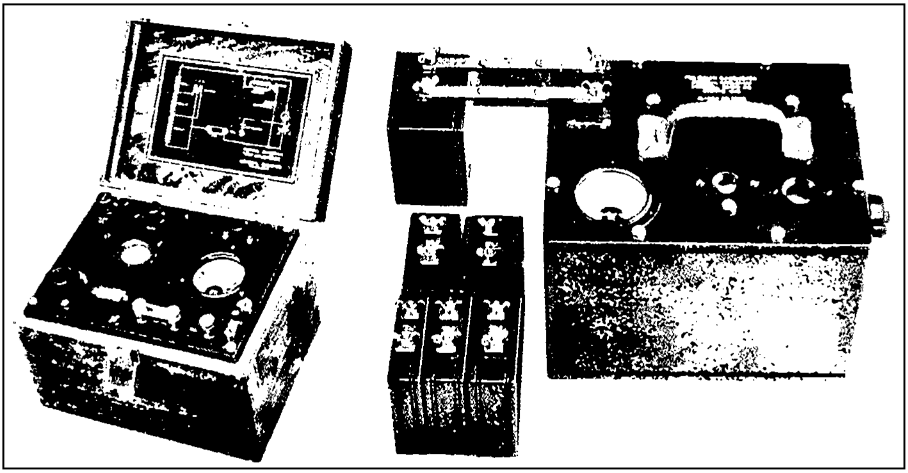
Courtesy General Radio Co.

Fig. 160—**Left:** Simple wavemeter designed to tune from 15 to 220 meters by means of four plug-in coils shown.
Right: Inside view of self-contained wavemeter having range of 75 to 1500 meters by means of 3-section coil. Resonance may be indicated by the hot-wire milliammeter or by earphones. The circuit diagram of this instrument is shown at (I) of Fig. 159. See also Fig. 161.

the circuit under test, as is consistent with a satisfactory reading of the indicator device. Coupling may be made as close as a few inches when very feeble currents exist in the circuit being tested, but with stronger currents the coupling may be several feet. With too close coupling, sharp indications of resonance cannot be obtained, since the close coupling broadens the resonance peak or may even make two distinct "peaks" or "maximum readings" separated considerably from each other. This effect is really caused by the fact that even when the wavemeter current is tuned way off resonance and is therefore presenting quite a high impedance to the flow of current of the frequency under test, enough voltage is being induced in the wavemeter coil by the close coupling to the test circuit so that some current is forced through the wavemeter circuit anyway, resulting in a reading on the indicator. This will of course cause inaccurate measurements.

In many cases, where it is impractical to inductively couple the circuit M *being tested*, to the coil in the wavemeter, on account of too distant separation, etc., coupling may be effectively accomplished by connecting a single wire from one end of the tuning coil in the wavemeter, to any point in the circuit under test, as shown at (E).

Wavemeters are usually built with the inductance fixed or semi-adjustable and the tuning capacitance variable, to enable them to be tuned to various frequencies within their range. All of the wires connecting the tuning coil and condenser must be heavy and as short and direct as possible, so as not to introduce extra resistance into the tuned circuit. When a wide band of frequencies is to be covered, it is frequently necessary to use several coils of different inductance, which fit into the wavemeter by a plug-in arrangement, If the coils are arranged so one has exactly four times the inductance of the next smaller one, the wavelength range with any one coil will be approximately doubled and the frequency range approximately halved by using the next larger coil. If the coils are all built so the same winding space is used but with the number of



Courtesy General Radio Co.

Fig. 161—**Left:** Top view of direct reading wavemeter shown at the right of Fig. 160. The wavelength in meters is read directly from the scale at the left. The hot-wire milliammeter is at the right.

Right: A precision wavemeter with plug-in coils, and a thermo-milliammeter resonance indicator. Notice the heavy copper connecting straps from the removable coils, to keep the resistance of the tuned circuit low. Additional coils are shown below.

turns in this space double for each next larger coil, these conditions will be approximately closely. In wavemeters using several plug-in coils it is desirable to have the ranges of the coils overlap somewhat.

A simple wavemeter provided with a set of four plug-in coils fitted with mounting pins to fit the special tuning condenser terminals, and providing a total tuning range from 15-220 meters (20,000 to 1363 kc). is shown at the left of Fig. 160. This unit, having an accuracy of one per cent is very useful in many radio measurements and tests in the home or school laboratory. The tuning condenser with one of the coils inserted in place is shown on top of the wooden carrying box supplied with this wavemeter. A small flashlight bulb in a special socket which automatically closes the tuned circuit upon removal of the bulb, is provided. Any of the other types of resonance indicators may be connected to this wavemeter externally. The chart shown at the left supplies the calibration curves for the four ranges.

The illustration at the right of Fig. 160 shows the inside of a very useful self-contained direct reading wavemeter having a three-section tuning coil arranged with a switch for obtaining the wavelength ranges of 75 to 200 meters, 200 to 500 meters, and 500 to 1500 meters with the tuning condenser shown at its left. For the low range, the small front section of the coil winding is used alone. For the middle range the first two coil sections are in series. For the high range all three coil sections are in series. The range may be extended by connecting an additional inductor in series with this tuned circuit. The tuning condenser is provided with a reduction gear and vernier knob arrangement to enable its setting to be adjusted very accurately to the resonance point. The accuracy of this meter is one per cent. The hot-wire milliammeter mounted under the coil may be used for resonance indication, or a crystal detector (which is not visible in this photograph) may be used in conjunction with a pair of earphones for this purpose. The circuit diagram of this wavemeter is shown at (I) of Fig. 159. A top view of the instrument in its wooden case is shown at the left of Fig. 161.

A precision wavemeter employed for general laboratory and service uses where rapid and fairly accurate wavelength or frequency measurement is required, is shown at the right of Fig. 161. The plug-in coils are mounted in individual wooden cases for mechanical protection as shown. A thermo-galvanometer is used to indicate resonance. The accuracy of this instrument is 0.25 per cent and the wavelength range is 15-600 meters (20,000 to 500 k.c.). Another instrument of the same type is made, having a range of 70 — 24,000 meters (4,290 — 12.5 k.c.)

For very accurate measurements, a wavemeter should always be calibrated while using the same resonance indicator and wiring connections that are to be used whenever the meter is employed later. This applies to earphones, lamps, milliammeters, phone cords and all other similar parts. Any changes in these may change the inductance or capacitance of the tuned circuit and so affect the reading. For ordinary measurements this is not so essential.

Some wavemeters are equipped with buzzers to enable them to send out a modulated high frequency radio wave which can be picked up by a radio receiver or other device under test. The wavemeter at the right of Fig. 160, has a special high frequency buzzer mounted in the rectangular metal case directly in front of the tuning condenser. This is operated by an ordinary 4.5 volt C-battery mounted inside the wavemeter case.

Heterodyne wavemeters are probably the most useful type and are used extensively. In these, a tuned circuit, an oscillating vacuum tube and a milliammeter, (usually in the grid circuit of the tube), are employed; and very sharp indications of resonance are obtained by noticing when the sudden change in the milliammeter reading occurs. The wavemeter may also be used as an oscillator to produce high frequency current or waves.

When using a wavemeter, the setting of the tuning condenser is varied slowly until the particular resonance indicating device employed shows that maximum current is flowing in the tuned circuit of the wavemeter. Then the wavelength or frequency is calculated from the values of inductance and capacitance in the tuned circuit at the resonance setting by means of the formulas previously given, or else they may be read directly from the condenser scale if it is suitably calibrated.

REVIEW QUESTIONS

1. Name the three main effects which a flow of electric current can produce, and give two examples of the application of each in some practical electrical device with which you are familiar.
2. Explain the construction of the D'Arsonval type movement used in the Weston d-c electrical measuring instruments.
3. What causes the movable coil of instruments of this type to turn when current flows through it?
4. What is the purpose of the mirror that is mounted on the scale card of some instruments?
5. Since the mechanical construction and resistance of the movable coils of a Weston d-c voltmeter, ammeter and milliammeter are all the same, what then is the essential difference between these instruments?
6. How must a voltmeter always be connected to a circuit? (sketch)
7. How must an ammeter always be connected to a circuit? (sketch)
8. How is a wattmeter connected to a circuit? (sketch)
9. Draw a circuit diagram of a 6 volt storage battery connected to supply current to the filament of a vacuum tube in series with a 10 ohm rheostat. Indicate how you would connect an ammeter in the circuit to measure the current flowing. Also indicate how you would connect a voltmeter to read (a) the p. d. of the battery, (b) the voltage across the tube filament, (c) the voltage drop across the resistor.
10. What causes the Weston type of d-c measuring instruments to be "dead beat"?
11. A 0-1 d-c milliammeter has a resistance of 30 ohms. Calculate the resistances of the shunts required to extend its range to (a) one ampere, (b) 10 amperes, (c) 50 amperes. What is the multiplying factor which must be applied to the meter scale readings in each case? Draw a diagram showing the connections of these shunts to the meter.
12. A voltmeter having a sensitivity of 1000 ohms per volt, has three scales, 7.5 volts, 150 volts, 450 volts. What is the value of the series multiplier resistance used for each range? Draw diagrams of the connections. How much current flowing through the movable coil is necessary to produce full scale deflection?

13. The range of the voltmeter of problem 12 is to be extended to 1000 volts. What multiplier resistance must be connected in series with the movable coil?
14. What is the essential requirement in a meter necessary to measure *e. m. f.* accurately and how is it fulfilled in the construction of a high resistance voltmeter?
15. What are the essential requirements of satisfactory meter multiplier resistors? How accurate need their resistance value be?
16. State the principle of operation of the hot-wire ammeter. Draw a sketch of a simple one and explain its operation. What are the advantages and disadvantages of this type of meter?
17. State the principle of the thermo-couple ammeter. What are its advantages?
18. Explain why hot wire ammeters or thermo-couple ammeters can be used either in a-c or d-c circuits.
19. Explain by a practical example, how a voltmeter having a comparatively low resistance may cause an appreciable change in the voltage of the circuit it is connected across. Show how the use of a high resistance voltmeter (1000 ohms or more per volt) eliminates this trouble.
20. Explain the operation and construction of a wattmeter and show why it can be used in a-c or in d-c circuits.
21. A power consumption test is made on a radio receiver by operating it and counting the number of revolutions of the aluminum disc in a recording watt-hour meter connected in the circuit. If the constant of the meter is 0.5 watts, and the disc makes 25 revolutions in 5 minutes how much does it cost to run the receiver per hour if electric power costs 8c per kilowatt hour?
22. Explain the construction and operation of the movable-iron type of a-c ammeter. What are its advantages over the dynamometer type? Why can this type of meter be used either on a-c or d-c?
23. Explain the construction and operation of the rectifier type a-c. instruments? What are their advantages over the movable-iron or dynamometer types?
24. What is a rectifier? (Explain with aid of a diagram.)
25. Describe the action and construction of two types of dry-plate rectifiers.
26. Explain the principle of the Wheatstone bridge (with diagram).
27. What is meant by "balancing the bridge", and why is this done when measuring a resistance?
28. Referring to (A) of Fig. 156, resistor R is 10 ohms, S is 30 ohms, and T is 5 ohms when the bridge is balanced. What is the value of the unknown resistance?

29. Explain the principle of operation of a simple ohmmeter (with sketch). What is the advantage of the ohmmeter method of resistance measurement over that using a Wheatstone bridge? What are its limitations?
30. Explain how capacitance may be measured on a Wheatstone bridge.
31. Explain how inductance may be measured on a Wheatstone bridge.
32. What is the difference between a wavemeter and a frequency meter?
33. Explain the principle of operation of a simple wavemeter with a resonance indicator consisting of a crystal detector rectifier and a pair of earphones. Draw the complete circuit diagram the indicator circuit is inductively coupled to the tuning coil.
34. When a wavemeter is tuned to resonance with a particular circuit under test, the inductance is 300 microhenries and the capacitance is .0003 microfarads. What is the frequency of the circuit being tested? What is the wavelength?
35. Draw a diagram and explain how you would measure the value of a rather low resistance by means of an ammeter and voltmeter.
36. Draw a diagram and explain how you would measure a high resistance roughly by using a voltmeter alone.
37. A filament rheostat is the resistor in Prob. 35. The voltmeter reads 6 volts and the ammeter reads 0.5 amperes. Calculate the resistance.
38. A voltmeter having a resistance of 100,000 ohms gives a reading of 86.5 volts when connected in series with the secondary winding of an audio transformer across a source of voltage. When the voltmeter is connected across the line alone, it reads 110 volts. What is the approximate resistance of the winding? What would the first voltmeter reading be if the transformer winding were open at some point?
39. How does an ohmmeter indicate (a) a short-circuit in a condenser? (b) an open winding in a resistor or a transformer?
40. A frequency meter having a frequency range of 1500 to 500 k. c. (200 to 600 meters) is to be used in connection with a crystal detector rectifier and a 0-1 d-c milliammeter resonance indicator, to indicate when the frequency of a test oscillator reaches 400 kc. The inductance of the wavemeter coil is 300 microhenries and the maximum capacitance of its tuning condenser is approximately .00033 microfarads. What standard size of fixed condenser must be shunted across the wavemeter condenser to bring the range down to say 318 kc when the tuning condenser is set at maximum capacitance?

CHAPTER 14

ELECTROMAGNETIC RADIATIONS

SOUND AND ELECTROMAGNETIC RADIATIONS — STRUCTURE OF THE ATOM — HOW RADIATIONS ARE PRODUCED — FREQUENCY OF ELECTROMAGNETIC RADIATIONS — FAMILIAR RADIATIONS — EFFECTS PRODUCED BY THE COMMON ELECTROMAGNETIC RADIATIONS — HOW RADIO RADIATIONS ARE PRODUCED — THE BROADCASTING STATION — REVIEW QUESTIONS.

222. Sound and electromagnetic radiations: In Chapter 2, we studied some of the characteristics of sound waves produced by the mechanical vibration of air, and having frequencies between about 16 and 20,000 complete vibrations per second. In Chapter 2, it was mentioned that the broadcasting of sound programs could be accomplished practically by making use of electromagnetic and electrostatic waves or radiations of high frequency (commonly called radio waves), radiated in all directions over long distances from the transmitting aerial. Distant reception of radio programs almost daily proves that it is possible to hurl into space and scatter literally to the four corners of the earth at a speed of 186,000 miles per second, electric energy in the form of waves or radiations exactly representing the spoken words of the human voice or the music of great orchestras; and anywhere thousands of miles away on land or sea, or even in the air above, to pick out of the atmosphere a tiny bit of this energy and from it reconstruct the sounds almost as perfectly as they were originally produced.

We will now study some of the important characteristics of these radiations and will find that they belong to the same family as do those which produce the common sensations of heat and light. There are many fundamental things regarding the production and propagation of electromagnetic waves through space, which have never been explained to the complete satisfaction of scientists, and it is upon these questions that many of the most brilliant scientific minds in the world today are concentrating their efforts. Important data is being collected almost daily toward a solution of some of these entrancing mysteries of nature. The fact that we do not know as much about these things as we would like to, need not prevent us from making practical use of them, because there are many things with which we are on familiar terms in our daily lives, but which we really know little about. The origin of life itself is still a mystery.

223. Structure of the atom: We found from our study of the structure of the atoms of substances, in Articles 16 and 17, that all matter is composed of atoms, each one of which consists of a central nucleus of positive electrical charges (protons) and negative electrical charges (electrons), surrounded by one or more negative planetary electrons revolving about it in more or less circular orbits or shells.

Note: The student is advised to read Articles 16 and 17 carefully at this point in order to obtain a good mental picture of the atomic structure. He should study Fig. 17 especially.

It is imagined that in the more complicated atoms, planetary electrons are arranged around the nucleus somewhat as if they lay in a series of concentric shells or orbits. In the first shell are two planetary electrons (except in the case of hydrogen) revolving around the nucleus. In those atoms which contain more than two planetary electrons, all of the electrons in excess of these first two are arranged in shells external to the one just described as shown at (C) of Fig. 17, the capacities of successive outer shells for electrons being 2,8,8,18,18,32 and 32 respectively. Every one of the 92 chemical elements has a different electron arrangement. The total number of negative electrons revolving about the nucleus of each atom of any element (planetary electrons) is called its *atomic number.* There are of course, additional electrons inside the nucleus but these do not affect the ordinary electrical or chemical properties of the elements. The characteristic distribution of the electrons in any atom determines the properties of the atom.

In the following table, the total number of planetary electrons (atomic weight) and the number of electron orbits or shells in each atom is given for all of the 92 chemical elements. This table should prove helpful and instructive to the student in visualizing the structure of the atoms of the various chemical elements.

Chemical Symbols	*Elements*	*Number of Planetary Electrons*	*Quanta or Number of Electron Shells*
H	Hydrogen	1	1
He	Helium	2	1
Li	Lithium	3	2
Be	Beryllium	4	2
B	Boron	5	2
C	Carbon	6	2
N	Nitrogen	7	2
O	Oxygen	8	2
F	Fluorine	9	2
Ne	Neon	10	2
Na	Sodium	11	3
Mg	Magnesium	12	3
Al	Aluminum	13	3
Si	Silicon	14	3
P	Phosphorus	15	3
S	Sulphur	16	3
Cl	Chlorine	17	3
A	Argon	18	3
K	Potassium	19	4
Ca	Calcium	20	4
Sc	Scandium	21	4
Ti	Titanium	22	4
V	Vanadium	23	4
Cr	Chromium	24	4
Mn	Manganese	25	4
Fe	Iron	26	4
Co	Cobalt	27	4
Ni	Nickel	28	4
Cu	Copper	29	4
Zn	Zinc	30	4
Ga	Gallium	31	4
Ge	Germanium	32	4
As	Arsenic	33	4
Se	Selenium	34	4
Br	Bromine	35	4
Kr	Krypton	36	4
Rb	Rubidium	37	5
Sr	Strontium	38	5
Y	Yttrium	39	5
Zr	Zirconium	40	5
Cb	Columbium	41	5
Mo	Molybdenum	42	5
Ma	Masurium	43	5
Ru	Ruthenium	44	5
Rh	Rhodium	45	5
Pd	Palladium	46	5

Chemical Symbols	*Elements*	*Number of Planetary Electrons*	*Quanta or Number of Electron Shells*
Ag	Silver	47	5
Cd	Cadmium	48	5
In	Indium	49	5
Sn	Tin	50	5
Sb	Antimony	51	5
Te	Tellurium	52	5
I	Iodine	53	5
Xe	Xenon	54	5
Cs	Caesium	55	6
Ba	Barium	56	6
La	Lanthanum	57	6
Ce	Cerium*	58	6
Pr	Praseodymium*	59	6
Nd	Neodymium*	60	6
Il	Illinium*	61	6
Sm	Samarium*	62	6
Eu	Europium*	63	6
Gd	Gadolinium*	64	6
Tb	Terbium*	65	6
Dy	Dysprosium*	66	6
Ho	Holmium*	67	6
Er	Erbium*	68	6
Tm	Thulium*	69	6
Yb	Ytterbium*	70	6
Lu	Lutecium*	71	6
Hf	Hafnium	72	6
Ta	Tantalum	73	6
W	Tungsten	74	6
Re	Rhenium	75	6
Os	Osmium	76	6
Ir	Iridium	77	6
Pt	Platinum	78	6
Au	Gold	79	6
Hg	Mercury	80	6
Tl	Thallium	81	6
Pb	Lead	82	6
Bi	Bismuth	83	6
Po	Polonium	84	6
—	Alabamine†	85	6
Rn	Radon	86	6
—	Eka-caesium†	87	7
Ra	Radium	88	7
Ac	Actinium	89	7
Th	Thorium	90	7
Pa	Protoactinium	91	7
U	Uranium	92	7

*These elements are the Rare Earths. †Tentative name-element recently discovered.

Notice that it is possible to tabulate the 92 elements in such a way that each one has one more planetary electron per atom than the element above it. This fact led to the discovery of many elements which were missing in this table several years ago, for it was known that the element with the electron structure enabling it to fit into the missing place existed somewhere. Some of the missing elements were found to exist in the atmosphere around the sun, etc. The search for and final separation of the missing element radium by Madame Curie, is a thrilling chapter in the history of science. Elements 85 and 87 have recently been discovered and named tentatively. Those listed beyond bismuth, exhibit radioactive properties similar to those of radium. Hydrogen with only one planetary electron is the simplest of all atoms, and uranium with 92 planetary electrons is the heaviest and most complex. It is one of the unstable radioactive substances, since changes are constantly taking place in its atoms with accompanying releases of tremendous energy per unit mass and change of chemical nature.

224. How radiations are produced: Normally, the planetary electrons are rotating around the nucleus of each atom in their proper imaginary orbits or shells and no external manifestations of energy are present. Each electron possesses a certain amount of potential energy depending on its distance from the nucleus. It requires the application of a force to move one of the electrons away from the atom, which would then contain an unbalanced positive charge. The actual potential energy becomes less as we pass from an outer shell to the one nearer the central positive nucleus. If, however, some external applied agency causes one of these electrons to be knocked or jarred out of its normal orbit or shell so that it is forced into one of the other shells an emission or absorption of energy takes place. If it is knocked from an outer to an inner orbit, the difference in energy corresponding to the two positions within the atom, must be given up in some other form. This entire energy is radiated in the form of electromagnetic radiations and for each electron moved, a certain definite amount of energy known as one *quantum* is radiated into space and propagated at the uniform speed of 186,000 miles or 300,000,000 meters, per second. If an electron were to be removed from one shell to another farther away from the nucleus the potential energy of that electron would be increased and therefore work would have to be expended by the outside source to effect the transfer. Of course some applied agent may cause this to happen to countless numbers of atoms simultaneously in a body. Thus when electric current is sent through a gas such as neon, helium, etc., the gas becomes ionized due to a disturbance of the electron orbits of its atoms and when the atoms and electrons re-combine, electromagnetic energy is radiated at a frequency which produces the sensations of light on our optic nerve, so we say light is produced. This principle is used in the neon sign lights which are so popular today for advertising purposes. Energy is being absorbed from the source of electric current in the act of ionization, and radiated when recombination of the electrons and atoms occurs.

The converse of this action forms the basis of the operation of photo-electric cells used extensively in industrial devices, television and sound pictures. When an insulated, negatively charged metallic plate, is illuminated by light of suitable frequency or wavelength, it loses its charge because of a photo-electric emission of electrons. It is supposed that the electrons are knocked loose and emitted from the atoms of the metallic plate by the impact of the small quanta or bundles of energy which constitute the electromagnetic light rays. A certain critical light frequency or color is necessary before the photo-electric emission takes place at all, depending on the material of the plate. For instance, for some metals, red light produces no emission while ultra-violet light is very effective. Only a few of the metals exhibit the photo-electric effect to any marked degree. In commercial photo-electric tubes or *cells* as they are called, various metals are used for the active surface depending upon the frequency or color of the light the cell is to be responsive to. For instance, zinc does not give off many electrons when exposed to ordinary light, but emits them quite freely when exposed to ultra-violet light. The commonly used metals for these cells are lithium, sodium, potassium, rubidium and caesium. The laws governing the photo-electric effect have been a strong argument in favor of the quantum theory of the corpuscular nature of electromagnetic radiations. (Photo-electric cells will be studied in Chap. 32.)

According to the Planck-Einstein theory of radiant energy, it is the scattering or radiating of these tiny units of radiant energy through space that constitutes the radio rays or waves that we commonly speak of. The exact nature of this radiant energy is not positively known as yet, nor is the exact way in which it travels through space known. We are not certain whether the energy is transmitted by a sort of wave-motion, as in the case of sound waves, or by tiny bundles of energy in a direct motion through space in straight lines like tiny bullets shot from a gun, and whether or not some material substance called the ether is necessary for their propagation through space. It is beyond the scope of this book to enter into an extended discussion of this subject, and even our most brilliant scientists have not yet reached definite conclusions on it. It seems probable at this time that the facts may best be explained by considering the wave theory to be an accurate representation of the facts when we have to deal with the operation of a large number of these bundles of energy (quanta), whereas in processes where an exchange of energy due to a single quantum is concerned, the quantum theory is necessary for a satisfactory explanation of the conditions.

Energy can be transmitted from one place to another by only one of two general means; either by a *wave disturbance* travelling through a medium which does not itself move as a whole (as illustrated by the case of sound waves in Figs. 2 and 3), or by the motion of corpuscles of matter from some source (as illustrated by the case of buckshot issuing from a shotgun), as shown in Fig. 162. According to the *wave theory,* an electromagnetic disturbance travels in the former way, by a wave motion through the ether. According to the *emission* or *corpuscular* theory, electromagnetic disturbances are propagated by invisible rapidly moving particles whose size varies with the frequency. As it is impossible for most minds to think of waves without a medium to carry the wave motion, it has been supposed that a hypothetical ether exists in all space, this ether serving as the medium to carry the wave motion. If the wave theory is upheld, then it must be assumed that at all points on a surface through which an electromagnetic wave is passing, energy is uniformly and continuously distributed. If the corpuscular theory is upheld, it must be assumed that the energy is distributed discontinuously in isolated bundles or quanta, being concentrated at points. At the present time, many facts do not find an adequate explanation in the simple wave theory and the quantum theory does not satisfactorily explain all observed phenomena associated with all types of electromagnetic waves. It seems probable that a combination of parts of the two theories will explain the observed facts more satisfactorily. The *wave mechanics* theory, which attempts to reconcile the conflicting views of these two theories, is rapidly gaining popularity. In this, it is assumed that in every mechanical system electrons are accompanied by waves. In this book we will speak of electrical and radio waves and also of bundles of energy or quanta, when dealing with the propagation of electrical energy from the radio transmitting aerial to the receiving antenna.

The exact nature of the little bundles of energy is not yet positively known but it has been definitely established by a series of extremely delicate experiments performed by Professor R. A. Millikan, that a quantum shot off from an electron whose orbit lies close to the atomic nucleus is larger than a quantum that is radiated from an electron rotating in a larger orbit, further away from the nucleus. It is also known that the frequency of emission, that is, the number of groups or clouds of quanta shot off per second from electrons rotating in the inner orbits, is greater than the frequency of emission coming from electrons in the outer or larger orbits. The reason for this may be easily understood by remembering that the frequency depends entirely on how long it takes the electron

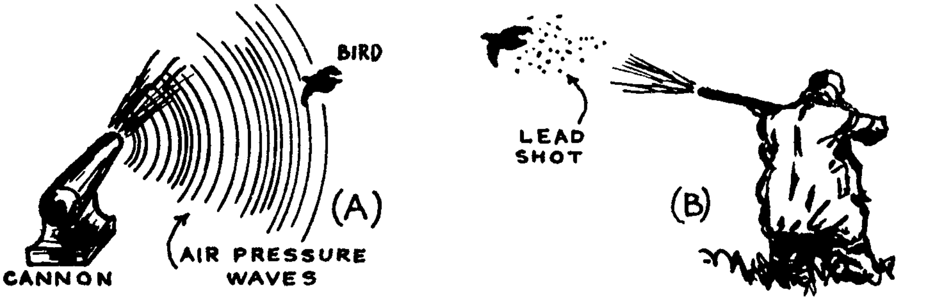


Fig. 162—(A) A bird may be killed at a distance by the concussion resulting from the explosion of a large cannon. The disturbance travels thru the air by wave motion from the region of the explosion. This illustrates rather crudely the propagation of energy by wave motion. (B) The bird may also be killed by being struck by lead shot from a shotgun. In this case the energy travels directly thru the air from the gun to the bird. This illustrates crudely the corpuscular theory of propagation of electromagnetic energy in tiny bundles.

to travel back and forth over its path. The shorter the path of the electron, the sooner it completes a round trip and is ready to start over again, and the more closely the outgoing streams of energy follow the preceeding ones, i.e., the higher the frequency and the shorter the wavelength.

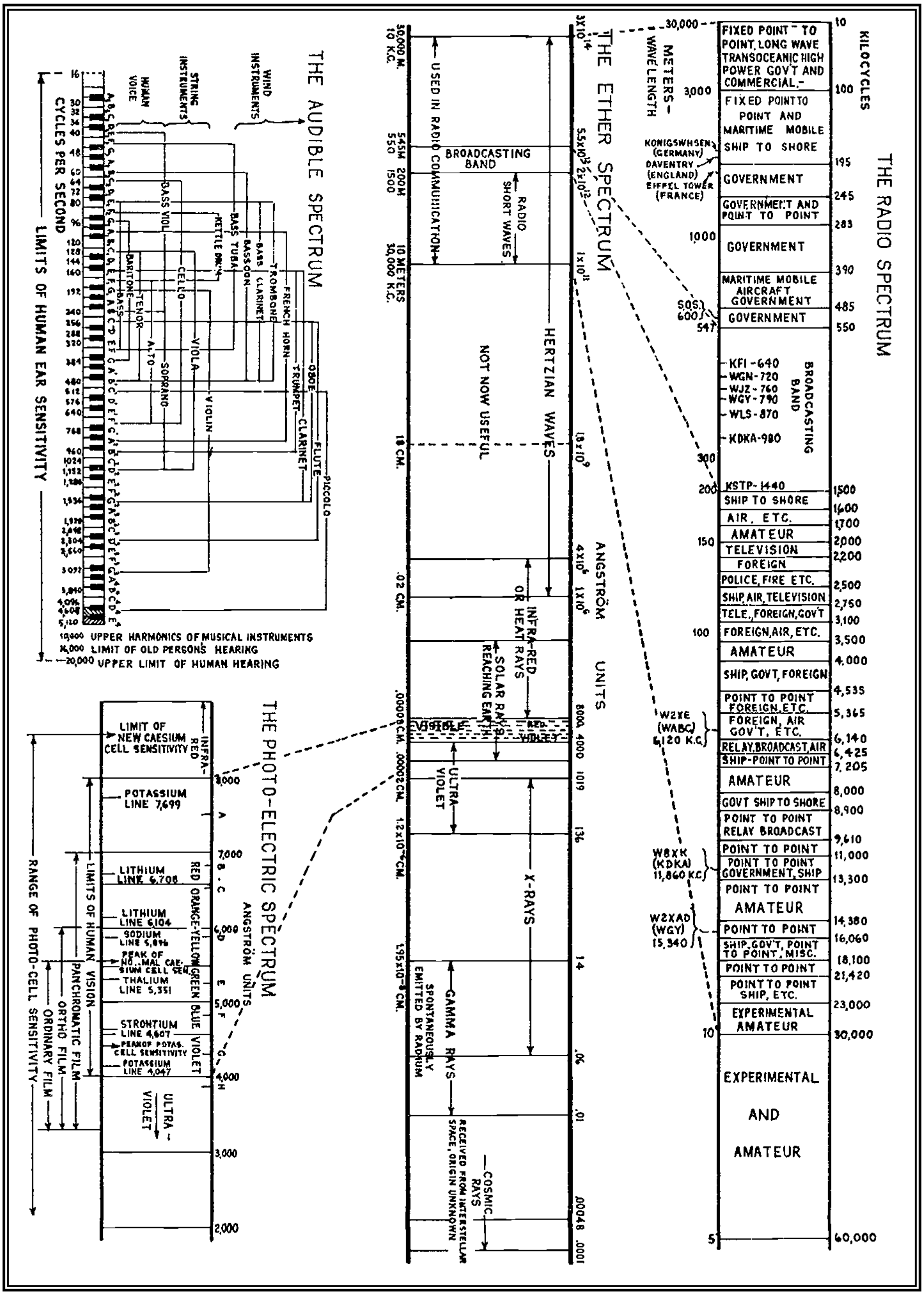
225. Frequency of electromagnetic radiations: Frequency, referred to alternating electric currents flowing in conductors, means the number of times the current or flow of electrons reverses in direction each second. Frequency as we apply it to radio, is simply the number of groups of these bundles of energy that are shot off into space from the radio transmitting aerial every second. It follows that the so-called *wavelength* is simply the number of meters that one group or cloud of quanta has travelled before the next one is started on its way. The energy is actually propagated through space at the speed of 186,000 miles or 300,000,000 meters per second. For example, if one million groups are shot off every second, the frequency will be one million, and each group will have travelled 300,000,000 $\div$ 1,000,000 or 300 meters before the next one is started. Therefore the *wavelength* is 300 meters. The greater carrying power of the shorter radio waves (high frequency) of 100 meters or less may be explained by considering that the higher the frequency the larger is the size of the individual particles of quanta radiated from the transmitting aerial.

226. Familiar radiations: Radio waves or rays, radiant heat rays, visible light rays, ultra-violet light rays, X-rays, gamma rays emitted by radium, and the cosmic rays received from interstellar space, are all produced by similar electromagnetic radiations. The difference between them is that they are produced by radiations of different frequencies.

In the chart of Fig. 163 the spectrum of all electromagnetic radiations and the audible sound waves is arranged for convenient study. The ether spectrum chart shows the various electromagnetic radiations divided up into bands according to their frequency in k.c. and cycles, and their wavelength in Angstrom units (1 Angstrom unit= 10^{-8} Cm.), meters and centimeters. The radiations having frequencies between 10 k.c. and about 60,000 k.c. constitute the so-called useful radio waves. This band is drawn to an enlarged scale at the top for convenience and labeled the *Radio Spectrum.* The small band from 550 to 1500 kilocycles is used for commercial radio and broadcasting, the transmitters of our common radio stations sending out into space electromagnetic radiations having frequencies lying within this band. The large band of higher frequencies between 1500 k.c. and about 60,000 k.c. is commonly termed the *short wave* band and is allotted for use by television broadcasting stations, amateur stations, etc., as noted. Radio amateurs are constantly pushing down into the shorter waves (high frequencies) and much experimental work is now being done on frequencies as high as 300,000 k.c. (1 meter wavelength). The short radio waves and radio heat waves discovered by E. H. Nichols and Dr. J. Tear comprise the range from about 3,000,000 cycles to 300,000,000,000 cycles per second.

Recently, radiations having frequencies between 10,000 and 14,000 k.c. (30 to 21 meters wavelength) were found to create artificial fevers in human beings by raising the temperature of the blood stream. These may prove helpful in studying the causes and cures for various fevers and other diseases. Above these lie the heat and infra-red rays, then come the visible light rays, arranged according to frequency as follows, (lowest frequency first) red, orange, yellow, green, blue, violet. This band from 8000 to 4000 Angstrom units is drawn to an enlarged scale at the lower left, and is labeled the Photo-electric Spectrum. Then comes the ultra-violet rays which are invisible and are sometimes referred to as "black light". These are given off by the sun, the electric arc, by X-ray tubes, etc. Above these is a gap which we know little about. Then come the X-rays, the gamma rays and the cosmic rays. The X-rays are produced in the X-ray tube by inpinging an electron stream travelling at speeds of the order of 100,000 miles per second on to a metallic target. Gamma rays are produced during the gradual disintegration of radium and by special recently developed forms of X-ray type tubes in which enormously high voltages are used to impinge an electron stream at very high velocity on to a metallic target.

Thus, all of the properties which we associate with the usual useful radio waves or rays, are produced by electromagnetic radiations having a frequency between 10 k.c. and 60,000 k.c. Radiations of higher frequency (shorter wavelength) produce manifestations peculiar to the shorter radio waves which are now beginning to be explored. For instance, during the ultra short wave transmission tests made across the English Channel on March 31, 1931, radiations having a wavelength of 18 cm. were employed. Since these lie in the frequency region near the infra-red and visible light rays (see Fig. 163) they behave similarly in some respects to heat and light rays, and ordinary reflectors were used at the transmitting and receiving stations for concentrating them, just as reflectors are used for concentrating heat or light rays. These so-called *quasi-optical* rays will be studied in Art. 570.



Courtesy Electronics Magazine.

Fig. 163—The complete spectrum of electromagnetic radiations. Electromagnetic radiations of different frequencies produce different effects as will be noted. Our eyes respond to only a small range of radiations (1 octave) as light. The audible spectrum of sound waves is at the upper left for comparison.

Little is yet known about cosmic rays of the type which are received from interstellar space, excepting that they are of extremely high frequencies and very penetrating. Only recently two Swiss scientists Professor Auguste Picard and Charles Kipfer made a most perilous flight to an altitude of 52,000 feet in a specially constructed baloon solely to collect data on the extremely high frequency penetrating cosmic rays radiated from interstellar space. Mr. G. Pendray writing in the Herald Tribune of May 31, 1931 says of these rays:

"Students of the cosmic rays, including their discoverer, Dr. Robert A. Millikan, of the California Institute of Technology, believe that thev arise in space through the creation of matter from electrons or protons, or through the building up of heavy atoms from lighter ones in the hot centers of stars or nebulae. The cosmic rays are distinguished from all others by their extremely short wavelength and exceedingly great power of penetration. There appears to be no other way to account for their origin except by assuming that they come from the stars or from space, and that they represent tremendous changes taking place somewhere, involving enormous amounts of energy.

Some day, perhaps, when the true constitution and behavior of the atom and its components are thoroughly understood, a way will be devised to accomplish the complete transformation of matter into energy. The present studies, however, look rather toward obtaining a portion of the terrific energy that would probably be released if it were possible to create new atoms out of "free" protons and electrons, or more likely still, by the building up of relatively heavier atoms, such as those of helium, from atoms of hydrogen.

This is known as the development of power by "atomic transformation," as opposed to the present method of developing energy by "chemical reaction." When coal is burned, for instance, the heat is released through the chemical reactions of oxygen with carbon and other combustible material in the fuel. There is no change in the atoms of the materials concerned—only a change in the molecules.

The only example we now have of atomic transformation, is that found in the radioactive elements, such as uranium and radium. In them a genuine change in the atom takes place, with the release of tremendous quantities of energy. This energy, unfortunately, is in such form that its conversion into mechanical power is difficult—though probably not impossible. If some way were to be found to transform more common elements in the same way, releasing energy of somewhat similar nature, it is likely that part, at least, could be converted into heat.

Once that had been accomplished, the harnessing of the heat to do useful work would be relatively easy, and the energy thus secured, in proportion to the amount of substance utilized, would be tremendous beyond human experience. A cheap and simple method of atomic transformation, even though much of the resulting energy were lost in the process, might well solve the power problems of the world for all time."

227. Effects produced by the common electromagnetic radiations: From the foregoing it is evident that radio rays, heat rays, visible light rays, ultra violet light rays, X-rays, radium rays, and cosmic rays, are really all produced by electromagnetic radiations and may all be explained on exactly the same basis, see Fig. 164. They differ from the radio rays only in frequency. Gamma rays are produced by radiations within a band of frequencies almost 4 octaves wide (an octave of a frequency is a frequency twice as high); X-ray radiations cover a band 8 octaves wide, as do also ultra-violet radiations. X-rays have the peculiar property of passing through substances which are opaque to longer waves. They are not able to excite the optic nerve but if allowed to fall on certain fluorescent substances they cause these substances to emit radiations which do affect the eye and permit vision. Lead resists the passage of

X-rays through it. The ultra-violet light radiations also do not affect the human eye directly, but their presence can be detected by a photo-electric cell or by a photographic plate upon which they produce the same photographic effects that the ordinary visible light rays do.

Our eyes are really radio receivers tuned to respond to only a very narrow band of very high frequencies or short wavelengths; a band of about one octave (see Fig. 163). When the frequency of radiation is about 400 million-million cycles per seconds, we perceive the color *red* by means of the impression made on our optic nerve. When it is increased to 750 million-million cycles our eyes interpret the rays as *violet* light. All other colors are caused by various frequencies or combinations

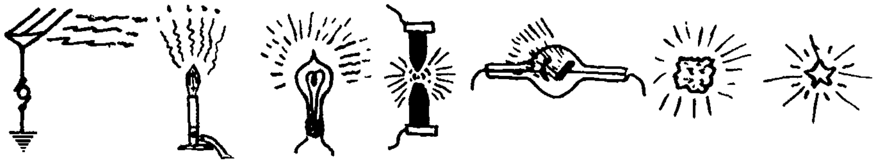


Fig. 164—Radio, heat or infrared rays, visible light rays, ultraviolet rays, X-rays, radium rays, and the cosmic rays are all similar electromagnetic radiations of energy—differing only in the "frequency" of radiation.

of frequencies lying within these two limits, as shown at the lower left of Fig. 163, outside of which our eyes cannot respond. Some grades of glass offer practically no opposition to light and little to heat. Metals offer little opposition to heat flow but are impervious to light.

The heat perception centers of our skin are also tiny radio receivers which are tuned to frequencies somewhat lower than those to which our eyes respond, and the physiological sensation we receive in that case is one of heat instead of color. The infra red or heat radiation frequencies lie within a band about 8 octaves wide. The production of electromagnetic radiations, of frequencies which affect our senses to produce the sensations of heat and light of different colors, may be illustrated by the following simple experiment.

Experiment: Heat a small piece of iron or steel (a hack-saw blade or a tenpenny nail will do) in a gas flame as shown at (A) of Fig. 165. It will first become warm and then hot, as you can prove by removing it from the flame every few seconds and placing your hand near it. Continuing the heating causes it to emit light and change color, first turning to a "dull red", then a bright "cherry red", to slightly "orange", and finally it gets "white hot". If the flame were hot enough to bring the temperature of the iron up to its melting point we would find it would give off a very bluish-white light just before melting.

What has taken place during this experiment? Applying heat to the iron caused its molecules and atoms to vibrate faster and faster as its temperature increased. This rapid vibration caused some electrons to jump to other orbits than their own, resulting in electromagnetic radiations within the particular band of frequencies which have the power of affecting our skin. Our nerves carried the effect to our brain, where the intelligible impression of heat was formed. As the heating was continued the rate of vibration of frequency of the molecules increased, causing the radiations to follow one another more closely, i.e., the frequency increased. These higher frequency radiations produced the sensation of light in our optic nerve and became visible as red light. Continuing the heating, increased the frequency of vibration of the molecules and radiations, resulting in the production of orange, yellow and finally blue-white light as shown by the wave band representation at (B). If we could increase the frequency of these electromagnetic radiations still more by some means, we would produce violet light, ultra-violet light, X-rays, and finally gamma rays and the cosmic rays. All of these radiations, heat, light, X-rays, gamma rays, etc., are fundamentally the same. They are all electromagnetic radiations differing only in

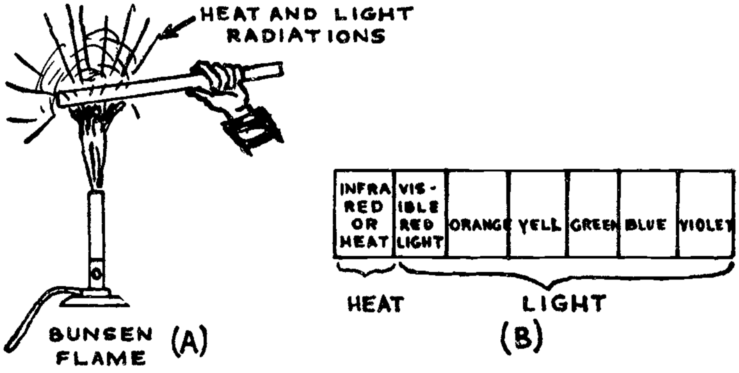


Fig. 165—Producing heat and visible electromagnetic radiations by heating a piece of iron in a flame. The spectrum of radiations produced is shown at (B).

frequency. Sound waves differ from these in that there is nothing electrical about a sound wave, it is simply a mechanical vibration, or actual to and fro motion of air particles.

228. How radio radiations are produced: There are many different methods by which atoms can be made to radiate at various frequencies, but we must confine ourselves now only to the one used for producing radio rays. In order to produce the frequencies used for radio transmission, which are very much lower than those necessary for light and heat, we must establish what might be called an artificial electron orbit, having a circumference infinitely larger than the largest natural orbit of the electrons found within an atom.

A coil of one or more turns of copper wire, or the aerial system of a radio transmitter, constitutes in effect, such an artificial orbit. If a stream of electrons, or in other words an electric current, is made to oscillate or flow back and forth in this circuit, radiation of quanta into space takes place at the same frequency as that of the electric current employed. If the frequency of the current lies between about 10 kc and 300,000 kc per second, the radiations produced will exhibit all of the properties which we associate with the so-called radio waves. One of the most important of these is that these radiations will travel over long distances through space without excessive dimunition in strength, so they may be used for the transmission of messages.

The frequencies found useful for radio transmission are far below those which our eyes or skin respond to directly, therefore we are compelled to construct artificial receiving instruments. When radio rays strike a receiving antenna or loop of metal they induce an e.m.f. in it and this causes a minute electric current to flow back and forth in the wire at the same frequency at which the energy has radiated. This minute electric current can be greatly strengthened by tuning the receiving circuits to electrical resonance at the frequency of the induced e.m.f. or current, and may be further amplified thousands or even millions of times and then converted into sound by the radio receiver.

Naturally, the actual amount of energy picked up by a receiving antenna is extremely small. It has been estimated that the amount of energy picked up by an average receiving antenna, coming from a broadcasting station 2,000 miles away, if made continuous day and night for thirty years, would about equal the energy expended by a common house fly in climbing up a wall a distance of one inch. The e.m.f. induced in an average receiving antenna by the radiations from a nearby broadcasting station of average power, is in the neighborhood of 50 microvolts (.00005 volts). Many modern radio receivers will produce a standard output of 50 milliwatts of power when as low as 5 microvolts is induced in the receiving antenna system of average dimensions connected to them (say 4 meters high and about 60 feet long).

This conception of the electromagnetic radiations employed in radio work, while still incomplete in many details, is probably far nearer to the actual facts than the older theory of a simple wave-motion in a hypothetical substance called the "ether of space," the actual existence of which has never been directly proved, while recent experiments seem strongly to indicate that it does not exist.

We do not know everything there is to know about radio-frequency radiations any more than we know everything about electricity, but just as with the case of electricity, we know how they behave under various conditions, and we are finding out more and more about how to control them for useful purposes. The question of how they travel, and what conditions affect them, is being investigated by many of our most brilliant scientific men, and it is safe to say that the time is not far off when we will know as much about the behavior of these radiations as we now know about simple electric currents, for they make modern radio broadcasting possible.

229. The broadcasting station: The electromagnetic radiations used in radio work are commonly produced by high-frequency alternating electric currents(called the "carrier current") flowing in suitably arranged circuits in the transmitting stations. These circuits will be studied later. The high-frequency currents (500,000 to 1,500,000 cycles per second used in ordinary broadcasting) are generated by large vacuum tubes known as "oscillators", since it is not practical to generate them with the rotating type of electrical generators employed for generating ordinary 60 cycle a-c for electric light and power work. Each broadcasting station is assigned to *broadcast* or radiate energy at a definite frequency, by the government department in charge of licensing. Practically, all stations in the same vicinity at least, are assigned to broadcast on different frequencies or wavelengths, so that in any receiving station the principle of electrical resonance may be used to allow the reception and amplification of the signal energy of the particular station it is desired to receive and present such a high impedance to the flow of currents of all other frequencies (from other stations) that they are excluded from the circuits; and therefore the other stations are not heard at the same time. This is accomplished by "tuning" the receiver.

Thus, station W E A F in New York City transmits with a carrier current having a frequency of 660,000 cycles per second. The transmitting aerial of this station produces electromagnetic radiations of this frequency, which travel outward in all directions to the antennas of thousands of receiving stations located over a wide area. The wavelength of these radiations (and that of the station), is 300,000,000 divided by 660,000 or approximately 454 meters. Also, station W A B C located near it, transmits with a carrier current of 860,000 cycles, or a wavelength of 349 meters etc. Radio stations schedules and programs printed in newspapers usually give the frequency or wavelength of the station, or sometimes both. For convenience in tuning for stations, the tuning dials on some radio receivers are calibrated in kc and others are calibrated in wavelength. Many are simply calibrated with a scale divided into 100 equal parts, there being no direct relation between the scale divisions and either the wavelength or frequency.

If our eyes were capable of responding to the radiations sent out from the aerials of radio transmitters, these aerials would appear to us like so many huge lighthouses flashing on and off, each one a different number of times per second corresponding to the sound vibrations in the program being transmitted, and all radiating their energy out into space to be picked up by the receiving stations. Since each transmitter sends out radiations of different frequency, these beams would all appear as lights of different colors to our eyes. Such a sight would truly be fantastic and wonderful to behold. It would also enable us to understand more easily just how these radio rays travel from each broadcasting station to the many receiving stations.

REVIEW QUESTIONS

1. What is meant by wave motion? What forms of wave motions are you familiar with?
2. What is the essential difference between the wave theory of the propagation of electromagnetic energy and the corpuscular or quantum theory?

3. Explain by means of the latter, how electromagnetic radiations may be produced from a body.
4. What is the velocity of propagation of all electromagnetic radiations? What is the relation between the wavelength, frequency and velocity of these types of radiations?
5. A radio station broadcasts energy into the surrounding atmosphere, using in its aerial circuit a current having a frequency of 700 kilocycles. What is the wavelength of the radiations produced?
6. Does sound or light have the greater velocity? How could you prove your answer to be correct?
7. What difference exists between radio-frequency electromagnetic radiations and (a) heat rays; (b) ultra-violet rays; (c) X-rays; (d) the gamma rays from radium; (e) cosmic rays?
8. State some of the different properties of the various waves of problem 7.
9. A radio receiving set and the human eye both respond to electromagnetic radiations. Why then, do we not see the radiations being sent out by the radio broadcasting stations all around us?
10. What difference exists between those electromagnetic radiations which produce the sensation of *red* light and those which produce the sensation of *orange* light?

Chapter 15

RADIO TRANSMISSION, THE BROADCASTING STATION

THE PROBLEM OF RADIO-TELEPHONY — SIMPLE TRANSMISSION SYSTEM — PRACTICAL ASPECTS OF THE RADIATED ENERGY — TRANSMISSION SYSTEM WITH A GROUND — RADIATION RESISTANCE — THE MICROPHONE — ELEMENTARY RADIO TELEPHONE TRANSMITTER — MICROPHONE MODULATION — PERCENTAGE MODULATION — PRACTICAL TRANSMISSION — THE BROADCASTING STATION — ELECTRICAL TRANSCRIPTIONS — REMOTE CONTROL — ARTIFICIAL SOUND EFFECTS — CHAIN-STATION HOOKUPS — REVIEW QUESTIONS.

230. The problem of radio telephony: In Article 1 we mentioned that, in general the purpose of radio broadcasting or radio telephony is to transmit sound programs (speech or music) through the atmosphere to one or more receiving stations, without the use of connecting wires. The purpose of television broadcasting is to transmit visual scenes in more or less the same way. We also discussed the reasons why it was not practical to attempt to transmit the sound programs directly through the air, as in the case of one person speaking to another across a room. It was found that the problem could be solved satisfactorily by employing alternating currents of high frequency flowing in a suitable antenna system at the transmitting station. These currents produce electromagnetic and electrostatic fields (which we commonly call radio rays or waves) having the desirable property of radiating or spreading out into space in all directions over great distances without serious decrease in strength. Furthermore, it is possible by employing a suitable metallic electrical conductor (antenna wire) at any place through which these fields are travelling, to induce in this conductor electric potentials or voltages which can be strengthened or amplified. If the original sound waves in the transmitting station are made to affect the strength of the outgoing high-frequency currents and fields, then at the receiving station the received and amplified electrical impulses may be converted by suitable apparatus back into sound waves similar to those of the original sound program.

We are now ready to study just how these high-frequency currents may be employed to produce the radiated electric fields through space.

231. Simple transmission system: We have already mentioned that the high frequency alternating voltages or currents employed for radio transmission (frequencies employed in radio broadcasting are from 500,000 to 1,500,000 cycles per second) are most conveniently generated by vacuum tubes connected up as *oscillators*. The operation of these will be studied later. Let us consider the simple transmission system shown at (A) of Fig. 166. Here a simple vertical antenna wire AB extends upward and a similar one AC extends downward to form a common *doublet* antenna. A generator G, of high-frequency voltage is connected at their junction. The two wires AB and AC have some capaci-

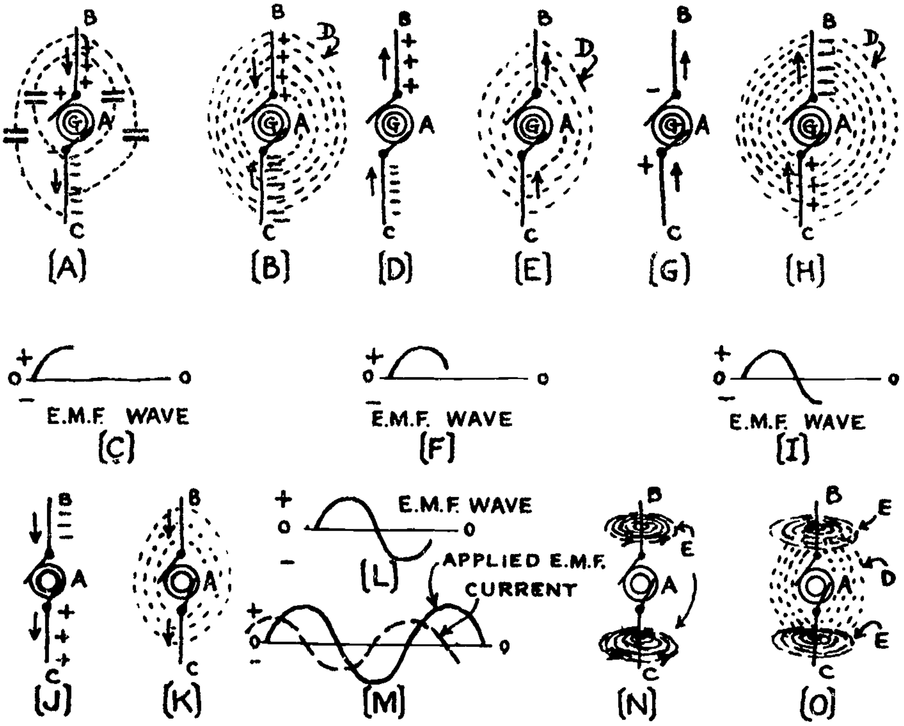


Fig. 166—Electrostatic and electromagnetic fields existing around an antenna to which a high frequency a-c generator is connected.

tance between them and since a difference of potential is maintained between them they may be considered to act as the plates of a condenser with the air between acting as the dielectric. The detailed actions of such a system may be explained as follows:

Let us suppose the a-c alternator G is just starting on a positive cycle and charges wire AB positively and AC negatively, that is, electrons are transferred through the wire circuit in the direction shown by the arrows and are crowded into wire AC. This excess of electrons in AC causes electric forces to act on the atoms in the air dielectric between, and strains or distorts the electron orbits of the individual atoms exactly as in the case of the ordinary condenser studied in Fig. 83. These electric forces set up in the space around the antenna may be represented by imaginary *electrostatic lines of force* D extending from one wire to the other as shown at (B). The student should always remember that these lines of force are *imaginary*, and are merely brought into our discussions to enable us to show the directions and intensity of these electric forces in diagrams. These electric forces immediately start to spread out from the antenna wires in all directions at the velocity of light

(186,000 miles per sec.). In the meantime, the alternator voltage advances to the peak of the positive cycle as shown at (C), at which time the electrostatic lines of force reach a maximum value. While the e.m.f. has been rising, the flow of electrons through the wire (current) has been diminishing on account of the counter-charge built up by the crowding of the excess electrons into wire AC. As soon as the alternator voltage passes the maximum value and starts to decrease, as shown at (E) and (F), the excess electrons in wire AC immediately start to flow back into wire AB in the direction shown at (D), wire AC is becoming less and less negative and wire AB becomes less and less positive, so that the strain on the electron orbits in the air dielectric around the wire diminishes and they tend to assume their normal positions, and we say that the electrostatic field around the wire diminishes as shown at (E). When the applied e.m.f. reaches zero, the field will also be zero. Now the alternator starts on its negative cycle as shown at (I), charging the wire AB negatively and the wire AC positively, that is, electrons are forced through the wire circuit in the direction shown by the arrows at (H) from wire AC and crowded into wire AB. The electrons in the dielectric are now strained in a direction opposite to the previous case (see Fig. 83) and an electrostatic field of force is again set up in the region surrounding the antenna wires as shown at (H), but opposite in direction to what it was before. As the generator e.m.f. diminishes to zero again, as shown at (L), the electrons crowded into wire AB begin to flow back toward wire AC in the direction shown by the arrows in (K), the excess negative charge on AB diminishes and the strain on the electron orbits in the dielectric is also diminished again, so the electrostatic field is diminished as shown at (K).

We have now completed one cycle of the applied e.m.f. Let us see just what has happened around the antenna wire during this time. First we see that an electrostatic field was set up around it and died down during each half cycle, the direction on one half cycle being opposite to that during the next half. Also, during the cycle, a flow of electrons took place through the antenna wires AB and AC, first downward, then upward, then downward, etc. This constitutes a flow of electric current in just the opposite direction. If we draw curves of the applied e.m.f. and antenna current together on the same axis O-O as shown at (M), observing proper regard for the instantaneous directions of flow and strength, we see that the antenna current leads the applied e.m.f. by a quarter cycle. This is exactly what we should expect to find, since this is a condenser circuit. We also find that since current surges up and down in the antenna wires, a circular magnetic field will be produced around the wires at right angles to them in accordance with the principles of electromagnetism. This field may be represented by the circular imaginary lines of force E, at right angles to the electrostatic lines of force and to the antenna wires as shown at (N). At (O) both the electrostatic field D and the magnetic field E are shown in their true relative directions. In order to avoid confusion, the magnetic field is not shown on the previous diagrams. The electrostatic and electromagnetic fields just discussed, which are set up in the immediate vicinity of the antenna wire are called the *induction fields* to distinguish them from the *radiation fields* which play the important part in radio communication. The induction field corresponds exactly to the field around, or associated with, a wire carrying an alternating current in an ordinary electric light circuit, or the field in an ordinary transformer. The induction electrostatic field corresponds exactly to the electric field set up in the dielectric of any common condenser in an a-c circuit. Since the induction electrostatic field is in phase with the applied e.m.f., the induction electromagnetic field is always in phase with the electron or current flow producing it, and since the antenna current is one quarter cycle or 90 electrical degrees ahead of the applied e.m.f., it follows that the variations in the induction electromagnetic field always take place one quarter cycle ahead of those in the induction electrostatic field.

232. Practical aspects of the radiated energy: The *intensity* of the induction electromagnetic field diminishes as the *square* of the distance from the antenna, since it spreads out over a large area. This means that if its strength is a certain value at a distance of one foot from the antenna, the strength at 5 feet is one divided by 5 squared, or 1/25 as much. At 10 feet it is 1/100 as much, at 100 feet it is 1/10,000 as much. This means that the effects of the field rapidly weaken as the distance from the antenna is increased. Therefore it plays practically no part in ordinary radio transmission, for at any considerable distance from the transmitter it does not exist at all.

Signals can be transmitted over relatively short distances by the induction field, using a-c of a frequency from about 300 to 3000 cycles. This is called "inductive signalling". One of its applications is in transmitting signals from a submerged cable to a ship almost directly over the cable, to aid the ship in navigating in darkness and fog through congested harbors.

Likewise, the induction electrostatic field around the antenna, diminishes in strength *directly* as the distance from the transmitting antenna is increased. Thus at two feet from the antenna the strength is one-half of that at one foot; at 1000 feet it is one one-thousandth of that at one foot etc. This assumes of course that there are no absorbing bodies in the path of the field. If the induction electrostatic and electromagnetic fields just described, diminish so rapidly in strength as we go away from the transmitting antenna and therefore do not take any important part in ordinary radio transmission over relatively long distances, what then makes it possible to receive our messages? The answer to this question is one of the things which our foremost scientists are now working hard to explain. We cannot see, feel or even measure these fields directly. We must measure them indirectly and must visualize them by means of the effects they produce.

If we accept the explanation offered many years ago, and still regarded as being substantially correct by many, we will believe that before all of the electrostatic field has had time to return to the antenna wire at (E), and (F), of Fig. 166, the alternator G, starts on its negative cycle, charging the wire AB negatively, thereby setting up a field that is opposite to what it was before, making it impossible for the remaining portion of the returning electrostatic field to give up its energy to the antenna. It is believed that this portion of the electrostatic field (called the *radiation* field) never returns to the antenna, but travels away from it with the velocity of light as a free wave, this action taking place during every half cycle of the alternator and continuing as long as the alternator voltage is applied to the antenna. It is assumed that this varying *radiation* field or electric force impresses in some way its variations or wave-form upon other vibrations, in the ether, which in turn, in some way transmit this wave-form with the speed of light through space, to be picked up by other electrical circuits, or antenna wires erected in its path.

If we think along the lines of the quantum theory explained in the previous chapter however, it would seem that when we apply alternating e.m.f.'s, of hundreds or thousands of volts and having the usual radio-frequencies of the order of say 500,000 cycles per second and higher, to the antenna circuit, the exceedingly rapid and intense straining action produced on the orbits of the planetary electrons of the atoms of the dielectric around the aerial wire, first in one direction and then in the opposite direction, as shown in Fig. 83, would cause many of them to be knocked from their normal orbits to orbits nearer the central nucleus of the atom. The difference in energy corresponding to the two positions in the atom would then be given up in some other form, this extra energy being *radiated* in the form of electromagnetic radiations or little bundles of energy. For each electron knocked into a new orbit a quantum of energy would be radiated into space and propagated at the uniform velocity of 186,000 miles per second. If we can visualize these tiny planetary electrons revolving about the nucleus in each atom, and can also visualize these almost inconceivably rapid electric forces tending to knock the electrons around first one way and then the next, thousands of times every second, it does not require a much greater stretch of imagination to see them moving in toward the nucleus of the atom where they will be attracted with a greater force by the nucleus and be better able to resist the outside forces acting on them.

While the author is naturally inclined to favor the explanation he has presented above in terms of the quantum theory, he wishes to caution the student against accepting either of these theories blindly at their face value. They have been given here in detail in an attempt to satisfy the natural curiosity of the student as to just how radio energy is produced and transmitted, to give some idea of what may be going on in the space around radio transmitting stations, and as an incentive for the student to do some original thinking on the subject for his own satisfaction and mental training. This entire new field of physics is stupendous in its possibilities and the student should try to reason these various actions out for himself to the best of his ability.

Leaving, for the time being, the question of exactly what the structure of the radiated field actually is and how it is propagated, let us study several of its important characteristics which are definitely known as a result of experiment.

First, no matter whether we assume that the energy is propagated in the form of electrostatic forces by a wave motion, or by quanta of energy radiated from the vicinity of the transmitting apparatus, it follows from our study of electric fields that the radiated electric field which is in motion will produce an associated magnetic field which is at right angles to it at every instant. Since this magnetic field is produced by the electrostatic field, any variations in it will be in phase with those of the electrostatic field. Thus the total radiation field really consists of a moving electrostatic field of electric forces and an accompanying inseparable magnetic field caused by its motion. These are not to be confused with the *induction* electrostatic and magnetic fields discussed previously, they are entirely different and separate. Their form will be shown later in connection with an antenna with an earth connection in place of the lower wire in the doublet here considered. It can be shown mathematically that the strength of the total radiation field falls off *directly* as the distance from the transmitter is increased. Thus, at a point a very short distance from the transmitting antenna, the intensity of the induction field may be stronger than that of the radiation field, but at greater distances, the induction field is exceedingly small compared with the radiation field, and its effect may be neglected so far as ordinary radio reception is concerned.

Neglecting any absorption of energy by the earth, by tall buildings with grounded steel frameworks, etc., the *total energy* in the radiated wave remains constant. Hence as the wave advances, the energy spreads out over an ever widening sphere with the transmitting antenna as a center, (assuming the antenna is not directional), and the *amplitude* of the variations in energy between the maximum and minimum during each cycle, decreases directly as the distance increases. The progressive decrease in amplitude of the radiated waves is somewhat analogous to the decrease in amplitude of water waves produced by throwing a stone in a body of water. As the wave disturbance spreads out in ever-widening circles, the amplitude of each succeeding wave and crest diminishes, since the original energy imparted to the water by the stone is spreading out over a larger and larger area. At great distances from the antenna the electric wave disturbance would be exactly perpendicular to the earth's surface if the earth were a perfect conductor. It is evident of course that the distance in meters (wavelength) travelled by the radiated electromagnetic disturbance during the time it takes the antenna e.m.f. or current to complete one cycle is equal to

$$\text{wavelength} = \frac{300{,}000{,}000}{\text{frequency}}$$

233. Transmission system with a ground: On ordinary broadcast band wavelengths, a doublet of the type considered in Fig. 166 suitable for radiating considerable amounts of power would have to be very long to be efficient, which means that the generating apparatus G, would have to be mounted very high. This, together with the cost of the high supporting towers necessary to support the wires would be prohibitive. To overcome this difficulty, the lower half of the doublet is omitted and a connection to the earth is substituted for it, as shown at (A) of Fig. 167. The capacity effect then exists between the antenna and the earth, and the lower half of the electrostatic fields of Fig. 166 are missing altogether. In short wave transmission, where extremely high frequencies are employed, doublets are commonly used, for in that case the wire of the doublet

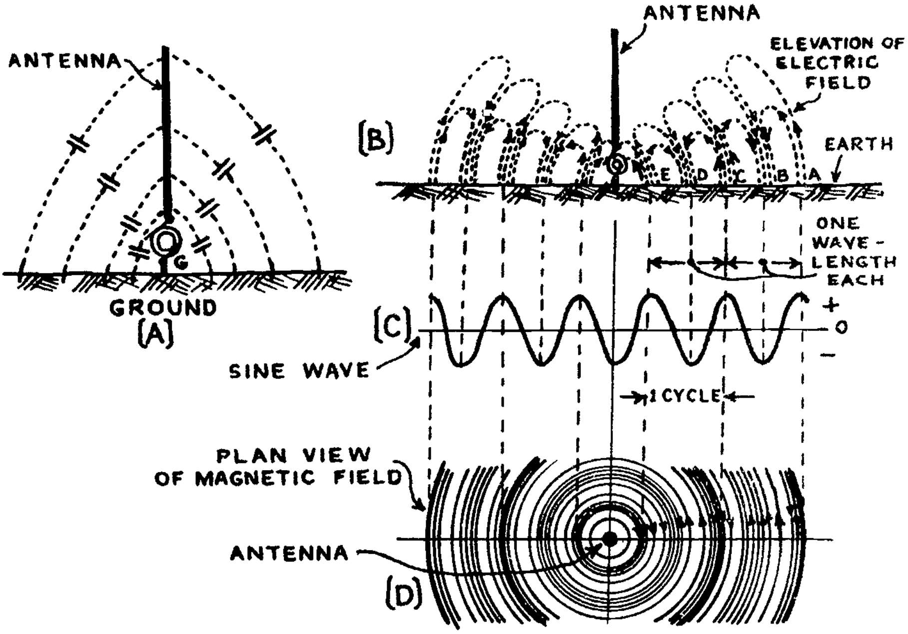


Fig. 167—(A) Condenser effect between antenna and ground. (B)-(D) Propagation of electric fields through space.

need only be a few meters long. It is usually possible to secure a much more efficient antenna arrangement with a doublet, since the resistance of the ground connection and that of the ground itself is eliminated.

The illustration at (B) of Fig. 167, represents what we would see if the radiated electrostatic field and associated electromagnetic were visible and we took a vertical cross-section view or slice right through the atmosphere in the plane of this paper. The illustration shows the fields which have radiated into the space around the antenna during the time it took to complete two and one-half cycles. At A the field is upward, and was produced by the current flowing say upward in the antenna wire just two and one-half cycles ago. During that time, this part of the field has moved out a distance equal to two and one-half wavelengths from the antenna as shown. At B the field is downward. This part of the field was produced by current flowing downward in the antenna wire two cycles ago. The upward field at C was produced by current flowing upward one cycle ago, etc. The radiated magnetic field is at right angles to this electrostatic field and since it would be perpendicular to the plane of the paper, part of it is shown in plan view at (D). The circular magnetic lines of force are shown as they would appear if we looked directly down on the transmitter from a balloon or aeroplane. Notice the comparative directions of the magnetic field and the corresponding electrostatic field at (B) at any instant. The wave-form corresponding to both is shown at (C). At the "maximum" points in each direction, the fields are maximum in strength; at the "zero" points, the fields are zero. If the generator (G) were applying a sine-wave e.m.f. to the antenna circuit, these radiated fields will follow one another in succession, each one being exactly like the next.

The two radiated fields move outward from the antenna, at all times perpendicular to each other, the magnetic field being parallel to the ground and the electrostatic field being perpendicular to it. At the same time, both fields are at right angles to the direction of propagation. At great distances from the antenna, the electrostatic field would be exactly perpendicular to the earth, if the earth were a perfect conductor. Actually the resistance of the earth's surface causes the field to tip forward somewhat, as shown at (B).

Possibly the following description by Dr. Fleming will serve to make the actions taking place during the propagation of these fields clear:

"If we can imagine a being endowed with a kind of vision enabling him to see the lines of electric strain and magnetic flux in space, he, standing at any spot on the earth's surface, would see, when the antenna was in action, bunches or groups of electric strain fly past. Near the earth's surface these strain lines would be vertical. Alternate groups of lines of strain would be oppositely directed, and the spectator would also see groups of magnetic flux fly past, directed in a horizontal direction or parallel to the earth's surface. The strain and flux lines would move with the velocity of light, 186,000 miles per second, or 300,000,000 meters per second, and the distance between two successive maxima of electric strain, directed in the same direction, would be the wavelength of the wave."

The higher the frequency of the applied e.m.f., the more the energy being radiated, the radiated energy being proportional to the *square* of the frequency. This shows why it is necessary to use high frequencies to get a radiation field sufficiently strong to allow successful communication with a medium amount of power employed. With the ordinary type of elevated antenna, the radiation field at a given point due to an alternating current having a frequency of 500,000 cycles (wavelength of 600 meters) would be 25,000,000 times as strong as that produced by an equal current having a frequency of 100 cycles. This is the reason why high frequencies, or "radio frequencies", are used for the carrier wave in radio transmission and why it is possible for the signals of amateur stations transmitting at frequencies above 6,000,000 cycles per second (below 50 meters) to reach nearly around the world, employing powers of but a few watts.

234. Radiation resistance: An antenna of the common type discussed here really forms a condenser. If the antenna were replaced by an air-dielectric condenser having no losses, and having a capacitance equal to that of the antenna, and the circuit were tuned to resonance by an antenna series inductance, it would be found that the current in this circuit is much larger than that obtained at the base of the antenna with the same power input, when the actual antenna itself is used instead of the condenser.

If a non-inductive resistance were now added to the condenser circuit and its resistance adjusted until the antenna current was the same(for the same power input) as before, this value of resistance is called the total *antenna resistance.* The added resistance consumes energy at the same rate as the antenna, and therefore the total effective resistance of the antenna must be equivalent to this resistance added to the antenna circuit. The power consumed in either case is equal to I^2R, in which I is the current and R is the resistance. Hence the total antenna resistance may be defined as the effective resistance that is numerically equal to the quotient of the average power in the entire antenna circuit divided by the square of the effective current at the point of maximum current.

Of this total energy, part only is radiated away, the remainder being converted into heat in the aerial circuit. Now the effective resistance **R** may be looked upon as consisting of two separate component resistances, one acoounting for the losses in the aerial circuit including radio-frequency resistance of the conductors, ground resistance, insulator leakage, dielectric losses, etc., and the other accounting for the useful power radiated. This latter fictitious resistance is called the *radiation resistance* of the antenna; it is that equivalent resistance which, when multiplied by the square of the antenna current, gives the useful power being radiated. The radiation resistance is used as a measure of the ability of an antenna to radiate power. An antenna with a high radiation resistance is a good radiator and vice versa.

It can be shown that the radiation resistance is proportional to the square of the *effective height* of the aerial, and to the square of the frequency or inversely proportional to the square of the wavelength. The effective height is not equal to the actual height of the horizontal portion above the ground because the earth is not a perfect conductor and trees, etc., influence radiation, and also because the vertical portion possesses capacity. Still, the effective height is roughly proportional to the actual elevation.

235. The microphone: In order to broadcast sound programs by radio we must first convert the to-and-fro vibrations of the air which constitute the sound waves, into corresponding variations of current in an electric circuit. The device for accomplishing this is known as the *microphone.* There are several types of microphones in use in radio telephony and in sound picture work, but perhaps the simplest one for us to understand at this time is the popular carbon type. The others will be studied in Art. 549. The principle of operation of the carbon microphone used in radio is exactly the same as that of the common telephone transmitter used in millions of homes. The microphones used for radio broadcasting are designed to operate satisfactorily over a wide frequency range which includes both that of speech and that of musical frequencies up to around 5,000 cycles. The ordinary house telephone transmitter is designed to operate only over the limited range of important speech frequencies from about 250 to 2700 cycles.

The method by which the carbon microphone changes the air pressure variations of sound waves into corresponding variations in current in an electric circuit, is really very simple, as we shall now see.

At (A) of Fig. 168 we have a "single button" microphone of the simplest kind connected in series with a dry cell, or other source of low-voltage of constant e.m.f. In this circuit may also be placed a d-c milliammeter having a range from 0 to 50 milliamperes. The light diaphragm A, of thin flexible duraluminum, is rigidly fastened to the polished carbon button B, and is held more or less fixed around its outside edge by the insulated housing E. A second carbon button D, is fastened in place at the back as shown, and the space between is filled with tiny loosely packed carbon granules C, about the size of fine granulated sugar. An electrical connection is made to each of the carbon buttons, so when the microphone is connected in an electrical circuit as shown, current must flow from one button through the carbon granules to the other one. The carbon granules make imperfect electrical contact with each other so they offer quite some resistance to the flow of current through them. In the common type of broadcast microphone, this resistance is normally about 100 ohms-per-button. Therefore, a small steady current $I = \frac{E}{R}$ will normally flow through the

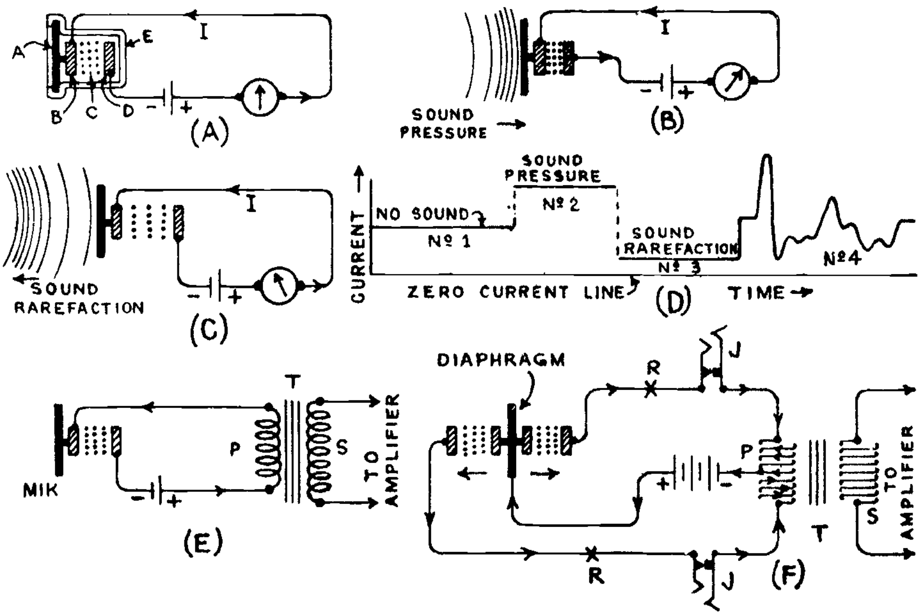


Fig. 168—Action of the single and double-button carbon microphones.

microphone circuit, where E is the applied voltage and R is the total resistance of the microphone and the rest of the circuit. This current will be indicated by the milliammeter in the circuit and is represented by No. 1 at the left of (D). Let us imagine now that someone speaks into the microphone. The sound waves which really consist of a series of alternate pressures and rarefactions in the air (see Fig. 3) will act against the diaphragm A and cause it to vibrate back and forth slightly in accordance with these pressures. For instance, when a pressure wave strikes the diaphragm, it pushes it in, as shown in exaggerated form at (B). This causes button B to move in with it, compressing the carbon granules tighter together and thereby making better contact between their surfaces, decreasing their resistance accordingly, and allowing more current to flow through as shown at No. 2 in (D). If now a rarefaction follows the pressure wave, the diaphragm and button B spring outward as shown at (C). This diminishes the pressure on the carbon granules and they loosen up, thus increasing their contact resistance and allowing proportionately less current to flow through the circuit, as shown at No. 3 in (D). In this way, sound waves acting on the diaphragm will cause variations in resistance of the microphone and corresponding variations in the current through the circuit. If for instance, the letter "a" as in father is spoken into the microphone, the sound waves are such that they will make the diaphragm vibrate back and forth and the resistance and current will vary as shown at No. 4 in (D). Other sound waves cause even more complex variations in the current.

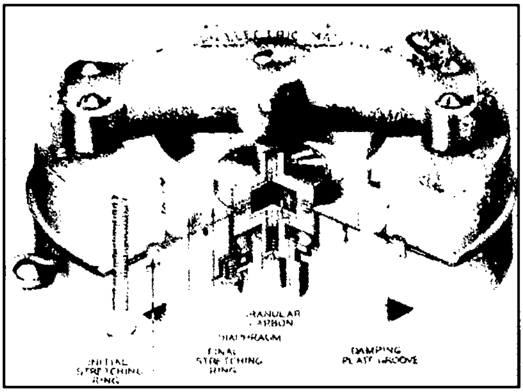
A microphone arrangement of this kind is very sensitive to changes in pressure on the diaphragm, that is, the resistance of the many contacts between the carbon granules varies greatly as the pressure upon them is changed. An idea of the sensitivity of these devices may be gained from the fact that the diaphragm in the ordinary microphone does not move more than a few ten thousandths of an inch, when a sound wave is acting on it. The current which such a transmitter can safely carry is very small, (ordinary microphones are designed to carry only from 15 to 35 milliamperes continuously depending upon the size), because of the fact that heat is developed at the contacts of the granules due to the resistance. At a current of 20 milliamperes, if the resistance is 200 ohms, $.02 \times .02 \times 200$ or .08 watt of electrical energy is being dissipated in the microphone in the form of heat. A limit is soon reached beyond which tiny electric "arcs" are developed between adjacent granules, the contact points of which become red hot and pack or stick together. When in this condition, the resistance does not vary much with change of pressure and the microphone becomes useless; also the intermittent arcs taking place cause spurts of current to flow through the microphone and when these are amplified by the usual audio amplifier they cause loud background sounds of a "scratchy" nature to be heard. A microphone that has become packed may usually be brought back to normal by disconnecting it and *gently* rotating or tapping it so as to shake up the carbon granules. The current in the microphone circuits of (A), (B) and (C) is a fluctuating unidirectional current when the microphone is spoken into, as shown at Nos. 1, 2, 3, and 4 of (D).

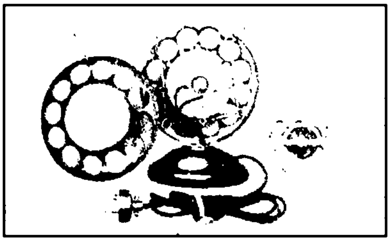
Experiment: The action taking place in a microphone may be demonstrated very simply by connecting up a 0-50 ampere d-c ammeter, a 6 volt storage battery, and two pieces of carbon, each about 2 inches square and one-eighth or more inches thick, all in series with each other as in (A) of Fig. 168. The carbon pieces are not connected together but are simply held face to face between the fingers. When a slight pressure is applied to press them together, the current will increase as shown by the ammeter reading. By quickly varying the pressure applied, the current and the ammeter needle may be made to fluctuate up and down quite rapidly. If the full 6 volt storage battery sends too much current through the circuit, tap off only one cell. Use heavy wire for all the connections.

If a transformer T, is connected in the circuit as shown at (E), an alternating voltage will be induced across the secondary by the fluctuating direct current flowing in the primary shown at No. 4 of (D). This is in accordance with the laws of electromagnetic induction, for when the microphone current through the primary is decreasing, the magnetic field in the transformer is collapsing and an e.m.f. is induced in the secondary in such a direction as to tend to aid it in accordance with Lenz's law; when the microphone current is increasing, the magnetic field in the transformer also increases and the induced e.m.f. is in the opposite direction so as to tend to oppose it, in accordance with Lenz's law. Thus an alternating e.m.f. is being induced in the secondary winding. A *microphone coupling transformer* of this kind is usually employed for coupling a microphone circuit to a vacuum tube amplifier. Carbon type microphone circuits are usually energized by a 4½ or 6 volt bank of dry cells or a storage battery. A current regulating variable resistor of about 400 ohms and a 0-25 d-c milliammeter are usually included in the circuit to enable the operator to adjust the microphone current to the best operating value. Single-button carbon microphones are used extensively for speech alone, in public address systems, etc. Where the entire musical range of sound is to be transmitted as in orchestra programs, etc., the double-button type is employed on account of its better frequency characteristics.

By using two sections of carbon granules and making connections as shown in (F), some of the defects of the single-button carbon microphones are done away with. This is known as the *double-button carbon type,* and it is used extensively.

This microphone consists of a thin, light, duraluminum diaphragm stretched between the two cups containing the carbon granules. A sound wave striking the diaphragm causes it to vibrate back and forth on each pressure wave. This increases the pressure on the granules in one chamber and decreases the pressure in the other chamber an equal amount. Therefore, while the current in one side increases, that in the other side decreases. By arranging the transformer with a center-tapped primary winding as shown, it may be seen by actually tracing the path of the currents through the two halves of the winding and remembering Lenz's law for electromagnetic induction, that since they flow in opposite directions their effects are such that an increase in the current say in the upper half tends to induce an e.m.f. into the secondary in the same direction as a decrease in current in the lower half does, and vice versa. Thus for a given variation in current, the e.m.f. induced in the secondary is twice as great as would be induced by only one side of the microphone, or by a single-button microphone. This makes a more sensitive arrangement and it also eliminates distortion produced by "even" harmonics. Also the steady value of current flowing through the microphone does not magnetize the iron core of the transformer at all, since the





Courtesy Elect. Research Prod. Corp.

Fig. 169—**Left:** Sectional view of popular type of double-button carbon microphone used for outdoor pickup work in radio broadcasting.
Right: The same mike in its desk stand.

field produced by the steady current in one half of the primary winding is exactly neutralized by that set up by current in the other half of the winding, provided the current through the two buttons has been adjusted to be the same. This is usually done by means of a 200 or 400 ohm variable resistor connected in each outside leg of the circuit at the points marked "R". A current measuring jack J is usually provided in each outside leg of the circuit as shown, so that a milliammeter may be plugged into each side at intervals to check up on the current through each button. In the broadcast type microphone shown in Fig. 169, the operating current through each button should not exceed 25 milliamperes. The normal operating current is 20 milliamperes per button. The difference between the current in the two sides should not exceed 5 milliamperes. The resistance of each button is about 100 ohms, and as the two are in reality in series for voice currents, the output impedance of the entire microphone is taken as 200 ohms. It is only the *changes* in the currents in the two sides of the microphone that produce a resultant flux in the core and an induced voltage in the secondary winding. Changes of voltage of the battery will have no effect at all on the secondary voltage, since any such change affects the currents through both sides equally and so the circuit still remains balanced. The idea of balancing an increasing effect by a decreasing one, is used often in radio apparatus, since in general it eliminates distortion produced by even harmonics in the current or voltage. It is the basis of the push-pull system of connecting vacuum tube amplifier stages.

The induced voltage variations set up across the secondary of the microphone transformer T are usually so feeble that in most applications they are amplified by a 2 to 4 stage vacuum tube audio amplifier to bring them up to sufficient strength.

Two views of a very popular double-button carbon microphone used for many years in practically all American broadcasting stations and still used for most outdoor pickup work are shown in Fig. 169.

At the left is a cut-away section of the microphone. The thin duraluminum diaphragm is very tightly stretched and is placed a short distance from a flat metal plate. The stretching makes its natural vibration period very high so it is outside of the usual audio range encountered and will therefore prevent any blasting which would be caused by the sounding of a musical note of the same frequency as the resonant frequency of the diaphragm. Placing the diaphragm close to the flat metal plate gives a high damping effect due to the compression of the air between them. This action is assisted by the cushioning effect of the air in the damping plate groove shown. Both of these features of construction help to make the variations in microphone current conform exactly to the variations in the impressed sound waves at all sound frequencies from about 50 to 6,000 cycles, so that the microphone faithfully reproduces these sounds; that is, it has a good flat *frequency characteristic.* They reduce the sensitiveness of the microphone however, so that proportionally more amplification must be used in the circuits which follow.

On account of the stretched diaphragm, these microphones used for public address and broadcast studio work are much less sensitive than the ordinary telephone transmitter, but their fidelity and frequency characteristics are infinitely better. Whereas an ordinary telephone transmitter has a workable frequency range only from about 250 to 2700 cycles, a high grade double-button broadcast type carbon microphone has a flat frequency characteristic from about 50 to 6,000 cycles or more. In these, special polished carbon balls are used instead of irregular carbon granules. At least 2 or more stages of audio amplification are required to bring the output of microphones of this type up to loud speaker volume.

The two piles of carbon granules, one above the diaphragm and one below it are clearly shown in Fig. 169. At the right the complete microphone in its housing for desk mounting is shown. The microphone is suspended in the case by springs to absorb all shocks and jars. A three prong plug serves to connect it to a proper receptacle in the studio. Carbon microphones of the type shown above are not used to any extent in high-class broadcasting stations today, excepting for outdoor pickup work. The condenser and magnetic type microphones, which will be described later, have practically supplanted them for this work, on account of their much more perfect reproduction and freedom from hissing and other background noises which are present in carbon microphones due to small arcs which take place between the carbon granules. The advantage of the carbon type for portable outdoor pickup work is that since it is more sensitive than the above types it requires a less powerful and cumbersome amplifier. This is rather an important consideration in this type of work since the batteries required for these amplifiers are rather inconvenient to carry around from place to place.

236. Elementary radio telephone transmitter: We are now ready to consider the operation of a simple radio telephone transmitting system. The simple transmitter shown at (B) of Fig. 167 will enable us to transmit electromagnetic radiations in all directions. These will induce corresponding e.m.f.s and electric currents in receiving antennas erected in their path. Let us suppose that the generator in the transmitting antenna circuit supplies a high-frequency alternating voltage of steady value as shown by the voltage wave at (D) of Fig. 170. By this we mean that the maximum value of the voltage during each successive half cycle is exactly equal to that during the previous half cycle, although it is in the opposite direction. The current in the antenna circuit will be of similar wave-form, and the train of electromagnetic waves radiated from the antenna will also be of similar wave-form as shown at (C) and (D) of Fig. 167. Consequently the e.m.f. induced in the receiving antenna will also look

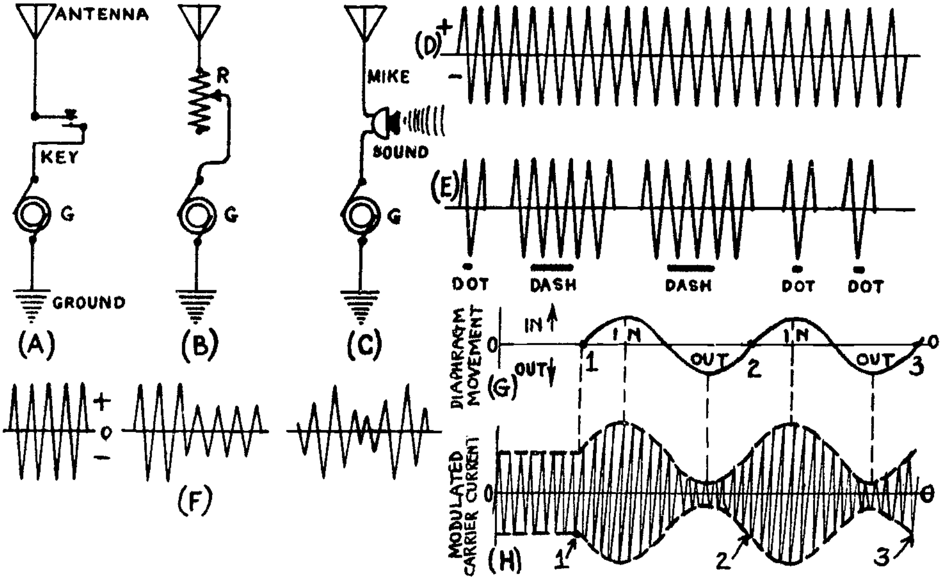


Fig. 170—Modulation of r-f carrier current in radio telephony.

like (D) of Fig. 170, but of course these e.m.f.s will be very much weaker in strength. Thus we have a continuous train of waves of uniform strength moving from the transmitter outward to the receiver. If we insert a switch or transmitter key in the antenna circuit as shown at (A), we can open and close the circuit at will, and thereby interrupt the flow of current and the train of waves sent out. If we opened and closed the switch according to some pre-arranged code of interruptions, forming short and long intervals of flows of current (dots and dashes), we could transmit messages which could be de-coded at the receiving end. The received e.m.f. or current waves in such a system would look like those at (E) of Fig. 170. Their representations as dots and dashes are marked directly below. This is the method used for continuous wave telegraphy.

If a variable resistor R were connected in series with the circuit as shown at (B), the current in the antenna circuit at each instant would be equal to the instantaneous value of the applied e.m.f. divided by the total antenna circuit impedance. With the resistor R at some fixed value, the current would be as shown at the left of (F). If the resistor were set at a higher resistance value, the amplitude of the antenna current would be reduced, as shown at the middle of (F). Now suppose we varied the resistance of the rheostat back and forth from its maximum to its minimum value; the amplitude of the antenna current would vary likewise as shown at the right of (F). The successive transmitted fields would also vary in strength in exactly the same way and the e.m.f.s induced by them in any receiving antennas would also look exactly like them. By means of a variable resistor in the antenna circuit then, we have succeeded in varying the strength or amplitude of the antenna current, the radiated fields, and the induced e.m.f. and current in the antennas of the receiving stations. This varying of the strength of the antenna current is called "amplitude modulation". Another type of modulation in which the frequency of the current is modulated, is called "frequency modulation". This will not be considered here as it is not in general use at the present time.

237. Microphone as a modulator: It is not difficult to see that if we connect a microphone in the antenna circuit as shown at (C), the current in the circuit could be varied exactly in accordance with the movements caused by speaking against the diaphragm. This scheme can then be utilized for radio telephone transmission. Let us see how it operates:

When the microphone is not being spoken into, the diaphragm remains stationary and exerts a constant pressure on the carbon granules. Their resistance therefore remains constant and the successive cycles of the radio frequency current in the antenna circuit are of constant maximum amplitude as shown at the left of (F) in Fig. 170. If the diaphragm is pressed inward, the pressure on the carbon granules increases and the amplitude of the radio-frequency antenna current increases and remains constant at this value as long as the diaphragm is held in that position, as shown in the next series of current impulses at (F). When it is released the resistance and the current return to normal value. If the diaphragm is pulled outward, the pressure decreases, the resistance of the carbon granules increases, and the antenna current decreases and remains steady at the lower value shown at the middle of (F), as long as the diaphragm is held in this position. Suppose now that a 2,000 cycle tuning fork is set vibrating and placed in front of the microphone, so that its sound waves cause the diaphragm of the microphone to vibrate at a frequency of 2,000 cycles. In (G), if the line O-O represents the normal position of the microphone diaphragm when idle, then the sine-curve drawn above and below it represents the action of the diaphragm when the tuning fork is placed in front of the microphone. Thus the diaphragm assumes its maximum inward and outward positions 2,000 times per second and the resistance of the carbon granules varies accordingly. The high-frequency alternating antenna current flowing through the microphone will then vary in accordance with the wave-form shown at (H), changing from maximum strength to minimum and back to maximum again 2,000 times per second and the radiated energy varies accordingly, as shown at (H). If an "envelope" were drawn to enclose this representation of the current flow it would look like the dotted lines in this figure, having exactly the same shape as the curve at (G). The radio-frequency current is called the *carrier current*. The frequency of the microphone diaphragm, which in this case in 2,000 cycles per second, is the *modulating* frequency.

Suppose the station were transmitting with a carrier current frequency of 1,500,000 cycles per second (wavelength of 200 meters.) Then if this current is modulated at 2,000 cycles per second, one cycle of the modulation frequency lasts 1/2000 of a second. During this 1/2000 of a second the radio frequency carrier current goes through 1,500,000 $\div$ 2000 $=$ 750 cycles. Consequently, if (H) were drawn accurately to scale, in one complete modulating wave from points 1 and 2, there would be 750 cycles of the radio-frequency current, that is, during the time it takes for this particular sound or modulating wave to complete one cycle, this carrier current passes through 750 cycles.

From the foregoing it follows that it is possible to modulate the carrier current by the voice and thus transmit speech and music. Instead of placing a tuning fork in front of the microphone, one may talk or play into the mouthpiece. This will vibrate the diaphragm in accordance with the complex air vibrations produced when speaking or playing. When sounds from several sources are impressed on the microphone diaphragm simultaneously, the diaphragm movement at any instant is in accordance with the resultant air pressure wave produced by the combination of all of the individual air pressure waves caused by the different individual sounds at that instant. In practice, it is not practical to employ a circuit as simple as that shown at (C) of Fig. 170, for several reasons. First, in order to set up a maximum flow of current in the antenna circuit with a given applied voltage, the antenna circuit should be tuned to resonance. This is done by means of tuning inductances and high-voltage condensers (see Fig. 176) connected in the antenna circuit. The source of high-frequency voltage is coupled to the antenna circuit by means of a tuning transformer, (see Fig. 176). Also since the microphone can only handle a fraction of a watt of electrical power it cannot be connected directly in the antenna circuit where the heavy antenna currents are flowing. Practical transmitting circuits employ a multistage audio amplifier to boost the energy of the signal output of the microphone, as shown in Fig. 172. This goes to the modulator circuit where it is made to act upon the modulator tube which modulates the carrier current supplied by the oscillator, in accordance with the audio currents coming from the speech amplifier. The resulting modulated current is fed to the tuned antenna circuit. (See D of Fig. 171.)

There are several possible forms of modulating systems in use, and while all of them do not operate exactly as decribed above, the system we have considered is perhaps the simplest one for the beginner to understand. A detailed study of various oscillator and modulator systems will be taken up in a later chapter. Also, the "percentage modulation," or the degree to which the radio frequency, carrier current is varied in strength or "modulated" by the voice currents is a very important consideration in broadcasting of speech and music.

238. Practical transmission: Radio broadcasting stations which transmit speech and music, all operate more or less on the same general principle. It is true that not all stations are exactly alike, but for our purpose their individual differences need not be considered. In all of them, the programs are transmitted by means of carrier currents of very high frequency which are made to vary in strength (modulated) according to the intensity and frequency of the sound waves to be transmitted. A steady carrier current of very high frequency, (the frequency is determined by the operating wavelength of the station), is generated by means

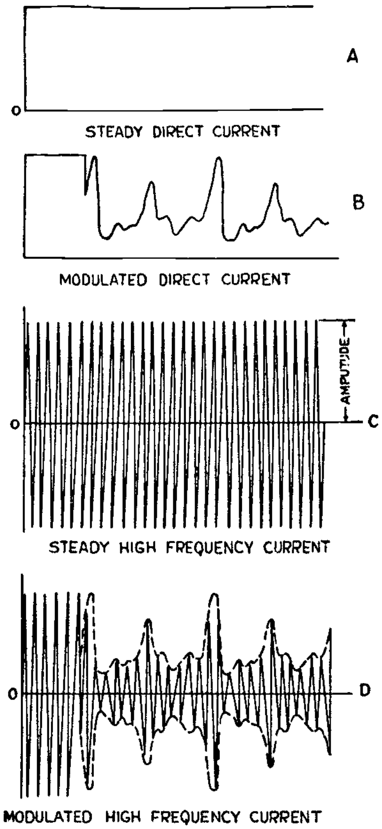


Fig. 171—Modulation of Direct, and High-frequency Alternating Current by Impressed Speech Frequencies.

of large vacuum tubes connected up as oscillators. This is shown at C of Fig. 171 and in Fig. 172A.

Notice that it is an alternating current and that the height or strength of the current during each cycle is exactly the same as during any other cycle. The fact that vacuum tubes suitably connected to a source of direct current and a special circuit, can be made to generate alternating currents of high frequency, (commonly called oscillations), is really the foundation of our present broadcasting systems. At A is shown the steady unidirectional current through the microphone when no sound is impressed on it. At B, the impressed sound waves cause the diaphragm to vibrate and the direct current in the microphone circuit is caused to vary in accordance with the sound.

If the voice current of B is allowed to regulate the flow of the radio frequency current of C, that is, to "modulate" it, the result is the modulated high-frequency current of D, called the modulated oscillating current. This current is no longer of constant amplitude, but its strength varies in exact accordance with the variations in strength and frequency of the voice current, or the spoken sounds. That is, the steady oscillating current has been modulated by the voice current. This is accomplished by a vacuum tube connected up as a *modulator tube.*

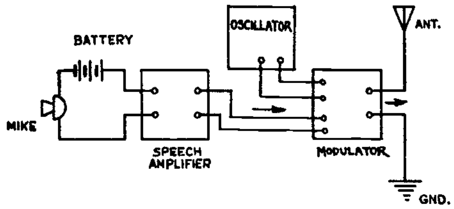


Fig. 172—Arrangement of main parts in the circuit of a transmitting station.

A simple analogy which may make this action clear, is to think of the high-frequency carrier current as a steady stream of water flowing out of the nozzle of a rubber hose. The voice current is represented by an adjustable opening in the nozzle, which is made to vary continuously in size by squeezing it between the fingers. If this variation in the opening is made to take place rapidly, the diameter of the stream will be varying constantly to conform to the size of the opening in the nozzle, and the stream of water issuing from the hose will look somewhat as shown by the dotted outline envelope at D of Fig. 171.

The modulated oscillating current goes to the antenna circuit, where it produces radiations travelling in all directions. The frequency of these radiations is the same as that of the high-frequency carrier current, so that the frequency or wavelength of the station is controlled by adjusting the oscillator tube circuit. The actual broadcasting equipment is made up

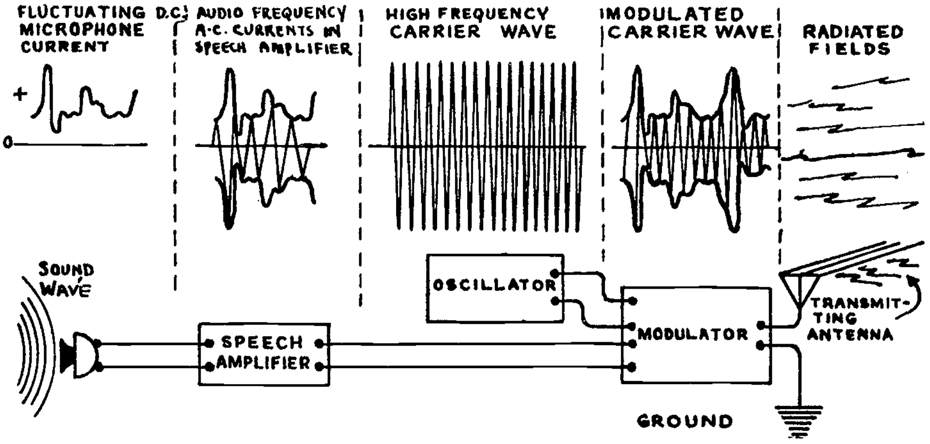
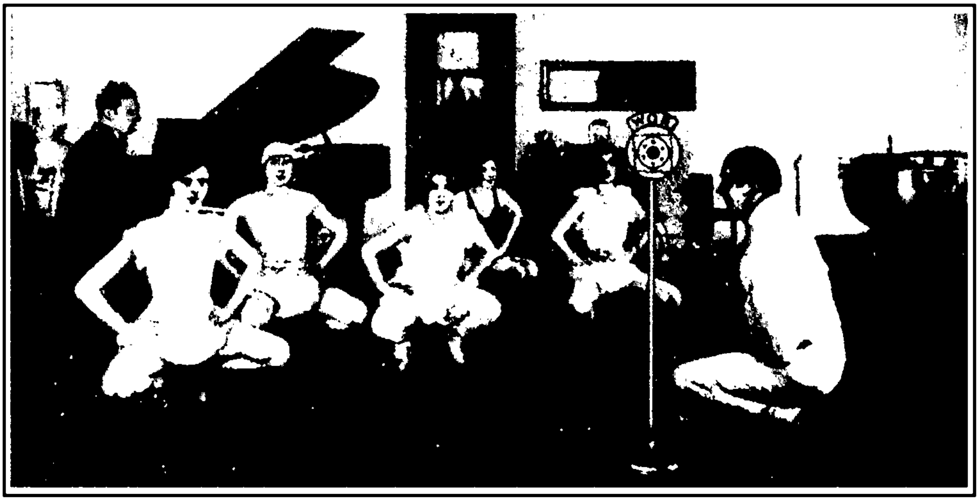


Fig. 172A—Analysis of current changes taking place in various parts of a radio-telephone transmitter, starting at the microphone at the left.

of the main units related to each other as shown in Fig. 172. In Fig. 172A, the types of currents existing in the various parts of this transmitting circuit are shown, starting with the fluctuating d-c microphone current at the left and ending with the modulated high-frequency fields radiated by the antenna at the right.

239. The broadcasting station: The speakers or artists perform in a studio (Fig. 173) where one or more microphones are located. This is usually a large room made sound-proof by means of special soundproof wall and ceiling construction, so that no outside noises will be picked up by the microphone and broadcast. The walls and ceiling are usually covered with a special acoustic celotex board having small air pocket holes punched in its surface. This acts as a sound absorber or deadener and helps to prevent echoes and reverberations which might cause blasting in the program reception. The floor is covered with thick rugs to deaden echoes and prevent footsteps from being heard. A small control unit having key switches, signal lights, and an intercommunicating telephone to the control room enables the announcer to switch the different microphones on or off and keep the control and radio station operators advised of the progress of the program. All microphone and control circuits are carried in lead-covered cables laid behind the wall sound-proofing. Connection boxes are usually located along the baseboard near the floor for the microphone outlets. The auxiliary studio is similar to the main studio but usually smaller, and is used principally for readings and lectures. Many of the larger stations have several large studios to enable them to run rehearsals while some other studio is "on the air".

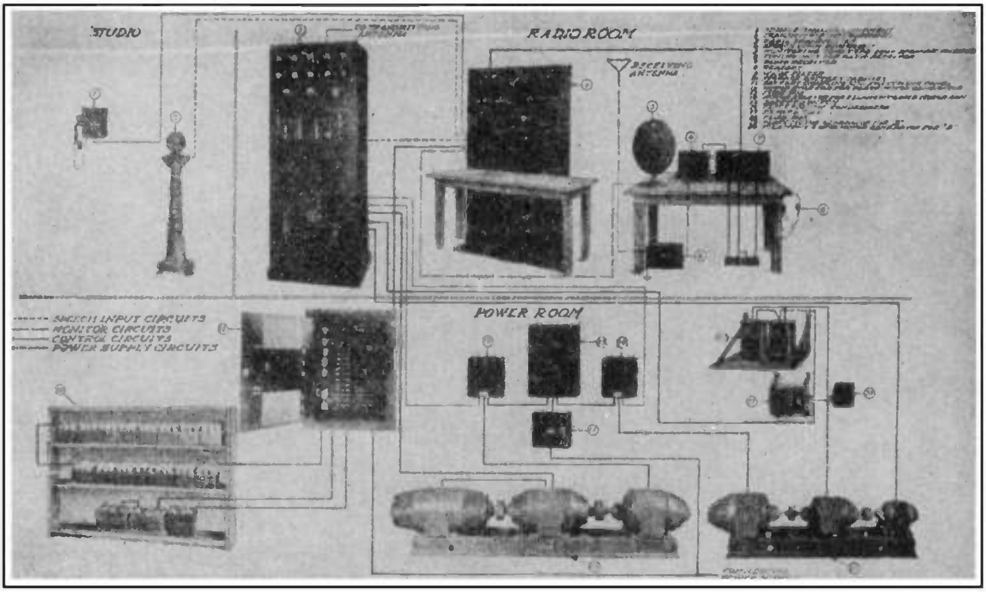


Courtesy Station WOR.

Fig. 173—Interior of a Radio Broadcasting Studio During the Transmission of an Early Morning "Daily Dozen" Program.

Since the amount of current handled by the microphone is necessarily small, it must be amplified in order to be strong enough to properly affect the modulator tube when impressed upon it. This is done in the control room by a 3 or 4 stage *speech amplifier*. Between the microphone and the speech amplifier is the "*mixer*" panel into which terminate the circuits from the various microphones which may be used for picking up music from different directions and points. The operator can boost or tune down the output of any one microphone at will, thus securing the best combined sound output. Since there is very wide variation between the loudness of voices and of musical instruments, the speech amplifier must be capable of adjustment so that when a particularly loud part of a program comes through, the operator can cut down on the control and not allow as much current to pass through the amplifier. This is necessary in order to avoid distorted and unnatural reception, caused by overloading of both the transmitting and receiving apparatus. In most stations, it is possible to reduce the amplification down to a very small fraction of maximum volume. This operation is accomplished continuously by a station operator and is known as *monitoring.* If the monitor is not quick and constantly on the alert, the loud notes of an orchestra may come in like thunder and the low, soft tones may be lost entirely. From here the circuit goes to the main control room, in which is a relay switching system to other studios, and a two stage line amplifier.

The next part of the transmitter is the modulator. This is a vacuum tube device and in the usual plate-power-variation, or Heising constant-



Courtesy Western Elect. Co.

Fig. 174—Pictorial view of the apparatus in a broadcasting station of medium size.

current method of modulation, it varies the plate power going into the oscillator tubes. In it, the plate voltage applied to the oscillator, (whose frequency is the "carrier" or high-frequency of the station), is varied by the audio-frequency modulating voltages. Since the oscillator current, and hence the antenna current, is proportional to the plate voltage, this current will vary, or be modulated by, the audio variations. The oscillator tubes are usually connected in a Meissner circuit for generating high-frequency oscillations.

The plate circuits of the vacuum tubes used as oscillators must be supplied with high-voltage, direct-current power. The filaments of all the tubes take quite a large current at low voltage. In order to provide this, some stations employ motor-generator sets operating directly from the electric light and power lines. The output passes through a coil and condenser filter combination designed to take out the commutator ripples.

Other stations transform low voltage a-c to high voltage, and then rectify it, changing it to direct current by special forms of large vacuum tubes called Kenotrons.

The station equipment also includes a special super-heterodyne receiving set tuned to the wavelengths used in commercial ship work. One operator is constantly on duty at this set to listen for possible SOS distress signals, so that the broadcast station can be taken off the air immediately upon their reception, to avoid possible signal interference.

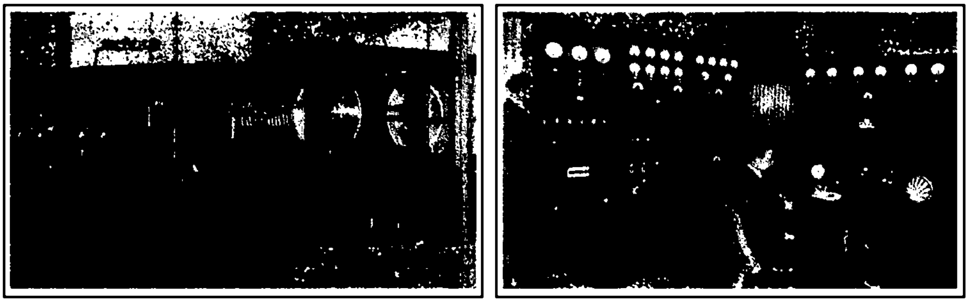
Courtesy National Broadcasting Co.

Fig. 175—**Left:** $1500 worth of vacuum tubes used in station WEAF. At the left is the smallest size tube used in the station. At the right is a UV862 tube used for generating the high frequency carrier current. Water is circulated in the metal jacket at the bottom.
Right: Operating control room at WEAF. At the left center is the oscillograph on which a continuous moving picture of the station output may be observed.

Fig. 174 shows a pictorial view of the apparatus in a modern broadcasting station. The various parts and circuits are labeled for easy reference. This is the complete equipment for a 1,000 watt station. The storage batteries are used to operate the speech amplifier.

At the left of Fig. 175, 1,500 dollars worth of vacuum tubes used in a transmitting station are shown. Mr. Gray, in charge of station WEAF is holding the smallest size tube used in this station, and Mr. Guy is holding a UV-826, the largest size tube used in modern radio stations. This station broadcasts with a power of 50,000 watts, and large water-cooled tubes of this kind connected as oscillators produce the high-frequency carrier current. At the right is shown the operating control room apparatus at this same station. At the left-center of this illustration may be seen the oscillograph on which a continuous moving picture of the station output may be observed so that the attendant may accurately control the degree of modulation and keep an accurate check on the quality of the transmission at all times.

At the left part of Fig. 176, may be seen the rectifier tube system of station WEAF, which makes available 12 amperes at 18,000 volts d-c for the plate circuits of the oscillator tubes. At the upper right of this part of the illustration are the huge aluminum disc high-voltage tuning condensers and below them the tuning inductance wound with copper strips on a wooden framework. At the right is shown a section of the main transmitter room and the operator's control desk, from which the amplifying and switching equipment is controlled. The low-power units,



Courtesy National Broadcasting Co.

Fig. 176—Left: Rear view of part of station WEAF transmitting equipment. The rectifiers are at the left. The huge high voltage tuning condensers and tuning coil are at the right.
Right: Section of the main transmitter room and operator's control desk.

including modulating and frequency control-devices, are at the left; in the left center is the 50 K.W. power amplifier; in the right center is the 20,000 volt high-power rectifier and at the extreme right are the power control equipment and dummy antenna system used for test purposes.

240. Electrical transcriptions: Although broadcast programs reproduced from the ordinary phonograph disc were common in the smaller stations even a few years ago, the latest improvements in the method of recording and reproducing sound programs on high quality phonograph records has increased the use of the special disc records as a source of broadcast station programs instead of having the artists perform personally before the microphone. When used for radio broadcasting purposes, they are called *electrical transcriptions*. The method employed, is simply to use an electrically driven phonograph turntable with an electrical pickup unit (see Art. 541) playing from the record and feeding directly to the speech amplifier in the station. This modulates the carrier current in the usual way.

The latest technical developments in the art have made possible the inscribing of a tone range extending from 30 to 9000 cycles in these discs.

This is far greater than can be distributed from studios to outlet stations by any other means. At the same time, facilities have become available to broadcasting stations for reproducing slow-speed transcriptions without the speed changes heretofore characteristic of phonograph reproductions. The combined use of these two major developments in this field, which have come to the forefront only lately, have won instant recognition by program sponsors and broadcasting stations alike. The electrical transcription method of broadcasting enables those smaller stations located, either in or away from the large cities, which cannot conveniently obtain the services of high-grade performers, to broadcast from records which were made in the cities by these highly paid artists. Thus the cost of a performance by such artists is spread out over a large number of duplicate records made and rented to the small stations. This enables them to offer programs of a quality and appeal which they would otherwise be unable to afford.

241. Remote control: If the broadcasting originates at some point away from the station, as in the case of a football game or other event, the microphones and usually a speech amplifier are installed at the field and special wire telephone lines are run to the transmitting apparatus in the broadcasting station. Usually, existing telephone lines are rented from the telephone company. Some stations employ a portable short wave radiophone transmitter of low power which is sent to the scene of activity, and the program is transmitted by radio directly from there to the main broadcasting station, where it is received and re-broadcast with increased power.

242. Artificial sound effects: Practically all broadcasting noises accompanying plays, special programs, etc., must be made to order in the studio. A most critical audience, often numbering millions of people, lends careful ears to the synthetic sounds. The action of a radio play is as broad as that in a theater, and the faithfulness of the illusion depends largely upon synthetic sounds.

An airplane engine, if picked up outdoors, would be heard for what it is. Inside a studio, the reverberations and echoes, clashing against the walls, would give the radio listener nothing but noise. But an old-fashioned foot-pump organ makes a noise exactly like an airplane motor and is used to create this effect in radio broadcasting.

The "zz-z-zziii--nnn-nngg-g-gg" of a bullet is simulated by plucking the steel string of a guitar. Hoof beats are hard to fake. Fire is simulated by cracking a bundle of canes together. Hissing water is easily imitated by letting off compressed air. If a house collapses, a box of bricks are allowed to fall down a chute. A firecracker celebration on the roof gives the radio listener an idea that a battle is taking place. Machine guns are simulated by riveting machines. Many ingenious devices have been developed for producing sounds of all descriptions and they are worked out so well that even careful listeners can never tell the difference.

242A. Chain-station hookups: It is often desirable to broadcast a single elaborate broadcast program over a number of stations simultaneously, to cover a large area,—especially for advertising purposes. The method which has been applied most successfully for achieving widespread distribution of a broadcast program, is that of interconnecting a number of stations by suitable telephone wire circuits so that they all broadcast the same program simultaneously. This is called a *chain-station hookup*. These broadcasting stations, located at strategic points scattered over the wide area to be served, permit the large majority of listeners to receive the program just as satisfactorily as they receive local programs.

In a chain-station hookup, the audio-frequency currents from the microphone which picks up the program, after passing through the control operator's amplifier, are delivered to a system of telephone lines which in many respects resembles an electric power-distributing network. Trunk wires go out from the program center to various parts of the country, and from these at appropriate points, connecting wires branch off to the broadcasting stations. Telephone repeaters are placed in the circuits at suitable points to amplify the currents so that they may reach the broadcasting stations without material loss in volume. As has already been pointed out, distortion of the telephone currents must be very small, or the faithfulness of reproduction at the receiving points will be spoiled. On this account, the very best kinds of telephone circuits and associated apparatus are employed.

REVIEW QUESTIONS

1. Explain with the aid of diagrams, what your understanding is of the way in which electromagnetic radiations are produced and sent out from the antenna of a radio transmitting station.
2. What is the induction field around a transmitting antenna? What is the radiation field?
3. Is it the induction field or the radiation field that is useful in radio communication? Why?
4. What is the phase relation between the radiation electrostatic field and the radiation electromagnetic field? How are they related?
5. State one reason why radio signals can be transmitted further with a given expenditure of power by means of very high frequency radiations (short waves) than they can by the use of lower frequencies.
6. Explain an application of signalling by means of the induction magnetic field around a conductor.
7. Draw a diagram showing the relative directions of the radiated electrostatic field from an antenna and its associated magnetic field in space.
8. How does a doublet antenna differ from an ordinary grounded

antenna? Why are doublet antennas used extensively in short wave work and not for broadcast band (200 to 600 meters) reception?

9. What is meant by the "radiation resistance" of an antenna? Would a good transmitting antenna have a high value of radiation resistance or a low value? Why?
10. Explain the construction and operation of the single-button carbon microphone.
11. Explain the construction and operation of the double-button carbon microphone.
12. Why is a carbon microphone of the type used for broadcasting purposes less sensitive than the transmitter used in ordinary telephones?
13. Explain how the changes in the current flowing through both sides of a double button microphone are made to add their effects in the split primary of the microphone transformer
14. Why is it that an alternating e.m.f. is induced in the secondary winding of a microphone transformer when the fluctuating direct current from the microphone flows through its primary?
15. Draw a diagram of a simple arrangement whereby you could transmit sound impulses by means of a microphone, a source of steady high-frequency r-f current, and a suitable energy radiator. Explain its operation, bringing out the detailed explanation of how the microphone modulates the r-f current.
17. Draw an outline diagram showing the connections of the following main parts of a radio broadcasting station; microphone, speech amplifier, oscillator, modulator, and antenna system. Explain in progressive order the actions taking place, from the microphone input to the outgoing modulated waves.
18. What is the purpose of "monitoring" in a broadcasting station?
19. Why are broadcasting studios lined with special sound deadening or absorbing materials?
20. Explain the method of broadcasting by means of "electrical transcriptions".
21. How are programs originating at places outside of the broadcasting studio, broadcast?
22. Why must a speech amplifier be used at the point of the pickup in a case of remote program pickup of this kind?
23. What produces such sounds as the whirring of an engine, firing of guns, noise of a locomotive, etc., which are heard in a broadcast program originating in the studio of a broadcasting station?
24. What is the electrical difference between a "short wave" transmitting station and a "broadcast band" transmitting station?
25. A broadcasting station is transmitting at a wavelength of 250 meters. What is the frequency of the carrier current generated by its oscillator tubes?

CHAPTER 16.

THE RECEIVING STATION, DETECTION WITH CRYSTALS

HOW THE ENERGY IS RECEIVED — INDUCING VOLTAGE IN THE RECEIVING ANTENNA — NECESSITY FOR TUNING — SINGLE CIRCUIT TUNER — TUNING THE SECONDARY CIRCUIT — TWO CIRCUIT TUNER — GAIN PRODUCED BY TUNED CIRCUIT — CHANGING THE ELECTRICAL ENERGY TO SOUND — EARPHONE OPERATION — NEED FOR THE DETECTOR — THE CRYSTAL DETECTOR — DETECTOR ACTION — THE CARBORUNDUM CRYSTAL DETECTOR — CONSTRUCTING A CRYSTAL RECEIVER — OPERATION OF THE ENTIRE RECEIVER — MEASURING CRYSTAL DETECTOR CHARACTERISTICS — LIMITATIONS OF CRYSTAL RECEIVERS — REVIEW QUESTIONS.

243. How the energy is received: The purpose of this chapter is not to present a complete description of modern sensitive receiving sets, but simply to set before the student an elementary conception of how the radio energy is received at the receiving station and what must be done to it to convert it most efficiently into a form that we are able to hear. While it is true that receivers with crystal detectors are used very little at the present time, the author has found that the student can gain a great deal of fundamental theory concerning radio receivers by studying a simple crystal receiver at first. By doing this, most of the theory of tuning and detector action may be developed simply, without the necessity for introducing any of the complications brought in by vacuum tubes. After these receiver fundamentals are firmly grasped, the study of vacuum tube receivers can be pursued with ease.

It will be remembered from the previous chapter, that in the broadcasting station we allow the sound waves to act on the microphone, producing corresponding variations of an electric current, as shown at the left of Fig. 172A. This varying microphone current is amplified by a speech amplifier and fed into the modulator circuit where it is made to modulate or vary the strength of the individual cycles of the radio frequency carrier current generated by the oscillator. The resulting carrier current is modulated or varied in strength somewhat as shown at D of Fig. 171, and at Fig. 172A, depending of course on the particular sound transmitted. This modulated radio-frequency energy is coupled to the antenna or radiating system. Here it sets up an electric field that radiates out in all directions at the rate of 186,000 miles or 300,000,000 meters, per second. Since the energy spreads out over a wide area, the *amplitude* of the fields varies inversely as the distance from the transmitting antenna. At twice the distance their amplitude is halved, at four times the distance it is one-quarter as much, etc. The radiated energy is in the form of a rapidly fluctuating electrostatic field with its accompanying magnetic field. In practical transmission, there is also a decrease in strength due to the fact that whenever the waves strike any object in which they can produce electric current (such as the steel framework of a building), currents are produced at the expense of the energy of the waves, and heat up to a minute degree, the material in which they flow. This dissipation of energy acts simultaneously with the inverse distance effect to reduce the strength of the waves and the signals received, as the distance from the transmitter increases. The latter effect is especially great around large cities like New York, Chicago, etc., and is one of the reasons for poor "distance" reception in these cities.

It should be remembered that these fields go through every non-metallic body which may be in their path. If now, a conductor of any kind is erected in their path, as for example the aerial wire shown in Fig. 177, a voltage will be induced in it by the rapidly passing fields. In the case of the reception of very high-frequency fields (short wave work), the antenna may consist merely of a wire, as shown at Fig. 166, but with the receiving apparatus at the center instead of the generator. This is called a "doublet" antenna. In order to be efficient for broadcast band reception, the length of such a doublet would have to be too long to be practical. Therefore an antenna or aerial wire of the form shown in Fig. 177 is commonly erected.

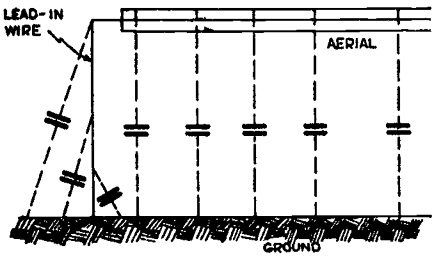


Fig. 177—How the antenna wire forms a condenser with the earth or ground.

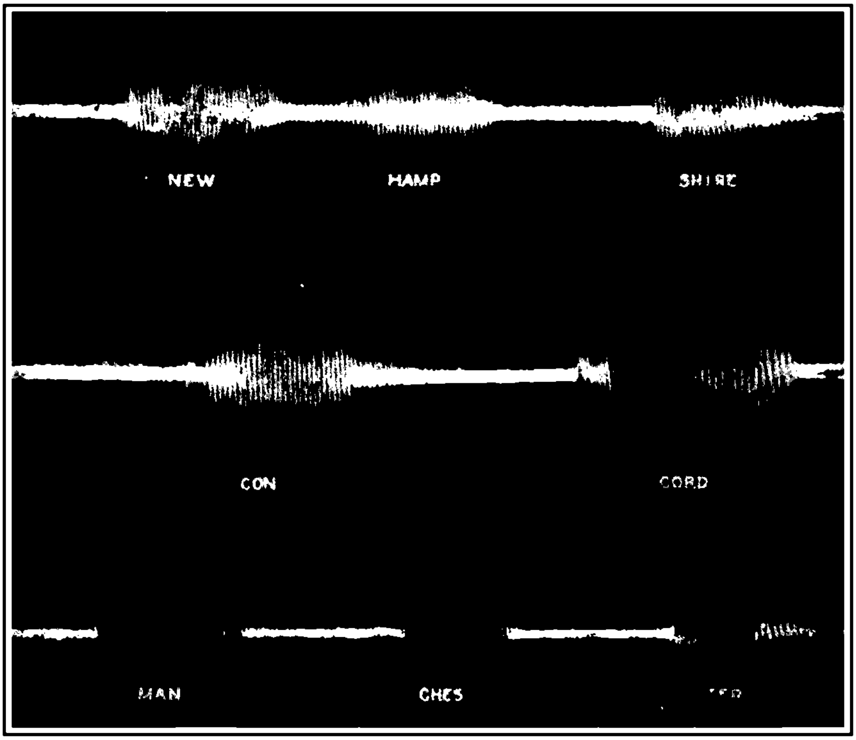
Note: The words *aerial* and *antenna* are used interchangeably by the layman, although accurately speaking, the top or elevated portion of the antenna is the *aerial*, and that portion which completes the electrical connection between the elevated aerial portion and the instruments is the *lead-in*. The *antenna* is the entire system consisting of the aerial and lead-in together.

The antenna usually employed consists of a flat-top aerial portion which is connected to the radio receiver by the *lead-in* wire. The other side of the receiver circuit is connected to the ground either by connecting it to a metal plate buried in the ground, or connecting it to a water pipe which serves the same purpose, since the pipe runs through the ground for a considerable distance and therefore makes electrical contact with it. It is evident from Fig. 177, that the combined aerial and the lead-in wires form one plate of a condenser and the earth and ground wire form the other. The distributed capacity action thus set up is illustrated by the small condensers shown distributed at intervals between the ground and these parts in this illustration. The capacitance of a simple receiving antenna of the type shown and used for radio broadcasting reception, may be as much as 150 to 300 micro-microfarads (200 mmfd. being a good average). The inductance of the wire may be as much as 50 to 100 microhenries and the total resistance may be anywhere from 25 to 100 ohms, depending on the length of the wires, resistance of the ground contact, etc.

Note: The arbitrarily selected *standard receiving antenna* which is used in measurement work is an antenna of 4 meters effective height, 25 ohms resistance, 200 micro-microfarads capacitance and 20 microhenries inductance. Such a standard antenna may easily be constructed artificially for test purposes (except as to height).

244. Inducing voltage in the receiving antenna: We may consider the voltage induced in the aerial circuit to really be caused by the following two actions:

First, the passing electrostatic fields which are alternating in direction very rapidly (at a rate equal to the carrier frequency of the broadcasting station), produce distortion of the electron orbits in the air dielectric around the antenna system. This causes unbalanced electrical forces which tend to cause motion of the free electrons in the antenna wire in contact with the atmosphere; in other words an e.m.f. is induced in the wire. The e.m.f. will vary in direction and strength exactly in accordance with the



Courtesy American Tel. & Tel Co.

Fig. 178—Oscillograph photograph of a carrier wave modulated by the words "New Hampshire," "Concord," and "Manchester." Notice the rapid and complex variations of the current.

variations in the passing fields, which as we have seen, may be represented by the modulated curves at D of Fig. 171. The action is practically the converse of the action taking place during the charging of a condenser by an applied e.m.f. as in Fig. 83.

The other portion of the induced e.m.f. may be considered as being caused by the electromagnetic induction set up by the rapid movement of the passing electromagnetic field. The high-frequency e.m.f. induced in the antenna circuit will cause a surge of electrons rapidly up and down the circuit at a frequency equal to that of the carrier wave of the transmitting station, the strength of the individual cycles varying in accordance with the modulation impressed on the carrier wave, as shown at D of Fig. 171.

The electrons surge up and down very rapidly in the antenna circuit, a surge taking place every time a wave of radio energy passes the antenna. This flow of electrons constitutes a flow of electric current. Fig. 178 shows the complex variations in the current set up in an antenna circuit by the passing waves of a single broadcasting station when the carrier wave of the station is being modulated by the words "New Hampshire", "Concord" and "Manchester" spoken into the microphone in the studio. It should be remembered that this current is an exact duplicate, as regards wave-form of that sent out from the broadcasting station, that is, the rises and falls of the e.m.f. and current in the receiving antenna circuit will follow exactly those in the transmitting antenna, the only change being that the voltages set up in the receiving antenna are unbelievably small, being in the order of a few millionths of a volt (microvolts), see Art. 348.

A connection to the earth is not necessary for the reception of radio signals. Anything which will serve the same purpose as the ground does in forming the other plate of the condenser made up by the antenna circuit, will operate just as well. We usually employ a connection to the ground for this purpose simply because this can be conveniently obtained by simply connecting to a conveniently located water pipe. This saves us the trouble of erecting a counterpoise. In some radio receiver installations, as in the case of a receiving set in a moving automobile or aeroplane, it is not possible to make an actual connection to the ground. The "ground" side of the antenna circuit may be connected to a wire or network of wires supported a short distance above the earth and insulated from it. This network of wires then acts as one plate of a condenser (taking the place of the ground) and the antenna as the other plate. It is called a *counterpoise* ground. The counterpoise is usually located directly under the antenna. When a radio receiver is operated in an automobile, a short wire is erected in the roof of the car, and the metal frame and body of the car are used as a counterpoise ground. In an aeroplane, the engine frame and bracing wires are electrically connected together and used as a counterpoise; a trailing copper wire usually being employed as an antenna. Instead of a suspended antenna wire and counterpoise, two metal plates or sheets of copper wire netting separated and insulated from each other may be used, one as the antenna and the other as the counterpoise. This scheme is also used in some "automobile receiver" installations as we shall see in Art. 532. The important point to remember is that the ordinary capacity-type antenna system really consists of two conductors separated from each other, and so arranged with the receiving equipment that electrons can surge back and forth through the circuit from one of these conductors to the other many times every second, this constituting a flow of current. These two conductors may take any one of many forms. We ordinarily make a connection to the earth simply because this saves us the trouble of erecting a counterpoise. In many cases where the earth is dry and rocky and therefore has quite high resistance, a correctly designed counterpoise ground (being of much lower resistance) will greatly improve the reception. Some receivers (especially those electrically operated) apparently work without any connection to the ground terminal of the set. In this case a counterpoise ground is being formed by the wires in the set, by the capacity action between the wires in the set and the ordinary ground, or by capacity to the electric light circuit which comes to the receiver and which always has one side grounded.

If a loop or coil antenna is used at the receiving station, the voltage induced in it is due almost entirely to the action of the magnetic field alone. This will be discussed in Art. 607 when dealing with "loop antennas."

245. Necessity for tuning: Up to this point in our discussion, we have assumed for simplicity that the only voltage induced in our receiving antenna is that caused by the action of the radiated fields of the one station we desire to receive. Although it may seem surprising at first, it is nevertheless true that practically every radio station in the entire world which is broadcasting radiations of any frequency (whether the transmission be that of code messages or sound programs), will induce voltages of corresponding frequency in our antenna circuit and therefore cause currents to flow up and down in it. The radiated fields from a 5-watt station located 1000 miles away are impinging on our antenna just as well as those of a local 50,000 watt broadcasting station (unless they have been greatly weakened by some material obstruction on the earth causing a shielding or screening effect; or are affected by skipping or fading). Although the induced voltages and currents caused by comparitively weak or distant stations will be very much weaker than those induced by powerful or local stations, nevertheless they are there just the same. Of course, we do not hear all of these stations with present day receivers because

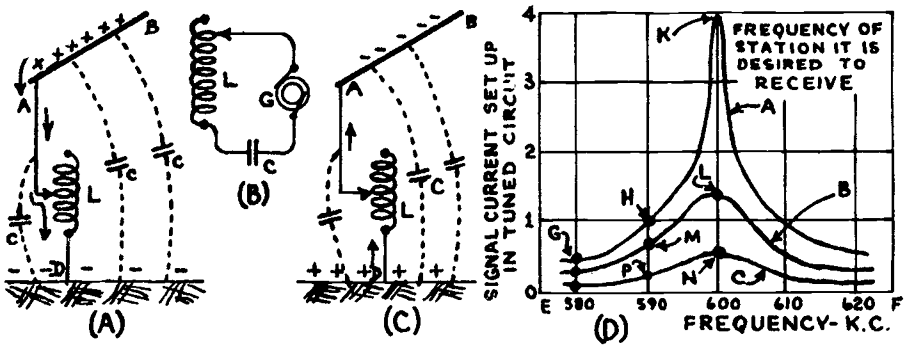


Fig. 179—Simple radio receiving circuit, and the effect of resistance in the tuned circuit.

many of these signals are so weak when received, that the receiver does not amplify them enough to make them heard. Nevertheless, there will be enough comparitively strong signals set up in any antenna which we might erect, to cause several of the stations to affect our receiving equipment strongly enough so they will all be heard at once, and thereby interfere with the clear reception of any one of them at a time. *Therefore, since we want to hear only one station at a time, we must in some way weaken the signal currents of all of the stations it is not desired to hear and allow the currents of the station it is desired to hear to flow through the receiving equipment with as little loss of strength as possible;* in fact in modern radio receivers we even amplify the signal we desire to hear by means of vacuum tube amplifiers. Fortunately, this can be accomplished by employing the principles of electrical resonance studied in Arts. 172 to 177. (The student is advised to review these articles at this time in order to refresh his memory on the theory of both series and parallel resonance.) All radio transmitting stations in the same vicinity send out their signals at different carrier current frequencies. Therefore the voltages and currents set up in our simple receiving antenna system of Fig. 177 will also all be of these different frequencies. We know from our previous work, that a series-tuned circuit offers a very low impedance (actually equal to its resistance) to the flow of current of the frequency to which it happens to be tuned to resonance, and offers a much higher impedance, in varying degrees, to the flow of currents of all other frequencies above and below this. Conversely, a parallel-tuned circuit offers a very high impedance to the flow of current of the frequency to which it happens to be tuned to resonance, through the circuit in which it is connected. It offers a much lower impedance, in varying degrees, to the flow of currents of all other frequencies above or below this value.

246. Single-circuit tuner: We can use the principle of series resonance to produce the desired separation of signals by means of the simple arrangement shown at (A) of Fig. 179. Here an inductor L, commonly called a tuning coil, is connected in the antenna circuit. This, together with the capacitance between the antenna system and ground (shown by imaginary condensers C), forms a series-tuned circuit, the resonance frequency of which is found from equation (20) in Article 173, which is $f=\frac{1}{2\pi\sqrt{LC}}$ where L is in henries and C is in farads. This may also be expressed as: $f=\frac{159{,}000}{\sqrt{LC}}$ where C is in microfarads and L is in microhenries.

This circuit is considered to be a *series circuit* because the signal voltage is induced in a part of it (in the antenna wires and lead-in) and is therefore in series with the rest of the circuit (see article 174). The circuit of (A) may be drawn in simplified form as shown at (B), where the induced voltage in the antenna circuit is considered as being supplied by the high-frequency a-c generator G.

By means of either of the equations above, we could calculate the inductance tuning coil L would have to have, which, when acting in the circuit with antenna capacitance C, would produce resonance in the antenna circuit at the particular frequency of the signal it is desired to receive. (Actually the antenna circuit has some inductance which must be added with L when making this calculation.)

Assuming that this value of inductance were used and connected as shown, when the passing fields cause an electron flow downward through the circuit into the ground, the ground becomes charged excessively *negative* and the aerial wire AB becomes charged *positive* due to a corresponding lack of electrons, ([A] of Fig. 179). When the next change in direction of the field takes place, the aerial becomes charged negatively and the ground is charged positively by the flow of electrons upward as shown at (C). Consequently, we have in this series tuned antenna circuit, a rapid surging of electrons (current flow), first from the aerial through the tuning coil to the ground, and then in the reverse direction from the ground through the coil to the aerial, over and over many times a second.

Since the series tuned circuit offers a low impedance to the flow of electrons or current having the same frequency as that to which it is tuned, the voltage induced in the antenna by the one station of this frequency is able to send a comparitively large flow of current through the circuit,—and the station will be heard loudly. Since a much higher impedance is offered to the flow of currents of all other frequencies above and below this, the voltages induced in the antenna by all other unwanted stations will only be able to set up comparitively weak currents in the antenna circuit so they will not be heard at all. (In practice, absolute separation of stations cannot be accomplished by a single tuned circuit, due to the fact that the resistance of the wires, ground contact, etc., broaden the tuning so that the wanted station does not set up so much more current than the unwanted stations as we might suppose. Therefore we find modern radio receivers using as many as four or more tuned circuits to obtain satisfactory separation of the received signals.)

The arrangement thus far employed at (A) and (C) would enable us to receive strongly, that station for which the particular values of L and C employed made the circuit in resonance. If we wanted to receive a station transmitting on a different frequency, the value of either L or C or both would have to be changed. In the old single circuit receivers, it was customary to make the inductance of the tuning coil adjustable, in order to tune the various station frequencies. In one form of tuning coil employed, a contact was arranged to slide over the wire and therefore vary the number of turns of wire and the inductance in the circuit. The coil was built somewhat as shown at (A) of Fig. 79, and was known as a *single circuit tuner.*

247. Antenna resistance and selectivity: Since the resistance of the entire antenna and ground wire and that of the contact between the earth and the water pipe, (or whatever is used for actual connection to the earth), is directly in the tuned circuit in the single-circuit system just described, the tuning is rather broad, that is, there is no great difference between the strength of the current set up by the signal of the *wanted* station and the currents set up by the signals of all the other *unwanted* stations.

Since the current flowing in the circuit at resonance is equal to the signal e.m.f. induced in the antenna divided by the high-frequency resistance of the total antenna circuit, it is evident that if this resistance is high we may not gain very much by tuning, for even at resonance the high-frequency ohmic resistance of the circuit might be high enough to keep the current set up by the wanted station from being very much stronger than that set up by the unwanted stations. In order to obtain sharp tuning therefore, it is evident that the ratio of the *reactance* to the *resistance* of the tuned circuit must be made high.

The effect of broad tuning may be seen from (D) of Fig. 179. Three resonance curves A, B and C are plotted for the tuned circuit. These show the values of the current which equal signal voltages of various frequencies will set up in the tuned circuit, (corresponding to the signal voltages received from several equally distant and equally powerful transmitting stations), for three different values of resistance of the tuned circuit. Let us suppose the circuit has such a value of inductance L and capacitance C that it is tuned to resonance at 600 k.c. Then considering the sharp tuning condition represented by curve A when the resistance of the circuit is kept low, a station transmitting on 580 k.c. would set up current in the receiving antenna circuit represented by the height of point G above the axis line E F (equal to about 0.5 arbitrary units of current); a station at 590 k.c. would induce a larger current of one unit represented by H, a station transmitting at 600 k.c. (the frequency to which the receiving circuit is tuned) will set up the largest value of current (4 units of current represented by K). Stations of higher frequency such as 610 k.c., 620 k.c., etc. will set up lower values of current as shown. Therefore, the current set up by the station to which the circuit is tuned (4 units) is 4 divided by 1, or 4 times as strong as the 1 unit of current set up by an unwanted station transmitting at say 590 or 610 k.c. Evidently the wanted station will be heard much more loudly than the unwanted station. The reason for this difference of current is of course due to the different reactance and impedance which the tuned circuit offers to the flow of currents of different frequencies. Referring back to the right of Fig. 116, where we considered in detail how the reactance of a series tuned circuit changes as the frequency is varied, we find that as we decrease the frequency from that at resonance, the capacitive reactance increases greatly (since now the condenser does not charge and discharge as many times per second as before and therefore there is less current in the external circuit between its plates); and as the frequency is raised above that of resonance, the inductive reactance increases greatly (due to a greater value of the induced counter—e.m.f.), and thereby reduces the current.

If now our tuned circuit had quite some resistance, the current at resonance (curve B), represented by point L, would be much less than in the previous case, being only 1.5 units now. Likewise the current at all other frequencies is much lower than before due to this greater resistance, as shown by the fact that curve B is lower at all points than curve A. The current set up by the station to which the circuit is tuned (1.5 units at point L) is now equal to only $1.5 \div 0.75 = 2$ times as strong as that set up by an unwanted station transmitting at a frequency 10 k.c. from that to which the circuit is tuned (point M). Therefore, it is evident that in this case since there is not very much difference between the strength of the current set up by the wanted station and that of an unwanted station differing in frequency by 10 k.c., both of them will probably be heard, the program of one interfering with that of the other. If the circuit had even more resistance, its tuning curve might be represented by curve C, and the current set up by the wanted station (point N) would be only about 1.5 times that set up by an unwanted station 10 k.c. away (point P), so that both stations would most certainly be heard together with practically the same loudness. Notice that the effect of having a tuned circuit with appreciable resistance is to reduce the value of the current set up in it by all signals received by the antenna, but that the current set up by the wanted station the circuit is tuned to receive, is reduced greatest of all. If these facts are firmly grasped by the student, he should experience no trouble in quickly and thoroughly understanding all conditions met with in problems of sharpness of tuning and separation of the signals received from the various broadcasting stations.

In general, the degree to which a radio receiver is capable of differentiating between signals of different carrier frequencies, is a measure of its *selectivity*. A highly selective receiver (sharp tuning), has a tuning curve somewhat like that of A, and is able to so weaken the currents of the unwanted stations, and not weaken the current set up by the wanted station, that only the signals of the station to which it is tuned, are heard. In a receiver having poor selectivity (broad tuning) the ratio of the currents set up by the station to which it is tuned, to those of all other unwanted stations, is low, so several of them may be heard simultaneously, creating *interference*.

248. Two-circuit tuner: A consideration of the foregoing discussion on selectivity makes it at once apparent that the simple receiving system of (A) and (B) of Fig. 179 will not be very satisfactory, for the simple reason that the tuned circuit which consists of the aerial wire AB, the lead-in wire to the tuning coil, the tuning coil itself, the wire to the ground, the resistance of the contact to the ground (this resistance may be high if a poor ground connection or contact is employed), and the part of the ground through which the electrons surge back and forth, will have quite some resistance and therefore the tuning will be quite broad. The resistance of an antenna circuit depends of course on the lengths and size of wire employed, ground resistance etc., but in some ordinary receiving antennas the total resistance may be as high as 25 to 100 ohms or even more, depending on the care with which the wires are run, the joints and splices made, etc. (This is the high-frequency a-c resistance, which as we shall see later, is somewhat higher than the simple d-c ohmic resistance.) Resistance as high as this in a tuned circuit will reduce the current very much and the tuning will be broad, as shown by curves B and C at (D) of Fig. 179. In order to keep the antenna circuit resistance out of the tuned circuit, we may employ the arrangement shown at (A) of Fig. 180. Here, the tuning coil consists of a primary winding P of a few turns of wire and a secondary winding S, usually having more turns. The primary P is placed near the secondary, so that the fluctuating magnetic field set up by the flow through it of the antenna currents of various frequencies produced by the voltages set up in the antenna circuit by the passing fields of all transmitting stations, will link and unlink with, and induce corresponding voltages in the secondary winding S. We will now discard the previous method of varying the resonance frequency of the tuned circuit by means of a coil of variable inductance, and use the more practical and common one of employing a coil of fixed inductance together with a condenser of variable capacitance. The variable tuning condenser may be a single section of the form shown in Figs. 98 to 101, with a set of movable rotor plates which can be rotated in or out between a set

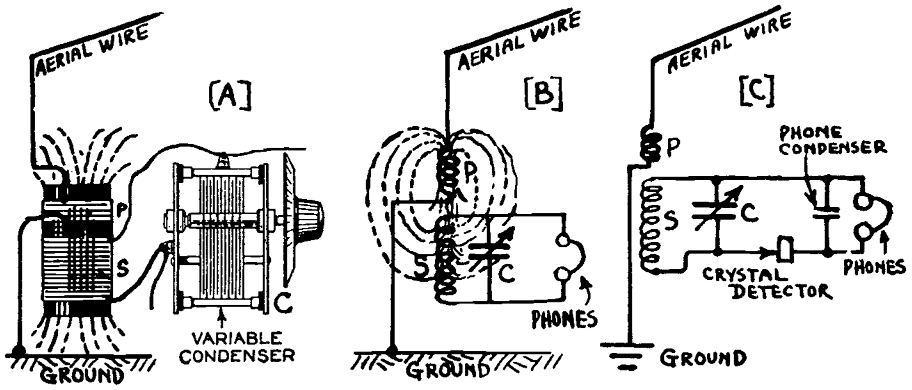


Fig. 180—Two circuit tuner arrangement. The need for, and connection of, the detector.

of fixed stator plates in order to vary the capacitance. For modern receivers in which single-control tuning is desired, this arrangement has been found to be mechanically and electrically superior to the variable-inductance arrangement.

Note: Variable inductances in the form of carefully designed tapped coils are used to a great extent in short wave receivers designed to cover a large range of transmitted frequencies, but are not used to any extent in ordinary broadcast band receivers. Commercial receivers of this type have a tuning range from 15 to 650 meters (about 20,000,000 cycles to 460,000 cycles). This range is obtained by means of special coil-switching arrangements which will be described in Arts. 557 and 563 of the Chapter on Short Wave Reception.

The tuning coil or transformer employed for the arrangement of Fig. 180 is of the air-core type, because an iron-core transformer in this position would have considerable losses due to hysteresis and eddy currents set up in the iron core by the rapidly alternating magnetic flux, which alternates as many as 1,500,000 times a second if the signal from a station transmitting on say 200 meters is being received. For these reasons, *radio-frequency* transformers of this type are almost always of the air-core form shown at (B) of Fig. 75, and elsewhere throughout this book. It is evident that the magnetic coupling between the primary and secondary windings can be varied between wide limits by using more or less turns on the primary coil and placing them closer or further away from the secondary. The ratio between the induced voltage in the secondary and the voltage applied to the primary in an air-core transformer is not equal to the ratio of the number of turns as in the case of an iron-core transformer, but depends on the closeness of the magnetic coupling between the primary and secondary since all of the lines of force of the primary may not link with the secondary. For some constructions and conditions of coupling, the secondary voltage may even be less than the primary voltage, even though the secondary has more turns than the primary.

The number of turns of wire used on the secondary winding is fixed by the capacitance of the particular tuning condenser to be used and the frequency range it is desired to be able to tune to.

It would seem advisable to use a large number of turns on the secondary winding in order to make the voltage induced in it as large as possible. If this is done, the inductance of the secondary winding becomes large and since the resonant frequency is equal to $f = \frac{159{,}000}{\sqrt{LC}}$ it is evident that if the circuit is to be designed to tune up to a given maximum frequency, the larger the value of inductance used, the smaller the value of tuning capacitance required. Thus, if the number of turns on the secondary is increased, the size of the tuning condenser must be decreased. However, we do not gain as much as we might think by using a large number of turns on the secondary, for as we increase the number of turns we use more wire and so increase the resistance of the coil. This resistance tends to reduce the current flowing in the tuned circuit and so reduces the voltage appearing across the coil and condenser, thereby tending to offset the advantage gained by more secondary turns. For broadcast band work, a satisfactory compromise between these factors has been obtained by employing variable tuning condensers having a maximum capacitance value of .00035, .000365 or .000375 microfarads and a secondary winding having the proper value of inductance to tune to 550 k.c. or 545 meters (the upper limit of the broadcast band) with this value of capacitance. The use of .00035, .000365 or .000375 mfd. tuning condensers has almost become standard for this purpose in the United States. For short wave work, it is common to use condensers having a maximum capacitance of about .00015 mfd., with suitable tuning coils to cover the frequency ranges required.

Problem: A tuning condenser having a maximum capacitance of .00035 microfarads is to be used in a radio receiver to tune the secondary winding of an r-f transformer up to 545 meters (550 k.c.) the upper limit of the broadcast band. What must be the inductance of the secondary winding of the tuning coil it is connected to?

Solution: Since $f = \frac{159{,}000}{\sqrt{LC}}$, we may solve this equation for L by squaring both sides, and then setting L alone. When this is done, we have $L = \frac{159{,}000^2}{f^2\, C}$. Substituting the values in the above problem in this equation, we have

$$L = \frac{159{,}000 \times 159{,}000}{550{,}000 \times 550{,}000 \times .00035} = 240 \text{ microhenries. Ans.}$$

The primary winding P, in the antenna circuit usually contains only a few turns of wire, so its inductance is small. Therefore, under this condition, the main antenna circuit will be rather broadly tuned because the resistance of the antenna circuit is relatively large compared with its total inductance and capacitance. Since its tuning is then very broad (as represented by curve C in (D) of Fig. 179), it does not exhibit any marked resonance properties and equal signal voltages of all frequencies induced in the antenna circuit, will cause equal currents to flow in this circuit. The antenna circuit is therefore said to be *aperiodic;* that is, without any definite period or frequency. It is true that the signal of the wanted station could be strengthened somewhat by tuning the antenna circuit to its frequency thereby strengthening its current, but as we have already seen, the resistance of the usual receiving antenna circuit is so high and the tuning therefore so broad, that most set designers have felt that not enough is gained by tuning it to make the cost of the extra tuning condenser and the need for manipulating it worth while. They have preferred to make up for this loss of signal strength by using more amplification in the vacuum tube amplifier employed. Therefore most of the radio receivers designed for home use have an aperiodic antenna circuit.

249. Gain produced by tuned circuit: At this point, we have reached the stage in our progressive design of a satisfactory radio receiving system where we have succeeded in making the passing electric fields of all transmitting stations induce voltages in an antenna system. These voltages produce a flow of rapidly alternating currents in the antenna circuit. By means of the r-f transformer shown at (A) of Fig. 180 we succeeded in transferring some of the energy by transformer action from the antenna circuit into the secondary circuit by means of the magnetic field between the primary and secondary coils. Then by means of a variable tuning condenser C, we formed a series resonant circuit, and utilized the principle of series resonance to present a very low impedance path in the tuned circuit to currents of the frequency of the wanted station, and a much higher impedance to the flow of currents of all other frequencies from all other stations. Therefore that voltage induced in the secondary winding which has the frequency of the wanted station for which the circuit is tuned, will set up a relatively large current in the tuned circuit. The voltage drop appearing across both the secondary S, and the tuning condenser C under this condition, will be greater than the voltage induced into the secondary winding by the electromagnetic induction from the primary; that is, the tuned circuit itself causes a "gain" of voltage.

The student is referred to article 174 for the detailed discussion of how a "gain" in voltage is produced by a tuned circuit considered alone. The gain is numerically equal to $\frac{2\pi f L}{R}$ where f is the frequency of resonance in cycles per second, L is the inductance in henries and R is the total high-frequency resistance of the tuned circuit in ohms. The expression $\frac{2\pi f L}{R}$ is sometimes referred to as the *figure of* *merit* of a tuning coil. Since the resistance of modern tuning condensers and that of the wires connecting the coil to the condenser is so low as to be neglected for practical purposes, the entire resistance of the tuned circuit is considered as being in the coil alone. Since $2 \pi f L$ is really the inductive reactance of the coil, it is evident that the higher the inductance of the tuning coil used, the greater will be its inductive reactance and hence it would seem that the gain would also be higher. This advantage of using a high-inductance tuning coil is partly offset by the fact that as the turns are increased in order to increase the inductance, the resistance will also increase (sometimes very rapidly, depending on the physical form of the coil) and as the resistance forms the denominator of the expression for gain, it would tend to reduce the gain actually obtained. Therefore, the ratio of the inductive reactance to the resistance of the coil must be considered as a measure of its efficiency in this respect.

The result of the voltage gain resulting from the use of the tuned circuit, is that a higher voltage appears across the coil and condenser in the tuned circuit at the frequency of resonance, than would otherwise exist across them as a result of the simple transformer action from the primary. This of course is a very worthwhile advantage resulting from tuning the receiving circuit.

250. Changing the electrical energy to sound: Up to this point, we have concerned ourselves merely with building up the received signal voltage and current from the wanted station as much as possible with the simple devices at hand, and opposing and weakening the current from all unwanted stations. The voltage impulses appearing across the tuning coil and condenser will be quite strong when the circuit is tuned exactly in resonance with the signal of the station being received. Since our ears do not respond to electric currents or voltages, the problem now is to convert these voltages back into sound waves exactly similar to those originating in the transmitting stations. The ordinary telephone receiver will perform this function, for in the telephone system it is used to change the variations in electric current transmitted over a telephone line, into corresponding variations in air pressure (sound waves), at the receiver. The same type of instrument, modified somewhat in construction and form in order to make it light in weight and more practical for the conditions encountered, can be used for radio telephone reception. It is commonly known by the various popular names of *earphones*, headset, phones, receivers, watch-case receiver, etc. Where a comparitively large amount of electrical energy is to be converted into sound, we use a larger instrument known as a *loud speaker*. The principles of operation of loud speakers are somewhat similar to those employed in earphones but they will be studied later. Let us now see how the ordinary earphone is constructed, and operates.

Earphones, like the ordinary telephone receiver, operate on the electro-magnetic principle. However, since the energy received by the antenna of a radio receiving station is very feeble, and therefore the energy available to operate the earphones in order to produce the sound is very small (we are not considering the case of radio receivers using vacuum tube amplifiers for increasing the signal energy as yet) earphones must be constructed to be much more sensitive than the ordinary telephone receiver for which stronger currents are available in the wired telephone line.

Earphones usually consist of two separate earpieces connected in series and held to the ears by a metal headband as shown in Fig. 181. Each earpiece has a metal or hard rubber cup D, with a hard rubber cap G. In the bottom of the cup is a strong permanent horseshoe magnet E, with pole pieces F. Around each pole piece, a coil

H, of many thousands of turns of fine insulated wire (No. 40 to 50) is wound. The magnetic field produced by the signal current flowing through these coils either aids or opposes the steady field of the permanent magnet, depending on which direction the current flows through them.

The two coils are connected in series, so the current passes through both windings. Sensitive headsets have several thousand turns of wire on the coils, so that even very feeble currents flowing through them produce an appreciable change in the magnetic field of the permanent magnet. Suspended above the pole pieces, and very close to them, is a thin, flexible, soft-iron diaphragm about .004 inch thick. A commercial set of earphones with headband is shown at the right of Fig. 181. The phone on the right has been opened to show the screw cap (center), and the diaphragm (right).

251. Earphone operation: The operation of each unit of an earphone of the type described above is as follows:

When no current flows through the coil, the magnetism of the permanent magnet attracts the iron diaphragm and bends it slightly, as shown by position A in Fig. 181,

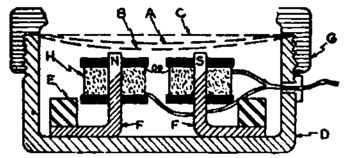


Fig. 181—(Left): Cross-section view of an earphone unit showing the permanent magnet, magnet coil and diaphragm.

(Right): A pair of standard earphones with headband. The two units are supplied with a 5-foot cord with phone-tips for connections.

producing an initial deflection. Assume the left-hand pole piece to be a north pole and the right-hand one a south pole. If one complete wave of an alternating current is flowing through the receiver, so that the current during the first half of the wave flows through the coils in such a direction as to produce magnet poles similar to those of the permanent magnet, then this magnetism adds to that of the permanent magnet and the field is strengthened. This increases the attraction on the diaphragm and pulls it down further, to point B. On the next half wave, the direction of the current reverses, and so the magnetic field produced by its flow through the coils also reverses, and opposes that of the permanent magnet. The resultant field is now weaker than that of the magnet alone, so the diaphragm springs back to position C. At the end of the cycle it goes back to A. Therefore, during one cycle it makes a complete vibration from A to B to C, the *amplitude* of the vibration depending on the *amount of variation of current* flowing through the coils. This rapid back-and-forth movement of the diaphragm sets the air in motion and creates sound waves that travel out through the opening in the cap. If the frequency of the current sent through the winding lies within the audible range (about 16 to 20,000 cycles per second), the sound waves produced by the corresponding movements of the diaphragm also being of the same frequency, will be heard by the human ear. Thus the earphones can be used to change *variations* in an electric current or voltage applied to them, into corresponding *variations* in air presure—or sound waves. It must be remembered that it is the amount or *degree of variation* of the current through the coils that produces the motion of the diaphragm and the sound, and not merely the total number of amperes or milliamperes of current sent through. Unless the current *varies*, there is no *change* of magnetic pull on the diaphragm and hence no sound is produced. If we sent an absolutely steady current through the windings, the magnetic field produced when the current started flowing, would cause a single change in position of the diaphragm and we would hear a "click". The diaphragm would stay in that one deflected position as long as this steady current flows through; and absolutely no sound would be produced, simply because there is no motion of the diaphragm. If the coils could carry it, we could send 1,000 amperes of steady direct current through a pair of earphones or a loud speaker without producing the slightest sound from it! This should be remembered, for as we shall see later, we design radio receiving equipment to produce the maximum signal current or voltage variations. These in turn produce the maximum amplitude of vibrations of the loud speaker diaphragm and hence maximum loudness or intensity of sound.

252. Need for the detector: Now that we have a device capable of converting variations in electric currents or voltages into sound waves, it would seem that our receiving equipment is complete. We might expect that we could simply connect a pair of earphones across the coil and condenser of our tuning circuit, (across which the maximum varying signal voltages appear due to the "gain" of the tuned circuit), as shown at (B) of Fig. 180. Unfortunately, if we did this we would not hear a single sound! In order to understand why this is so, we must go back to our broadcasting station. It will be remembered that in order to successfully accomplish the radio transmission of sound programs, we varied or "modulated" the strength of the individual cycles of the radio-frequency carrier current in accordance with the sounds transmitted, as shown in Fig. 172A. For instance, for the transmission of sound of "a" as in father, the high-frequency alternating current flowing in the antenna circuit of the transmitting station would look like that at (A) in Fig. 182 and at the right of Fig. 172A. Let us see what happens when this is received by our receiver. The currents set up in any receiving antenna by the radiated wave of this station would be exactly the same as this, only much weaker in strength of course. The current flowing in the tuned circuit of the receiver, and therefore the voltage variations appearing across the terminals of the coil or condenser at (B) of Fig. 180, would also vary exactly the same. Consequently we are applying to the terminals of our earphones a high-frequency (radio frequency) alternating voltage, each cycle fluctuating in value in exact accordance with the sound variations shown in Figs. 172A and 182. For transmitting stations in the broadcast band, the frequency may be anywhere from 550,000 cycles to 1,500,000 cycles per second depending on the particular station being received. What happens? The answer is,—nothing! We shall now see why:

First, the magnet coils of the earphones, (or loud speaker) having a necessarily large inductance due to the fact that they consist of a great number of turns of wire wound on the iron core, offer a very high impedance or opposition to the flow of signal currents of such high frequency through them, and will not allow them to flow through. A set of earphones having a direct current ohmic resistance of 2,000 ohms may have an impedance of four or five thousand ohms at a frequency of only 1,000 cycles. Remembering that the impedance of an inductor varies directly as the frequency is increased, we can imagine what impedance they would present to the flow of the received r-f currents of 550,000 cycles or higher.

Second, even if some of the high-frequency current did flow through the earphone coils, and the diaphragm made a complete vibration for each individual cycle, it would be vibrating so rapidly that the ear would not respond to it, for the highest frequency sound that the human ear can hear is around 20,000 vibrations per second. Actually it is impossible for any diaphragm which has some inertia due to its mass, and which is not perfectly flexible, to vibrate as fast as this current would tend to make it move. It is evident from these considerations that the circuit shown at (B) of Fig. 180 is impractical.

Let us see what is to be done. Referring back to Fig. 171 it is evident that B represents the original sound pressure variations. Therefore we want the diaphragm of our earphones or loud-speaker to move in accordance with these variations. Now refer to curve D. This is the form of the modulated high-frequency carrier current. Our sound wave-form is now represented by the dotted line wave connecting the peak values of the individual *half cycles of current in one direction*—which one does not matter—it may be either the negative half-cycles or only the positive ones. Now refer to (A) of Fig. 182 which represents the high-frequency alternating current or voltage variations existing in the tuned circuit of the receiver. It is evident that we do not want the diaphragm of our earphones or loud speaker to follow the variations in current of each individual cycle of this a-c for this is not the wave-form of the sound. What it must do in order to faithfully reproduce the sound wave of A in Fig. 171 is to merely follow the *variation in the maximum or peak values of the current or voltage in one direction only*, that is, it must move according to the dotted envelope curve drawn through the peak values of the individual half cycles in one direction as shown. It is evident that to do this, it is first necessary to make the current alternations in only one direction effective, so the current flows through the earphones in one direction only. This may be accomplished by means of a rectifier of some kind, that is, a device which allows current to flow easily through it in one direction only, and offers a very high resistance to the flow of current through it in the opposite direction.

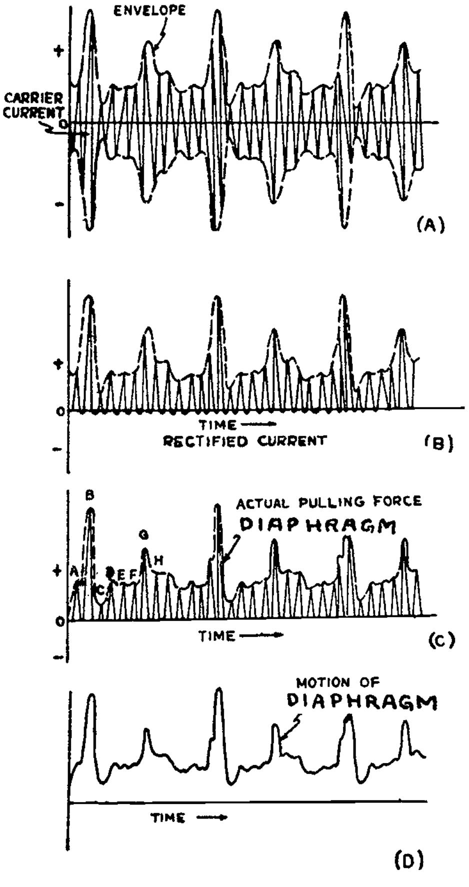


Fig. 182:—(A) Wave-form of received current for message of "a" as in "father." (B) Current rectified by detector. (C) Pulling forces on the earphone diaphragm. (D) Final motion of diaphragm and sound wave produced.

253. The crystal detector: A vacuum tube connected as a detector is used for this purpose in modern receivers, but for our purpose in developing a simple receiving system we may use the common *crystal detector* in series with the earphones as shown at (C) of Fig. 180 to perform the function of rectification or detection. The construction and operation of this is as follows:

The crystal detector usually consists of a very fine wire called a catwhisker, arranged to make light contact with a crystal of some particular material such as galena (lead sulphide) held in a cup by a metal alloy of low melting point as shown at the left of Fig. 183. Other mineral combinations such as iron pyrites, carborundum, silicon, molybdenite, etc. can be used, but for our purpose of explanation, the simple galena detector will suffice.

When an alternating voltage is applied to the combination, it tends to make current flow from the catwhisker to the crystal during the first half cycle. The resistance which the crystal and contact offer to current flow in this direction is low, so the current is able to flow through easily. On the next half cycle, the voltage is reversed and tends to send current in the opposite direction. The detector contact offers a very high resistance to current flow in this direction, so very little current is allowed through. The action is repeated for each cycle. This is shown graphically in (A) and (B) of Fig. 182. At (A) we have the modulated high-frequency varying voltage impressed across the detector and phone circuit by the tuned circuit. At (B) we have the half wave rectified current which gets through the crystal rectifier and earphones. Notice that this is still a varying high-frequency current, but it now flows only in one direction since one half of each cycle of current flow has been eliminated. A very small amount of current does get through the detector in the opposite direction, as shown at (B) by the small loops below the axis line. It is the difference in strength of these two currents which determine how well or how poorly the crystal operates as a detector. A good crystal will almost entirely eliminate the flow of current in one direction.

254. Detector action: It would seem that the pulses or fluctuations of current flowing through the rectifier and earphones as shown at (B) of Fig. 182 are still much too rapid to actuate the diaphragm, since their frequency is now half that of the carrier current (the current flow during half of each cycle has been eliminated). Their effect on the receiver diaphragm however, is for each wave-train to give force by successive addition, as can be seen from the following:

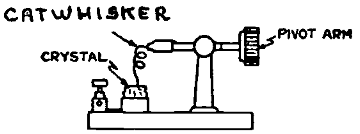
The first impulse "A", shown in part (C), passes through the earphone coils and produces a slight movement of the diaphragm. If the station is transmitting at say 200 meters, corresponding to a frequency of 1,500,000 cycles per second, then the time interval between two successive maximum values of current. as A and B, is one one-million five hundred thousandth part of a second. Obviously, since the diaphragm has inertia and stiffness, it is somewhat sluggish in action and cannot possibly make a complete vibration in this time, so the second impulse B will occur before the diaphragm has had time to spring back in place, and will therefore deflect it further. The next impulses C, is a weak one and the diaphragm will therefore spring back a bit. Impulse D, is stronger and causes the diaphragm to move outward again, etc. The result is, that the diaphragm does not move from its zero or initial position out to some other position and back for every half cycle of the high frequency current but instead, is deflected slightly in or out from its mean position by each pulse of current and therefore its motion follows more or less faithfully, the shape of the envelope wave of this current, as shown by the dotted lines at (C). This movement is shown at (D) for clearness. By referring back to (B) of Fig. 171, and to Fig. 172A, it will be seen that the movement of the diaphragm and consequently the sound waves it produces are exactly the same as the original sound wave in the transmitting station. The volume, and frequently the quality, of the sound in the phones is improved by connecting a small fixed condenser of about .0005 mfd. capacity across them, as shown in the circuit at (C) of Fig. 180.

The operation is then as follows: During the duration of one impulse A of the rectified current of (B) and (C) of Fig. 182, the current flows through the earphone coils and also charges this condenser. During the next half cycle no current flows through the detector. At this instant, the phone condenser being connected across the phone coils, and having an electric charge on it, partially discharges through them. The discharge current of the condenser is in the same direction as that of the impulse A. This acts to keep the diaphragm in position until the next impulse B comes along. The current flowing in the telephone receiver is then like that shown in the somewhat enlarged and exaggerated dotted line in (C). There is, then, during each wave-train a more continuous attraction on the earphone diaphragm, with resulting improved reproduction, since the diaphragm follows more nearly the outside curve or envelope of the current.

In earphones and loud speakers there is some capacity existing between the individual turns of wire on the coils, and the usual five-foot external connection leads supplied with earphones being close together, also form a condenser. This combined capacity is usually enough to give the above action; so that no additional phone condenser is necessary. In diagrams in future chapters the condenser will be omitted, although the reader should remember that a capacity really does exist there.

In this way, by the aid of a receiving antenna system, electrical resonance, a rectifier or detector, and a device for changing variations in an electric current into corresponding sound waves, we are able to successfully receive the electrical impulses sent out by radio transmitting stations, select the current of the station we want to hear, rectify this to pulsating direct current, and finally convert it back to sound waves similar to those of the original program, and which can be heard by the listener.

The crystal detector is sometimes called a *square law* detector since the current flowing through it varies as the square of the applied voltage.



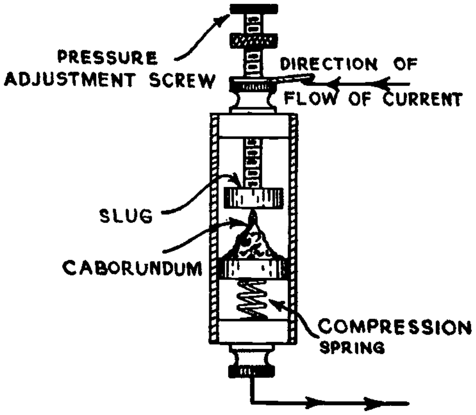


Fig. 183—**Left:** A simple crystal detector with a light catwhisker resting against a galena crystal.
Right: A modern semi-adjustable carborundum crystal detector with the crystal and contact slug held together under pressure.

Thus if twice the signal voltage is applied to it, the current flowing through it will be four times as much. Evidently such a device does not follow Ohm's law, because its resistance is not constant but varies with the applied voltage.

255. The carborundum crystal detector: The carborundum crystal detector has become popular as a rectifier in simple receivers due to its very stable operating characteristics. A commercial form of carborundum crystal detector cut open to show its parts is shown at the right of Fig. 183. Its construction and operation is as follows:

A crystal of carborundum is held in contact with a slug of metal under a pressure of about five pounds by a compression spring. The pressure may be regulated for best operation by the pressure adjusting screw which comes out at one end. The entire unit is enclosed in an insulated protective casing. This combination offers a very low resistance to the flow of current from slug to crystal, but presents a very high resistance to current flow from crystal to slug, thus acting as a detector or "rectifier".

Fig. 184 shows two practical circuits for a Carborundum detector. At A, the rectifier is placed across the entire tuned circuit. At B the rectifier is placed across only a portion of the circuit. The arrangement in B is preferable as it gives much better selectivity with very little loss in efficiency, when the tap is properly located.

256. Constructing a crystal receiver: A very cheap and efficient crystal set for earphone reception can be constructed from the circuit diagram of Fig. 185. A set of this kind is very useful as a preliminary receiver with which to learn the characteristics of tuning circuits in radio receivers, and is also a very good project for radio set construction before advancing to more involved and complicated vacuum tube receivers.

The primary coil P consists of a total of 32 turns of No. 28 B. and S. gauge double silk or cotton covered copper wire wound in a single layer on a tube four inches long and two inches in outside diameter. The coil is tapped at 2, 4, 8 and 16 turns. In winding the coil, twists should be made for each turn from which taps are made,

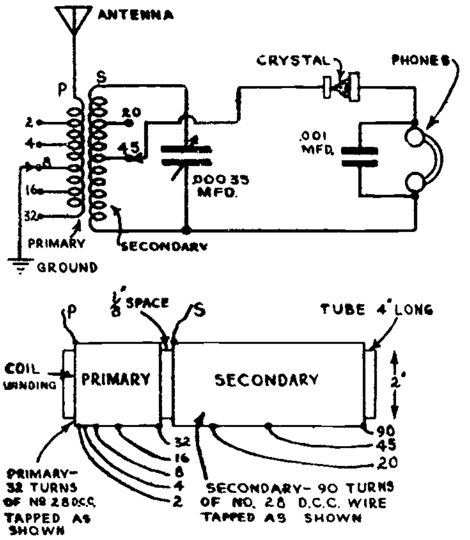


Fig. 184—Two carborundum crystal detector receiving circuits.

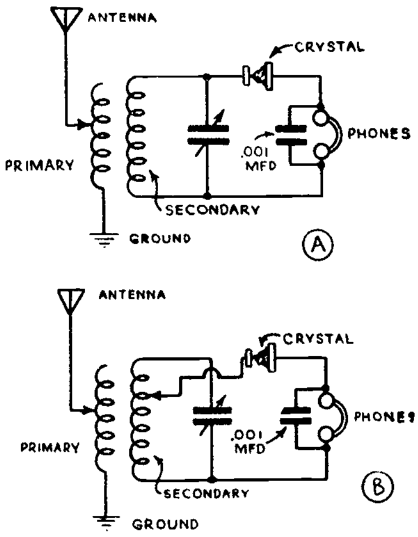


Fig. 185—A practical radio receiver with crystal detector (see lower left of Fig. 187)

so as to make connections to the taps easy. The secondary coil consists of 90 turns of No. 28 D.C.C. wire wound in a single layer on the tube next to the primary and separated from it by ⅛ inch. A tap is made at the 20th and 45th turn. The tap which gives best volume consistent with good selectivity should be used. An aerial from 75 to 100 feet long should be employed. Tuning is accomplished by the .00035 mfd. capacity variable condenser. The phones are by-passed by a .001 mfd. fixed condenser. A complete receiver of this kind is shown in the photograph at the lower left of Fig. 187. The layout of the various parts is shown. The Carborundum crystal should be connected as shown. Adjustment for best selectivity can be made by operating the set with the ground connected to the various taps of the primary coil in turn, until the best operating point is found.

257. Operation of the entire receiver: An idea of the various changes which take place in our simple crystal receiver may be gained from a study of Fig. 186. At the left, the weak modulated r-f signal is induced in the antenna circuit. Of course many signals of different frequencies are induced here by the various stations, but these are not shown here as they would confuse the diagram. Then this r-f voltage is strengthened by the gain of the tuned circuit, then the current is rectified by the crystal detector; the rectified current sent through the earphone coils produces vibration of the diaphragm in accordance with the peak values of the individual pulsations and produces the sound waves which are practically an exact duplicate of those originating in the broadcasting station.

258. Measuring crystal detector characteristics: The operating characteristics of crystal detectors or rectifiers can be determined very easily by the arrangement shown at (A) of Fig. 187.

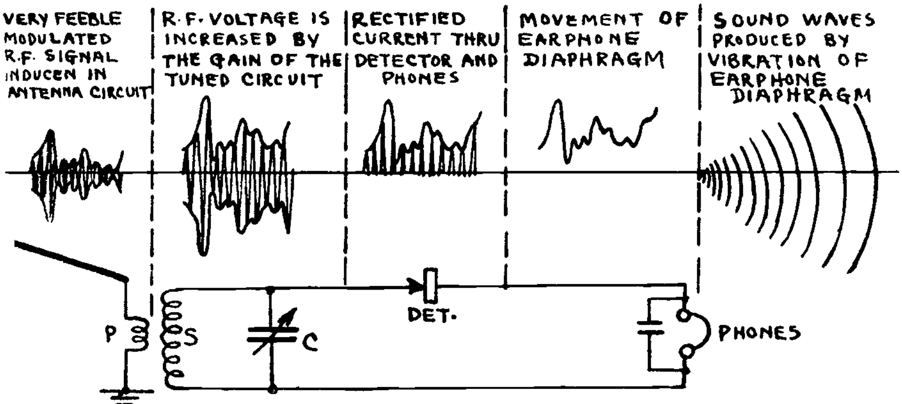


Fig. 186—Analysis of the changes which the received electrical energy undergoes in the various parts of a simple crystal-detector radio receiver.

The source of e.m.f. is a single dry cell. The voltmeter is a good low reading instrument sufficient to register the voltage of the battery. The milliammeter has a range of 0 to 1 milliampere. The 200 ohm potentiometer P is used to apply any definite voltage to the crystal. The milliammeter measures the current which the crystal allows to flow. The reversing switch S is used to apply either a positive or negative potential to the detector. The potentiometer is set for voltage steps of 0.1 volt and the corresponding currents are read on the milliammeter. This is done for both positive and negative voltages.

At (B), a graph of current flow plotted against applied voltage is shown for the carborundum crystal detector of Fig. 183. Curve O-B represents the current flow when e.m.f. is applied in the positive direction (slug to crystal). Curve O-C represents the current flow when e.m.f. is applied in the negative direction (crystal to slug). Notice that practically no current flows through the crystal in this direction (unless the applied voltage is made quite high). This illustrates the rectifying properties of this crystal arrangement.

Most crystal detectors can be roughly checked for rectification by connecting a dry cell (1½ volt), pair of phones and the detector in series. A strong click should be heard when the detector is connected in one direction, and almost no click when reversed. This indicates that the detector rectifies properly.

259. Limitations of crystal receivers: The simple receiver circuits discussed thus far, furnish a system of radio reception by which sound programs can be heard, and in which the volume of sound produced depends *entirely* on the strength of the electric fields acting on the receiving antenna. The energy of the ordinary transmitter is radiated out in all directions around the transmitting antenna. Owing to the comparitively small size of the receiving antenna, the latter can cover only an extremely small part of the large area over which this energy is spread, so that the energy actually imparted to any receiving antenna is very very small, and the voltages and currents induced in the antenna circuit are very feeble. It is evident that simple crystal detector radio receivers of the type just described cannot be used for long distance reception, be-

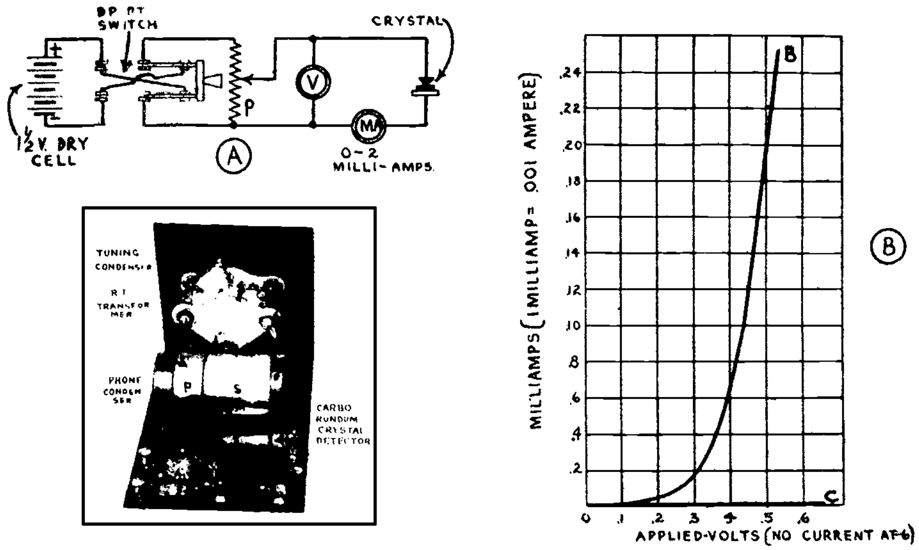


Fig. 187—(A): Rectifier test circuit which may be employed to test the rectifying properties of a rectifier. (B): Rectification characteristics of a carborundum rectifier. (Lower left): The complete crystal-detector radio receiver whose circuit diagram is shown in Fig. 185.

cause the received currents will not be strong enough to operate the earphones.

The use of earphones is unpopular, as people desire to hear the sound programs in comfort with loud speakers which produce enough volume to fill good sized rooms. Loud speakers require a stronger operating current than do ordinary earphones since they set a greater volume of air in motion and produce larger amplitudes of sound vibrations, so amplifiers have been developed to amplify the received radio voltages to make loud speaker operation possible. These employ vacuum tubes in their operation. The crystal detector, while producing remarkable clarity of reception, is unable to handle either very weak or very strong impulses of current satisfactorily and simple crystal receiver circuits do not pass enough energy on to a loud speaker to operate it satisfactorily. To be able to listen to distant stations and operate a loud speaker we must strengthen or amplify the incoming signal voltages.

Crystal detectors have been superseded almost entirely by vacuum tube detectors, due to their greater sensitivity, ease of adjustment, and property of not only rectifying, but also amplifying at the same time.

The rectifying ability of a crystal is an inherent property of the crystal and cannot usually be altered or improved. The point of best selectivity must be determined by trial by moving the catwhisker over the surface of the crystal. In most cases, this point is never located. The adjustment is not permanent, and heavy currents such as those received from powerful nearby broadcasting stations may make the detector inoperative by setting up a comparatively great amount of heat at the contact point; thus oxidizing the catwhisker and destroying the conducting properties. The use of the Carborundum crystal detector eliminates the adjustment difficulties but does not satisfy the amplification requirements for loud speaker operation. Some receivers have been devised to use a carborundum crystal with radio and audio frequency amplifiers employing vacuum tubes. Such *hybrid* receivers are capable of very fine performance if correctly designed but their use is not very widespread.

The use of vacuum tubes makes it possible not only to perform the function of detection or rectification, but also to build up the strength of the feeble voltage impulses induced in the antenna circuit to practically any degree so that one or more loud speakers may be operated with ample volume to fill a room or an auditorium with sound. We will now study the theory of operation, and construction of the various types of vacuum tubes employed in modern radio equipment and later we will study the various circuits in which they are employed.

REVIEW QUESTIONS

1. What is the approximate frequency range of the sound vibrations in (a) speech, (b) music?
2. What is the approximate frequency range of the carrier currents used in radio broadcasting stations in the band between 200 and 550 meters?
3. What sets up the voltages and current in the antenna circuit of a radio receiving station? Explain the action in detail.
4. Station WEAF in New York City transmits with a power of 50,000 watts, radiating it out into space in all directions. Why does the amount of signal power picked up from this station's field by a receiving antenna amount to only a few microwatts?
5. What is the purpose of (a) the receiving antenna; (b) the connection to the earth or "ground"?
6. What is a counterpoise ground, and why is it used? Draw a diagram showing an ordinary aerial and counterpoise ground connected to a radio receiving set.
7. What is the receiving antenna made up of? Would copper wire having an outer covering of ordinary insulation be satisfactory? Why?
8. Explain how the antenna, lead-in wire, ground wire, and ground form a condenser.
9. What would be the effect on the total antenna circuit capacitance, of connecting a small fixed condenser in series with the lead-in wire? What is the effect of connecting a small condenser between the antenna and ground? Explain!

10. Explain with diagrams, how current is able to flow in the wire circuit between a receiving antenna and ground, when apparently this is an open circuit.
11. Show by diagrams and explain, the difference between a "tuned" and an "untuned" antenna circuit.
12. What is an aperiodic antenna circuit? What are its advantages and disadvantages?
13. What is meant by "tuning" a radio receiver and how may it be accomplished? Why is tuning necessary? State two benefits received from tuning a radio receiving circuit.
14. Under what conditions of inductance and capacitance value is the tuned circuit in a radio receiving circuit said to be in resonance with, or tuned to, the frequency of the incoming signal impulses of the station it is desired to receive?
15. What value of capacitance is required with a 200 microhenry coil to form a tuned circuit resonant at 600 meters?
16. Explain how a voltage gain is obtained by means of a series tuned circuit.
17. Explain two objectionable effects caused by excessive resistance in a tuned circuit.
18. Why are the transformers used in the radio-frequency circuits of radio equipment usually constructed in air-core form?
19. What is meant by the process of "detection" and why is it necessary in a radio telephone receiver?
20. What function does the crystal detector perform in a simple crystal type radio receiving set? What is the function of the earphones or loud speaker?
21. What is the purpose of (a) the permanent magnet; (b) the coils, (c) the diaphragm, of an earphone? How are the current impulses changed into sound waves?
22. Explain why crystal detectors are not used in receivers which are to operate loud-speakers.
23. What is induced first in a receiving antenna by the action of the passing fields, voltage or current?
24. How does the action in a resonant tuning circuit make it possible for you to hear the signals from one station, and make all others so weak that they are not heard?
25. What electrical devices are necessary to form a tuned circuit?
26. Show by a circuit diagram, the connections of the following parts to be used in a simple crystal detector receiving set, radio frequency transformer, variable tuning condenser, crystal detector, earphones, earphone condenser, antenna, ground. Explain the operation briefly, starting at the antenna and following through to the earphones.
27. Explain the action of the phone condenser of small capacitance connected across the earphones or loud speaker of a receiver.

CHAPTER 17.

ELEMENTARY STUDY OF THE VACUUM TUBE

IMPORTANCE OF VACUUM TUBES — OUTLINE OF STUDY OF THE VACUUM TUBE THE EDISON-EFFECT — ELECTRONIC EMISSION FROM SOLIDS — PRODUCING ELECTRON EMISSION FROM SOLIDS — PRODUCING ELECTRON EMISSION BY HEATING — PRODUCING ELECTRON EMISSION BY LIGHT — ELECTRON EMISSION BY ELECTRON BOMBARDMENT — ELECTRONS FROM GASES — IONIZATION — CHOICE OF ELECTRON EMITTER — TWO-ELECTRODE VACUUM TUBE — SATURATION CURRENT — SPACE CHARGE AND SCREEN GRID TUBE — TWO ELECTRODE RECTIFIER — THREE ELECTRODE TUBE — AMPLIFYING PROPERTY — TUBE CHARACTERISTIC CURVE — TYPES OF TUBES — REVIEW QUESTIONS.

260. Importance of the vacuum tube: The basic idea of the thermionic vacuum tube has probably been the most important single invention in the development of the radio art, for without it, the high power—high quality radio transmission and reception we are all accustomed to today, would be impossible. It is used in radio transmitting stations for amplifying the speech currents set up in the microphone circuit; and for generating and modulating the high frequency carrier current which produces the electromagnetic radiations from the antenna. In modern radio-telephone receivers, vacuum tubes are employed for greatly amplifying and rectifying the weak signal voltages set up in the receiving antenna, in order to make loud speaker operation possible. They are also employed for rectifying the a-c current supplied by the a-c electric light circuits for the operation of radio receivers. The transmission and reception of television signals also depends entirely upon their use to perform these functions.

Hundreds of new applications are daily being found for various forms of vacuum tubes and their associated circuits in all branches of industry outside of the field of radio. As we shall see when studying some of these uses in a later chapter, they are being employed for such functions as, amplification; rectification; detection of current or voltage impulses; operation of counting and sorting devices, alarms and signal systems; controlling large amounts of energy and machinery; measuring all sorts of quantities; converting electrical energy for high voltage transmission in d-c form; etc. There are seemingly an endless variety of uses for this marvel of metal, glass, insulation, and empty space, and any person who expects to associate himself with either the radio or electrical industry must be on intimate terms with at least the simple fundamental theory upon which the vacuum tube operates. It will be to his advantage to know, in addition to this, the various forms employed in industry, together with the special circuits in which they are employed in commercial devices.

Many forms of vacuum tubes are constantly being developed to perform most suitably the particular tasks which they are intended for. Thus we hear the terms 2-electrode, 3-electrode, 4-electrode, 5-electrode, a-c, d-c, screen-grid, variable-mu, high-mu, pentode, power, rectifier, thyra-

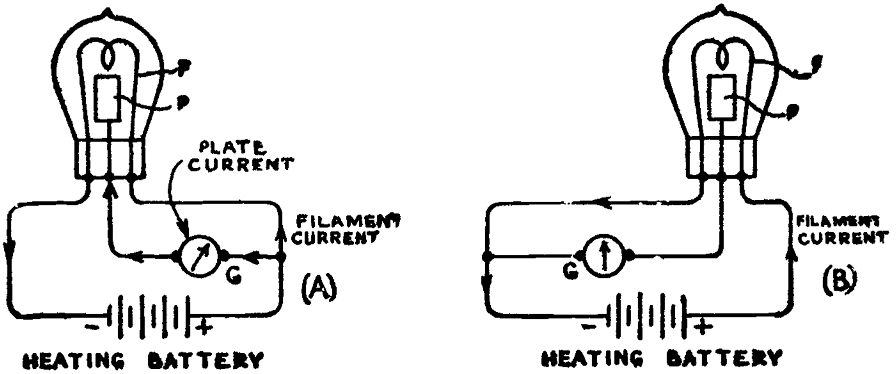


Fig. 188—The Edison-effect, which depends for its action, on the emission of electrons from an incandescent filament.

tron, grid-glow, photo-electric, etc. applied to the various forms of vacuum tubes in use today. We will first study these simple principles of operation before passing on to a discussion of the various forms in which they are constructed and the special circuits in which they are employed.

261. Outline of study of the vacuum tube: To the student attempting a serious study of radio, or that of vacuum tubes, for the first time, the fact that there are so many types now made and used, must make it seem like an almost impossible task to try to understand the construction and operation of all of them. Fortunately, this is not so, for as we will now see, they all operate on the same fundamental principles. Once these principles are understood, the subject merely resolves itself into a systematic study of the particular mechanical construction features employed in the various types of tubes used, and the electrical characteristics which result from these special forms of construction. By pursuing the study in this way, the subject will be found to be not only very much simplified, but extremely interesting as well, for we will be dealing again with those fascinating little fellows, the "electrons". Since the emission and flow of electrons forms the basis of the operation of all electronic vacuum tubes, this phase of the subject will be studied first.

262. The Edison-effect: Almost fifty years ago (in 1883), Thomas A. Edison was at work on the development of the incandescent electric lamp which we now use for lighting purposes. Edison was troubled by frequent burnouts which occurred at the ends of the carbon filaments he was using. Investigation disclosed that nearly all of the lamp failures occurred at the positive ends of the filaments. He constructed a special lamp in which he placed a metal plate terminal P, between the loop of filament wire, as shown in Fig. 188. The filament was heated by current from a battery or generator as shown. He found that when he connected the plate to the "positive" filament connecting wire, with a sensitive current indicating galvanometer in series, as shown at (A), a current flowed through the shunt circuit PFG thus formed, as indicated on the galvanometer. If the plate was connected to the "negative" filament connecting wire as shown at (B), no such current flowed, as shown by the fact that the galvanometer did not deflect. Furthermore, the direction of deflection of the galvanometer pointer in the former case showed that the current appeared to flow always from the *plate to the filament* when the plate was made positive, and never in the opposite direction. The current ceased as soon as the filament was allowed to become cold.

Here was a real mystery, for at that time nothing was known of the emission of electrons from hot bodies. A current was apparently flowing inside the tube, from the plate across the vacuum to the filament. A vacuum had always been thought of as a perfect electrical insulating medium because it contains nothing to conduct electricity. It is true, that a perfect vacuum without electrons in it, is a better insulator than any known substance; but at that time Edison did not know of course that there actually was something in between the plate and filament wire of his lamp. The action just described is now known as the "Edison Effect". Edison was too busy with the development of his lamp to spend much time investigating this effect at the time, but he made a record of it, and its causes remained a mystery until in 1899, J. J. Thompson showed that the phenomenon was due to electrons or particles of negative electricity given off by the filament when it was heated. The explanation now accepted in the light of our modern knowledge of electrons and the atomic structure of matter is based on the electron emission from solid bodies.

263. Electronic emission from solids: We have already studied in Articles 16 to 18, that every atom of any body is composed of one or more planetary electrons rotating around a central nucleus co sisting of electrons and protons as shown in Fig. 17. We will now review this briefly:

Metals and other conducting substances are supposed to have many *free* electrons which are constantly wandering around, mostly through the comparatively large spaces between the atoms. If an e. m. f. is applied to a conducting material, a drift of these electrons takes place in a definite direction along the conductor, at a speed of about 300 to 125,000 miles per second depending on the intensity of the electric forces of the e. m. f. applied, and we have what we commonly call *a flow of current*. Unfortunately, the actual direction of the movement or flow of the electrons is just opposite to that in which the resulting current is conventionally said to flow (see Article 25), since the rules regarding directions of currents through electric circuits were formulated arbitrarily before electrons were even thought of.

Under ordinary conditions of temperature, the electrons and atoms of a substance are in a constant state of motion and possess some energy (kinetic energy) due to this motion. They do not escape from the substance, because according to a theory advanced by O. W. Richardson in 1901, there exists at the surface of the substance a force which tends to keep even the free electrons from escaping. (Of course the electrons in each atom are held to it by the force of attraction of the positively charged nucleus.) In order to escape from the surface of a substance, an electron must do work in overcoming the force which tends to hold it in the substance, just as a horse does work in attempting to draw away from a loaded wagon. This amount of work must be done at the expense of the kinetic energy of the electron. For all known substances, it would require far more energy than most of the electrons possess, for them to escape from the body at ordinary temperatures, so they are held within the substance and practically no electrons are emitted by the body. It is possible, however, to impart sufficient energy in some form to the electrons of many substances by some external means, so as to make them able to shoot out of (or be *emitted* from) the body. Of course, as soon as an electron is emitted, the unbalanced electrical force in the body tends to attract it back again, so that the final movement of the emitted electron depends upon what other external forces are acting on it at that time.

264. Producing electron emission by heating: It has been found that the forcible emission of electrons from a body (commonly called *electronic emission*) can be produced in several ways.

It is interesting to note that all of these methods involve imparting of electromagnetic radiations to the electrons of the body, in order to increase their kinetic energy enough to enable them to overcome the restraining forces. These forms of electromagnetic energy are heat, light, and moving electrons.

Probably the most common method is to heat the body in some manner, either by the application of a hot flame as shown at (A) of Fig. 189, by passing an electric current through it as shown at (B), or in any other way. It is interesting to note that heating by a gas flame was employed by De Forest in his original three-electrode vacuum tube. Heating by means of an electric current is now used exclusively, because of its convenience. In some vacuum tubes the electron emitter is heated by current from a battery, in others it may be heated by a-c or d-c current from the electric light circuit.

When the body is heated by any means, the electromagnetic radiations of energy, which really constitute what we call heat, go to the body and are given up to the electrons. This increases the speed of movement of the electrons and thereby increases their kinetic energy. As the imparting of the energy to the electrons is continued in this way by sufficient heating (raising the temperature of the body to a high enough value), some electrons will finally acquire enough kinetic energy to enable them to break away from the restraining forces, and shoot out from the body into space, that is, they are *emitted.* As the heating is continued, more and more of them acquire the necessary amount of energy needed to overcome the restraining forces, and they are emitted. The result is, that a steady stream of electrons is obtained from the hot body as shown. The rate of emission of the electrons from a body is approximately proportional to the square of its temperature above that of red heat. It should be thoroughly understood that the heat for the emission can be supplied by any means we may want to use.

The emission of electrons from a heated body may be likened to the evaporation of water. If we raise the temperature of a vessel full of water by heating it, the

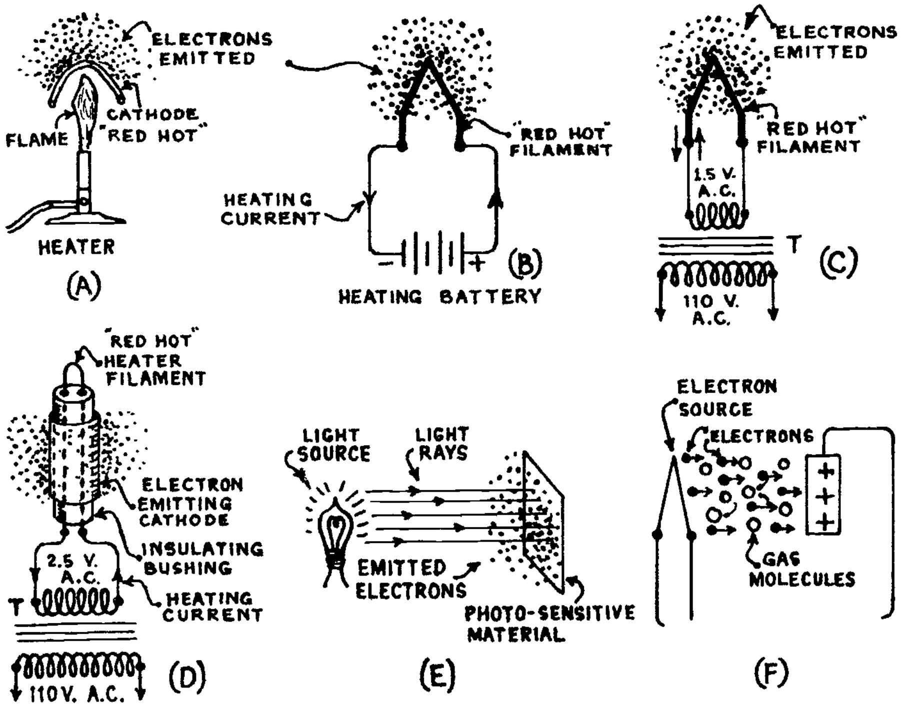


Fig. 189—Various ways in which bodies may be made to emit electrons. (A) heating directly with a flame; (B), (C) heating directly with an electric current; (D) heating indirectly by means of electric current; (E) by photo-electric action of light; (F) by electron bombardment.

agitation of its molecules increases and when the temperature commonly known as the "boiling point" is reached, the molecules have gained enough kinetic energy to enable them to break through the surface tension of the liquid and shoot out into the atmosphere in the form of tiny particles of water vapor. Of course this action is not exactly like that of electron emission for in this case droplets of water, each containing many atoms and electrons are boiled off; in the case of electron emission only the tiny single free electrons are emitted.

Emission of electrons caused by applying heat to a body is called *thermionic* emission to distinguish it from emission produced in other ways. Devices in which this is made to take place are commonly called *thermionic* devices. The body which emits the electrons is generally called the *electron emitter* or the *cathode.* The body to which the emitted electrons may be attracted, is called the *plate* or *anode.* These terms should be remembered. In almost all practical *thermionic* devices, the heating of the electron emitting body is made to take place by means of the flow of electric current through a conductor which may, or may not be, the actual electron emitter. At (B) is shown the method used for producing electron emission in the ordinary forms of battery-operated vacuum tubes. The heating current, supplied by a primary or storage battery, flows through a filament wire which gives off the electrons when it is heated to a red heat. At (C) the a-c heating current from a step-down transformer, flows through the electron-emitting filament. In some applications of thermionic emission it is preferable not to have the heating current flow through the body which is emitting the electrons. In these cases, it may flow through a separate heater device placed in mechanical contact with, or near, the electron-emitting substance, as shown at (D). This construction is employed especially when the heating current is obtained from an a-c source such as an a-c electric light circuit. In this case, it is common to use a step-down transformer T, to step down the 110 volts of the line to the low voltage required for the heater filament, as shown at (D). Here the heater is used merely to heat up the electron emitter by the conduction and radiation of heat from it. It performs no other function, although it may incidentally give off some electrons itself due to its high temperature.

This construction is used in the popular separate-heater types of vacuum tubes such as the 227, 224 and 235, designed to be heated with alternating current from the electric light circuit, as well as in the 236, 237 and 238 types designed especially for use in automobile radio receivers or d-c electric receivers, as shown at (D). The current flows through the heating filament bent in hairpin shape, which imparts its heat energy by conduction and radiation to the separate metal cathode or electron emitter which surrounds it, but which is electrically insulated from it by the insulating bushing.

The filament wire runs through two tiny holes drilled in the insulating bushing. The latter is made of some ceramic material such as "isolantite" which is a good heat conductor and also a good insulator even when it is heated to a red heat during normal operation by the filament. It conducts this heat to the closely fitting metal sleeve on its outside. The sleeve is coated with barium oxide or some other material which emits electrons freely at moderately high temperatures, and so acts as the cathode. In some tubes of this type designed so the cathode will be heated to its emission temperature quickly when the heater current is turned on, the insulating bushing is made thin to reduce its mass so it will heat up more quickly. In some quick-heater tubes, the insulating bushing has been omitted altogether, the designers relying entirely on the small space between the heater filament and the metal cathode sleeve, to keep the heater filament from touching, and making electrical contact with the metal cathode sleeve. These tubes heat up very quickly, but short-circuits frequently occur when the filament or other parts are bent out of line by accidental severe jars or shocks during shipment.

Some substances do not emit electrons in any appreciable quantities, even though they be heated to extremely high temperatures. The electron-emitting characteristics of various substances will be studied later.

265. Producing electron emission by light: It has been found that a similar electronic emission occurs when light rays of certain frequencies, colors, or wavelengths, are made to fall upon certain materials, as shown at (E) of Fig. 189. This is known as the *photo-emissive* effect; the emission of electrons by this method is known as *photo-electric emission,* and devices employing this effect are known as *photo-electric devices.* The *photo-electric cell*, or *tube*, employed in television and sound picture equipment, and in many commercial counting, sorting, and controlling devices operates on this principle. The principles of photo-electricity have been known to the scientific world for over 40 years, but it was not until the recent development of television and sound pictures that practical photo-electric cells were made available commercially.

The energy of the electromagnetic light rays striking the substance is imparted to its electrons, enabling them to acquire sufficient energy and velocity to overcome the force of attraction at the surface of the substance, and escape with a velocity which depends on the energy in the light rays and the amount of energy they must expend to overcome the surface force. Those which happen to be near to the surface have to overcome only the surface force, while those further in the interior will have to do an extra amount of work in forcing their way out.

The photo-electric effect is very interesting because its iscovery has resulted in further strengthening the electron theory and the quantum theory explained in previous chapters. It has been found by experiment that the maximum velocity of emission by this effect is independent of the temperature of the cathode and is also independent of the *intensity* of the light with which the cathode is illuminated. If the intensity of the light is increased, only the *number of electrons emitted* increases, but their velocity stays the same. The frequency, color, or wavelength of the light (see Fig. 163) is the only factor that influences the velocity of the emitted electrons, when considering any one substance. The higher the light frequency (the nearer the light is toward the ultra-violet end of the spectrum) the higher is the velocity of the emitted electrons. For a given light frequency (color), the emission depends on the electron affinity of the substance upon which the light is acting. Therefore all substances do not give off electrons with equal ease when exposed to light.

Zinc gives off electrons quite freely only when exposed to light rays of very high frequency, such as ultra-violet light. Other metals such as potassium are very sensitive to light in the visible part of the spectrum. Potassium is therefore used in some photo-electric cells where its function is to emit electrons in proportion to the amount of ordinary white light that is permitted to fall upon it. Other of the alkali metals which emit electrons when subjected to light rays are sodium, lithium, caesium and rubidium. These will be studied later when a detailed study of photo-electric cells is made in Chap. 32.

The source of light may originate in some common light source such as an incandescent lamp, daylight, etc., or may originate in fluorescent chemicals which have been caused to emit the required light by reason of previous exposure to electromagnetic radiations from some other source.

266. Electron emission by electron bombardment: Electrons may also be forced out of a body by the impact of other electrons projected against its surface. This action is called *secondary emission.* Thus, X-rays are electromagnetic radiations produced by causing a stream of electrons to impinge on a target. In order to produce penetrating X-rays, the velocity and frequency of the stream of electrons must be quite high, which means that the applied voltage causing the movement of the stream of electrons must be quite high. At the lower voltages employed in ordinary vacuum tubes, the action of the electron stream impinging on a metal plate may cause a considerable *secondary emission* from the plate, especially where the plate voltage is high. This will be referred to again in Art. 318. When the velocity with which the electrons strike the metal plate increases beyond a certain critical value, one primary electron can knock out more than one secondary electron from the plate. This is the principle on which the *dynatron* operates, (see Art. 636).

267. Electrons from gases, ionization: If a stream of electrons is caused to move through a gas, they will bump into the larger and heavier atoms of the gas. (The hydrogen atom, which is the simplest and lightest of all atoms (see Fig. 17) has a mass approximately 1,800 times as great as the mass of the electron. The masses of the more complex atoms of other chemical elements is proportionately greater.) If the electrons are moving with a high enough velocity, they will split up the atoms of the gas when they collide with them and electrons will be detached from the atoms, leaving the remainder of each atom with an unbalanced positive charge due to the loss of the negative charge of the electron knocked off, as shown at (F). This causes these atoms to be ionized positively, and the freed electrons join the stream of moving electrons under the directive force of the applied e.m.f., possibly colliding with some atoms on their way and thus helping to liberate more of them. The positive ionized atoms are attracted toward the source of electrons by the negative charge and move slowly toward it. The gas is then said to be *ionized.* Electrons are detached from the gas atoms by collision with them, so this process is usually referred to as *ionization by collision.*

The least energy with which an electron can collide with an atom and completely detach an electron from the atom of any gas or vapor is usually expressed in terms of the voltage required to impart enough velocity to the moving electron to enable it to strike the atom with sufficient force to dislodge an electron from it. This is known as the *ionization voltage.* The ionization voltage required to ionize mercury vapor is 10.4 volts, for helium it is 29 volts, for hydrogen it is 13.6 volts, etc.

If the electron strikes with insufficient velocity and force to completely dislodge an electron from the atom, against the attractive force of the nucleus, the energy of the striking electron is gained by the gas atom. The energy gained by the gas atom manifests itself at first by a displacement of one of the electrons of its inner orbit, to an outer orbit. This condition of instability of the atom does not last long, and the displaced electron will soon return to the inner orbit. Since an electron in an outer orbit possesses more potential energy than one nearer the nucleus, it must get rid of this energy as it moves from the outer orbit back to an inner one. This takes place in the form of a small quantity of radiated electromagnetic energy (a quantum) but it is of such a nature that it will not produce the sensation of sight.

If the electron strikes the atom with sufficient velocity to dislodge an electron to a point outside of the atom beyond where any possible orbits of its electrons exist, then in this position the potential energy of the electron is a maximum and it will be attracted along with the moving stream of electrons toward the source of positive charge which is causing the motion. Meanwhile, the positive ion will migrate in the opposite direction, toward the source of electrons, and when it gets near to it, it will attract an electron to it with sufficient velocity to bring it into one of its orbits. In doing so, it radiates the excess energy in the form of light of a characteristic color depending on the chemical nature of the gas. Thus, in the neon gas used in the familiar electric display signs which possess the characteristic red or pink light, the light is due to the ionization of the neon gas in the tube, caused by the application of a voltage to it to cause the electron stream to flow through the gas at a high velocity. The blue glow observed in vacuum tubes that are not well evacuated is also due mostly to the impact of the electron stream on the gas atoms which may be present. This fact is used as a test for the presence of gas, during the evacuation of vacuum tubes.

The tungar rectifier tube employed in battery chargers operates by ionization of the argon gas it contains. The electron stream is furnished by a filament which is heated to incandescence by an electric current. A positive potential applied to a carbon plate in the tube attracts these electrons at high velocity. On their way they collide with atoms of the gas and liberate many more electrons by collision. These liberated electrons are immediately attracted by the plate, and move to it. This makes the electron stream and the current flowing through the rectifier and available externally for useful purposes, much greater than if no ionization took place.

268. Choice of electron emitter: From the foregoing, it is evident that a stream of electrons could be obtained for use in vacuum tubes in either of the three ways described. Up to the present time, the method of heating a suitable substance which gives off electrons when it is heated to a red heat by the passage of an electric current through a heating filament, has been used exclusively in vacuum tubes. Much research work is being carried on toward the development of vacuum tubes in which electrons are emitted by some method less crude and less wasteful of energy than by the application of heat.

Some experimental tubes have been produced in which an ionized glow discharge was employed to produce a field between a cathode and a plate. Lately, the principle of photo-electric emission has been applied to produce some very interesting experimental photo-electric vacuum tubes. In one of these, a single source of ultra-violet light placed at the center, illuminates as many as five independent cathodes placed around it, each one being coated with a light-sensitive material which gives off electrons freely due to the action of the light shining upon it. One of the problems encountered in this work, is that of increasing the very limited amount of electrons emitted by photo-electric devices of the present ordinary design with the photo-sensitive materials now available. The current flowing in photo-electric cells is in the order of *microamperes* rather than the current of *milliamperes* which exists in ordinary thermionic vacuum tubes. Such small currents are troublesome to handle, for slight variations affect them greatly. Another problem in these devices, is the development of an economical source of absolutely steady light for causing the electron emission. Any variation in the *intensity* of the light at once causes a change in the electron emission, resulting in a change in the current through the device. Also the methods of producing light at the present time are much less efficient from the standpoint of the loss of energy, than those of producing heat. Nevertheless, new developments along these lines may be expected in the next few years, for the elimination of the heaters and the heater current in modern vacuum tubes would result in the elimination of many of the troubles and ills to which radio equipment is now subjected.

Since our present forms of vacuum tubes employ electrons produced by heating certain substances, we will now study their operation.

269. Two-electrode vacuum tube: In 1896 Dr. J. A. Fleming investigated the "Edison effect" described in Article 262. His work resulted in the development of the two-electrode tubes shown in Fig. 190. It was referred to at that time as the *Fleming Valve*, and the term *valve* is still used in Europe, to designate what in America is familiarly known as a *vacuum tube* or *electronic tube*. The term *valve* is roughly descriptive of the real operation of the tube.

As shown at (A) of Fig. 190, a V-shaped filament is connected across the terminals of a battery (called the "A" battery), or other source of e.m.f., with an adjustable resistor R, in series, to control the current flowing through it, and therefore its temperature. The tungsten filament wire, is mixed or coated with a substance such as barium oxide which emits electrons freely when heated to a low red heat. In order to prevent rapid oxidation and burning up of the filament when it is heated to incandescence by the current flowing through it, it is sealed in a glass bulb from which every trace of air has been pumped out. This is represented by the circle around the tube elements in the diagram. The ends of the filament are sealed into the glass bulb, to prevent any leakage of air. Removing the air from the bulb also performs the function of removing these comparitively large air or other gas atoms from the space surrounding the filament, for they, having a mass over 1,800 times as great as that of an electron, would block and interfere with the emission and movement of the electrons, as explained later. When the filament is heated, it will emit electrons in rapid motion. These will form a sort of miniature cloud around it, as shown at (B) of Fig. 189, much like the cloud of water vapor which hovers over a pan of boiling water. These electrons have no particular place to go, and since they are all negative charges of electricity, return to the filament. The collection of all of these negative charges of the electrons in the space around the filament forms a rather strong negative charge

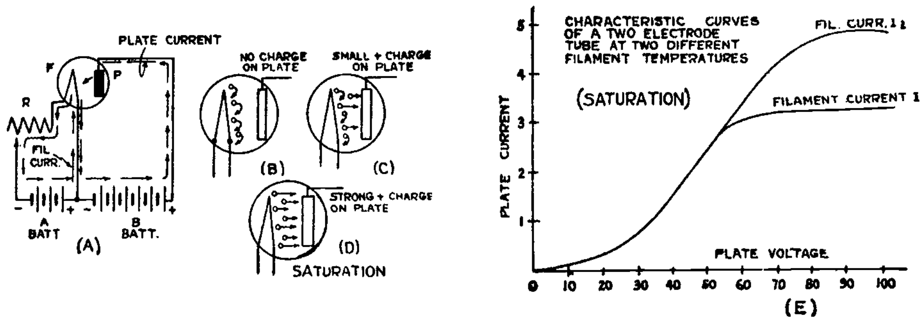


Fig. 190—Arrangement of the elements and action of the 2-electrode vacuum tube. The plate saturation characteristics produced by complete attraction of all of the emitted electrons is shown at the right.

called the *space charge*, which will tend to repel back to the filament, those negative electrons which are being emitted after them (like charges repel each other).

If now, a metal plate P, or second electrode is sealed into the glass bulb as shown at (A), we have a duplication of the effect which puzzled Edison. If the plate is kept at a positive charge or potential with respect to the filament, either by connecting it to the positive terminal of a second battery (called the "B" battery), or to some other source of unidirectional e.m.f., as shown, to make the charge stronger, it will attract the negative electrons to it (a positive charge attracts a negative charge) as soon as they are emitted from the filament. If the plate is made negative, that is a negative charge is put on it, by connecting it to the negative leg of the filament circuit or to the negative terminal of the B battery, with its connections reversed, it will repel the electrons back to the filament, and none will go to the plate. We are not interested in the latter connection, for tubes are not operated this way in practice. It is evident that the negative end of the B battery may be connected either to the negative end of the A battery or to the positive end of the A battery. Very little difference results from either connection. In some battery operated receivers the A+ and B— terminals are connected together, in others the A— and B— go together. The latter method has several advantages, one of which is convenience in grounding the A— and B— lines both to the metal chassis of the receiver.

With the plate positively charged, a steady stream of electrons will be attracted from the filament to the plate and will then continue their journey around the circuit from the plate to the B battery, through the B battery from the + to the — terminal, up through the filament leg on the right, and back to the filament. We thus have a *circulation of free electrons from filament to plate* and back through the B battery to the filament or electron emitter again, just as many returning every second as are emitted during that second, i.e., there are no electrons lost or gained. This circulation of electrons in the *plate circuit* constitutes the flow of electric current, called the *plate current* or *emission current*, in the opposite direction, i.e., from *plate to filament*, for the reasons mentioned in Article 25. It is important to keep in mind always this difference in direction between the plate current flow and the electron flow in the vacuum tube and all other electric circuits. At (A) in Fig. 190, the directions of both the filament *current* and the plate *current* flows are indicated by the arrows (from the + terminal of the source of e.m.f. to the — terminal), at the left of Fig. 191 the relative directions of both the electron flow and plate current flow in the plate circuit are indicated. If a milliammeter were connected between the B battery and the plate, it would indicate a flow of current in the plate circuit, just as the galvanometer used by Edison in his test indicated.

It is evident that the apparent mystery in the effect which Edison noted in his incandescent lamp was really due to the fact that while it was then supposed that the space between the filament and the plate was absolutely empty, actually it was filled with moving electrons emitted by the hot filament, and constituting the flow of electric current which was indicated on his meter. No electrons are usually given off by the plate, because it is maintained at a low temperature.

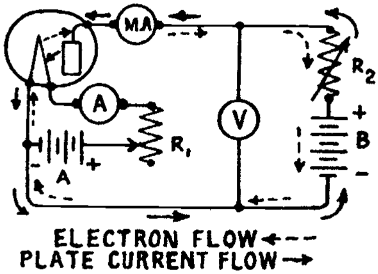
270. Saturation current: Let us study this interesting device further, with particular regard to the manner in which the plate current varies and the means by which such variations may be brought about. Obviously, the number of electrons which pass in a given time across the space from the filament to the plate and then around through the external plate circuit back to the filament, is limited by the number of electrons emitted by the filament and by the ability of the plate to attract the electrons so emitted. The electron emission for a given filament, depends on its temperature, which in turn depends upon the heating current flowing through it. The ability of the plate to attract the negative electrons depends upon the difference of electrical potential maintained between the plate and the electron emitter by the B battery.

Due to the fact that there is a uniform I × R drop through the filament due to its resistance and the current flowing through it, different points along the filament are at different potentials, so that we must decide upon some one definite point on the filament as the reference point from which all differences of potential in the tube shall be measured. It has become standard to consider this point to be the *negative end* of the electron emitter or cathode. In tubes of this kind, since the cathode is the filament, the negative terminal of the filament is considered as the reference point from which all differences of potential are measured. Thus, in speaking of the plate potential or voltage, we mean the difference in potential between the plate and the negative terminal of the filament, etc. (In the case of separate-heater type tubes, the *cathode* is the potential reference point in the tube.)

It follows then, that the plate current is limited by the filament current and the plate potential. *Therefore, the plate current of a two electrode tube may be varied either by varying the plate potential or the filament current.*

Let us next investigate just how the plate current changes with variations of either of these two factors:

Experiment: Connect up the two-electrode tube as shown at the left of Fig. 191. (An ordinary 3-electrode type 201-A tube can be used with its grid terminal connected to its plate terminal so they both perform the function of a plate. This will then be equivalent to a 2-electrode tube.) The actual set-up of the simple apparatus for this test is shown in the photograph at the right of Fig. 191. A variable resistance R_1 having a maximum resistance value of about 30 ohms is connected in series with the 0-0.5 amp. d-c ammeter in the filament circuit, as shown. This rheostat is the one shown in the foreground in the photograph. A variable high resistance (about 0-50,000 ohms) shown in the rear, is connected in series with a B battery or other source of steady d-c potential of about 90 volts, and a voltmeter having a range at least from 0-100 volts are connected as shown. Set the filament current constant at about .2 amperes, and starting with zero plate voltage, take readings on the plate milliammeter and voltmeter for each increase of 10 volts in the plate potential. Set the plate potentials carefully by means of the resistor R_2. Now set the filament current fixed at 0.25 amperes and repeat the test. It may be necessary to increase the plate voltage above 90 volts in order to reach the condition where the plate current increases very little with each 10-volt increase of plate voltage. Each test should be continued until



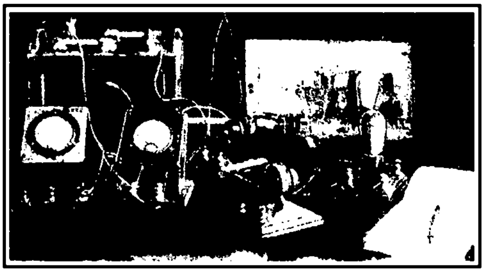


Fig. 191—Left: Apparatus connections for measuring the characteristics of a 2-electrode vacuum tube.
Right: Actual set-up of the apparatus for this test.

this condition is reached. If it is necessary to go above the voltage limit recommended by the manufacturer for the tube used, keep this voltage applied only long enough to make the test. Now plot a graph with plate voltage as abscissae (horizontal scale) and plate current in milliamperes as ordinates (vertical scale). Do this for each set of readings, one for the filament current at .2 amps. and the other for the filament current at .25 amps.

The graphs will be of the general shape shown at (E) of Fig. 190. They show at a glance how the plate current varies as the plate potential or voltage is increased. An examination of the curve for the lower value of filament current shows that as the plate voltage is increased, there is a rapid increase in the plate current at first. After a certain value of plate voltage is applied, there is no appreciable increase produced in the plate current by increasing the plate voltage. This is shown by the fact that the curve becomes horizontal when this point is reached. If the curve for the higher filament current is plotted, it is found that the curve coincides at the lower end with the one already plotted, but that the plate current continues to increase above the bend reached before. After a certain value of plate potential is applied, the plate current again fails to increase for further increase in plate potential. In this case, however, a higher limit of plate current has been obtained from the tube than before. If a series of similar curves were constructed, with each one corresponding to a definite filament current, the same characteristics would be noted in each, namely a part where the plate current increases with plate voltage, and a part where the plate current no longer increases if the plate voltage is increased.

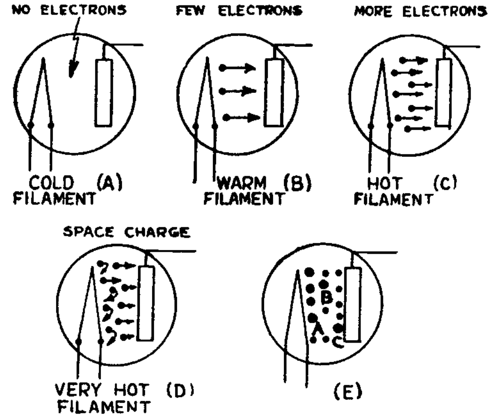
From this family of curves, it is at once evident that with any constant filament current there seems to be a definite plate current which cannot be exceeded. Moreover, this set of curves shows us that if the filament current is increased to a higher fixed value, the maximum value of the plate current also increases. From this data, it is evident that some condition exists within the vacuum tube which limits the amount of plate current which can flow in it. In the second place, it seems quite certain that this limiting factor depends upon the filament temperature, which in turn is controlled by the filament current. We can now summarize these experimental facts by saying that the maximum plate current which can flow for a given plate voltage depends upon the temperature of the filament. We will now see the reason for this.

The proportion of the emitted electrons which are attracted to the plate, depends on the strength of the plate potential. When the filament temperature is kept at a constant value, and the plate potential is gradually increased, the number of electrons attracted to the plate per second, and therefore the current in the plate circuit, will gradually increase as shown at (B) and (C) of Fig. 190. This will continue until a condition is reached where the plate attracts the electrons over to it at the same rate as they are emitted from the filament, as shown at (D). It is evident that when this condition is reached, any further increase in the plate potential will not cause any increase of the plate current, since if the plate is attracting *all of the electrons* as fast as they are given off by the filament, it cannot attract a greater quantity unless the filament is made to give off more electrons per second by increasing its temperature. This maximum plate current, beyond which there is no increase for increased plate potential, is known as the *saturation current* of the tube, for the corresponding filament temperature and plate voltage.

For any given filament temperature then, there is a definite value of maximum plate current which can be obtained, *occurring when the plate attracts the electrons at the same rate that they are emitted.* It is essential that a tube be designed so its filament is able to emit electrons at a sufficiently rapid rate so that *saturation* never occurs at the normal filament current and plate voltage at which the tube is to operate in practice. Modern tubes are designed with electron emitters able to supply an ample quantity of electrons.

271. Space charge and the screen grid tube: Let us now keep our tube connected as in Fig. 191, and with the plate potential fixed at about 60 volts, vary the filament current from 0 to about 0.3 ampere (taking the readings above 0.25 ampere quickly), taking readings of the plate current and filament current for every increase of about .02 ampere of filament current. This is repeated for a fixed plate potential of about 90 volts, and graphs are plotted from the readings as shown at (F) in Fig. 192. It will be noticed that the plate current increases as the filament current and temperature of the filament are increased, up to a certain value, after which further increase of filament current has no effect on the plate current. If the plate potential is then increased, a larger value of plate current may be obtained, but a critical point is again reached where further increase of filament current does not result in any increase in plate current. Let us see why this is:

When the filament is cold, since no electrons are being emitted, no electrons and current flow in the plate circuit, as shown at (A) of Fig. 192. If the filament is gradually heated, by increasing the current from the "A" battery, it begins to give off electrons when it has attained a dull red heat, as shown at (B). The number of electrons emitted by the filament increases approximately as the square of the excess filament temperature above red heat. At any instant, the space between the hot filament and plate contains those emitted electrons moving on toward the plate, to be absorbed there. As the filament current is increased and the filament temperature is thereby raised, as shown at (C) and (D), the rate of emission of the electrons increases. Therefore, at any instant the number of electrons present in the space between the filament and the plate depends on the rate of emission by the filament and the rate of attraction by the plate. The steady increase of filament temperature increases the electron emission from the filament and also the number in this space. As these electrons are all negative charges of electricity, the cloud of them around the filament causes a combined negative charge in the space around the filament. This tends to repel back any electrons emitted from the filament. Also, between the filament and the plate there is an electric field due to the positive plate. This tends to pull the emitted electrons toward it; while at the same time there is this other electric field due to the cloud of electrons around the filament, tending to repel them back to the filament. This latter charge is known as



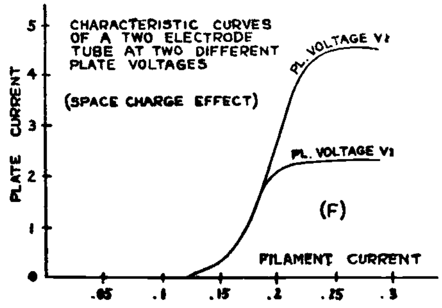


Fig. 192—Space-charge effect of the cloud of negatvie electrons around a filament. This combined negative charge repels the electrons back to the filament.

the *space charge*; it is the negative charge due to the accumulated electrons in the space between the filament and plate. A more detailed explanation of this follows:

At (E) of Fig. 192, let A, B and C be three electrons occupying different positions at some instant while on their way to the plate. Electron C is near the plate and is therefore attracted strongly by the positive charge on the plate, and is repelled toward the plate by the negative charges of all the electrons back of it, since they have like charges. Therefore, it will undoubtedly go to the plate. Electron B is attracted by the plate, and repelled back by the elctrons between it and the plate. Electron A is urged toward the plate by the hot filament, is attracted toward the plate by the positive charge on the plate, and is repelled back toward the filament by the combined negative space charge due to the individual negative charges of all the electrons in the space between it and the plate. Whether it will move toward the plate or re-enter the filament depends upon which of these opposing forces is greatest. If the plate voltage is made high enough, the plate will of course attract it over to itself.

It is evident that when the electrons moving across the space between the filament and plate become so dense that their combined negative charge—"space charge"—is equal to, or greater than, that of the plate, they neutralize the action of the plate and the electron flow to the plate cannot increase even though the temperature of the filament is raised. When this condition results, any additional electrons emitted into the space of the tube by the filament, will make the space charge overbalance the plate charge and repel the excess emitted electrons back to the filament as shown at (D). In order to increase the plate current under this condition, the attractive force of the plate must be increased by increasing the plate voltage applied to it. Thus, for every fixed value of plate voltage, there is a certain value of filament temperature beyond which no increase in plate current can be obtained.

As a result of this repelling action of the electric field caused by the space-charge of the electrons moving in the space between the filament and the plate, it is evident that the resultant effective electric field intensity and attractive force of the plate for the emitted electrons, is much less than we would expect to find from a consideration of the applied value of the B battery voltage alone. Since the attractive effect of the positive charge on the plate is lessened by this space charge, it follows that fewer electrons will move from the filament to the plate during each second for a given filament current and plate voltage, and consequently a smaller plate current will flow. As we shall see later, the harmful effects of the space charge are eliminated by the construction employed in the *screen-grid* tube. In this, an open-wire mesh or spiral wire is placed around the heater or filament and is kept at a positive potential with respect to it and thereby neutralizes the space charge. It is of open construction to allow the electrons to shoot through its open spaces freely and it is kept at a positive potential much lower than that of the plate so the latter will tend to draw the electrons right through the open spaces in it.

An idea of how large a number of electrons are travelling from the filament to the plate and back through the external plate circuit in the modern vacuum tube, may be gained from the fact that an ordinary 227 type tube has a plate current of 5 milliamperes flowing when the plate voltage is 180 volts. Remembering that a flow of one ampere of current constitutes the flow of 6.28×10^{18} electrons flowing past every point in the circuit each second, we can easily calculate that in this tube 3.14×10^{16} electrons are flowing from the filament to the plate every second. This means 3.14 times a thousand million million electrons per second. The cathode supplies these electrons.

272. Two-electrode rectifier: The two-electrode tube just described was used in the early days of radio as a detector in place of the crystal detector described in Chapter 16. It is still used as a detector (commonly called a *diode detector*) in some radio receivers. It finds its greatest use however, as a rectifier of alternating current in high-voltage B-power supply units, for which it is marketed in the special form known as the '81 type rectifier tube. When an alternating radio-frequency signal voltage, or a-c line voltage is applied to the plate circuit instead of the "B" battery, no current flows during each half cycle when the plate is made negative with respect to the filament, since the electrons do not reach the plate on account of the repulsion from it; but electrons and current do flow when the plate is made positive. Thus only one-half of each alternating current voltage wave is effective in causing a plate current to flow and the tube acts as a half-wave rectifier. The half-wave current flowing in its plate circuit is of the form shown at Fig. 151. When another plate is added as in the '80 type tube, we have a full-wave rectifier. Vacuum tube rectifiers play an important part in the successful operation of electric receivers, for changing the alternating current obtained from the a-c electric light socket, to direct current. They will be studied in detail later, in Chapter 27.

273. Three-electrode tube: The development of the two-electrode tube by Dr. Fleming was the forerunner of the modern three-electrode vacuum tube which was invented by Dr. Lee De Forest in 1906. He called it the *audion*, probably because he found that on inserting a third electrode (the grid) between the filament and plate, he obtained a large increase in sensitivity, and louder volume of sound when this arrangement was used as a detector in place of the crystal detectors and coherers then in use. This resulted from the grid's action in responding to the feeble flow of energy collected by the antenna, and so affecting the plate current (electron flow from filament to plate). The introduction of the grid also made possible audio-frequency amplification, radio-frequency amplification and the adaptation of the vacuum tube to radio-telephone and telegraph transmission where it is employed as a generator and modulator of high-frequency currents. There is no doubt that without the

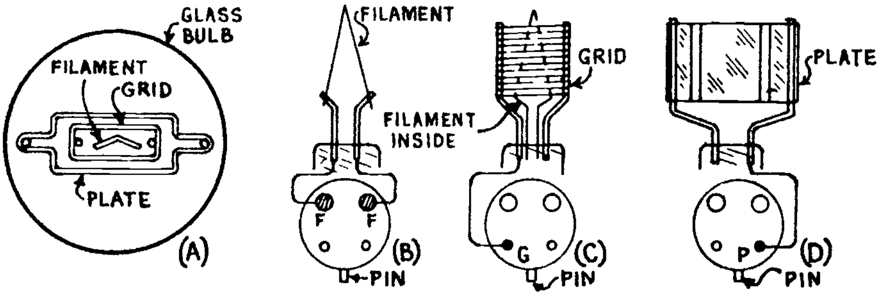


Fig. 193—Relative positions of elements in a 3-electrode tube. The connections between the elements and the base prongs are illustrated looking up at the bottom of the tube.

"triode" or three-element vacuum tube, radio telephony could never have even approached the state of perfection it enjoys today.

The three-electrode tube is essentially the same as the two electrode type, but has in addition a third electrode or *grid* in the form of a metallic mesh, (or usually a coil of very fine wire with widely spaced turns), placed between the filament and the plate. The elements are arranged as shown at (A) of Fig. 193 which shows a top view looking down on the top of the tube. The filament is surrounded by the grid (shown in elevation at (C), and the grid is surrounded by the thin metal plate (shown in elevation at D). In this way, the electrons emitted from all sides of the filament wire are attracted by the plate and must flow through the open spaces in the grid winding or mesh.

The connections made from the grid, filament and plate to the prongs of the tube base, as they would appear when looking up at the bottom, are shown at (B), (C) and (D). On one side of the base of some tubes is a small pin which acts as a guide when inserting the tube in the old shell-type socket. In the three-electrode tube, the two ends of the filament connect to the two prongs of larger diameter as shown. One of the grid supports connects to one of the remaining thin prongs. The other grid support serves no purpose other than to support one side of the grid wires. One of the plate supports is connected to the remaining thin prong on the base.

In making radio diagrams it is not convenient to draw the parts of the tube as shown here. Therefore the symbol shown in Fig. 194 is generally used to indicate the glass bulb containing the filament, grid, and plate. The symbol places the grid between the filament and plate just as it is actually placed in the tube itself. The symbols commonly used to represent the various common types of vacuum tubes will be found in the Symbol Chart in Appendix A at the back of this book.

Since, in the two-electrode tube, with a given filament temperature the rate of flow of electrons depends on the potential of the plate, if a third electrode, or "grid," is inserted between the filament and plate so that the electrons must go through the open spaces in it on their way to the plate, then, by varying the potential of this third electrode, the electron flow can be controlled. Since the grid is in the midst of the space charge, when it is made more positive (with respect to the negative terminal of the filament) by means of a battery (called the "C" battery) as shown at (B) of Fig. 194, or some other source of potential (such as the radio signal voltage), it tends to neutralize the effect of the space charge, thus reducing the opposing force of the space charge and consequently making

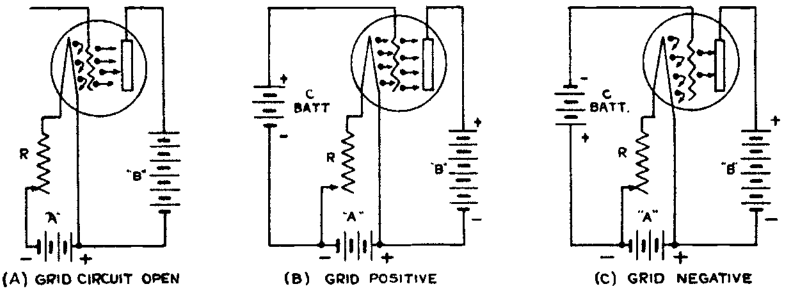


Fig. 194—Action of the 3-electrode vacuum tube with (A) grid circuit open; (B) grid positive; (C) grid negative.

it easier for the emitted electrons to get to the plate. This therefore increases the electron flow and the plate current.

When it is made more negative (by connecting the negative terminal of a battery to it as shown at (C), or by some other source of e.m.f. such as the radio signal voltage), it assists the space charge in repelling more of the emitted electrons back to the electron emitter. Therefore the emitted electrons meet more opposition than ever in attempting to pass from the filament through the grid to the plate. Fewer of the electrons get through to the plate and consequently the plate current decreases. If it is made sufficiently negative, the plate current will be reduced to zero that is, the flow of electrons through the grid to the plate will be shut off completely. The grid therefore acts like a valve in controlling the flow of electrons (plate current) in the tube. It is for this reason that it is commonly referred to as a *valve* in Europe. When the grid is made positive, it collects a few electrons itself, acting like a second plate, giving rise to a current in the grid circuit from grid to filament. This should be remembered, as it becomes important in the practical use of the three-electrode tube as an amplifier in modern receiving sets. The flow of grid current is generally undesirable in tubes used as amplifiers (see Art. 340).

This effect of the grid in either increasing or decreasing the electron flow and the plate current, is of exceedingly great importance in radio work.

It is this effect that enables us to control comparitively large currents in the plate circuit either by impressing the varying *signal-voltage* upon the grid ("input") circuit, so that it drives the grid alternately "positive" and then "negative"; or else so that it serves to raise and lower the voltage of the grid above and below a sufficiently large steady negative voltage which is also applied to the tube. This latter voltage is called the *C-bias* voltage. In the latter case, the grid always remains "negative". The incoming alternating signal voltage merely makes it successively more and less negative from its C-bias value. This is the more common way of operating vacuum tubes as detectors and amplifiers.

274. Amplifying property: It is evident from the foregoing considerations, that the plate current in a three-electrode tube can be varied by varying any of three factors, the filament current, the grid potential, or the plate potential. *The grid of the tube, being much closer to the filament than the plate, can, when a potential is applied to it, control the electron emission far more effectively than the same potential applied to the plate.*

Suppose the grid potential of a tube is increased in the positive direction by, say, two volts. This would result in a plate current increase of, say, four milliamperes. Now, obviously, the plate current could also have been increased the same amount of four milliamperes by increasing the plate voltage instead of the grid potential. But it takes a considerably larger increase in plate voltage to affect the plate current to the same extent as that caused by a given increase in grid potential, since the grid is much nearer to the filament than the plate is, and therefore controls the electron flow more effectively. In the standard 201A tube a given grid voltage change will produce *eight times* as much plate current change as an equal change in plate voltage will. For a 224 type tube this ratio is about 400! That is, it requires *400* times as large a plate voltage change to affect the plate current to the same extent as that accomplished by the "control" grid. Consequently, the *voltage amplification factor* of the 224 tube is 400. We thus have a sort of trigger action here, a small voltage change applied to the grid varying the plate current just as effectively as a much larger voltage change on the plate would do it. The relative effects vary inversely as the cubes of the relative distances between the elements in the tube.

In a radio receiving set, we are interested in taking the very weak varying a-c incoming signal voltage set up in the aerial circuit and amplifying it greatly by making it produce large plate current changes in amplifying tubes arranged in proper circuits. Knowing that changes in plate current can be produced by either a change in grid voltage, a change in filament voltage, or a change in plate voltage, it is evident that the varying signal voltage could be applied in either one of these three circuits in the tube, as shown in Fig. 195, and it would produce a variation of plate current in each case. (We will neglect the fact that the signal must first be rectified in order to be heard in the phones.) If we connect a sensitive earphone or loudspeaker in the plate circuit as shown, any change in the plate current which flows through the magnetizing windings, will produce motion of the diaphragm. This will in turn produce sound waves. We are interested in finding out in which of these arrangements a given variation in signal voltage will produce the *greatest* corresponding variation in plate current, because the greater the variation in the plate current the larger will be the amplitude of vibration of the earphone diaphragm and the louder will be the sound produced. At (A) the signal voltage is applied to the grid circuit, at (B) it is applied to the filament circuit, at (C) it is applied to the plate circuit. The exact mathematical relation for the amplification produced will be studied later.

If the incoming varying signal voltage is applied to the *grid* circuit it will produce much larger changes in plate current (depending upon the amplification factor of the tube used) than if it were applied to either the plate circuit or the filament circuit. Hence, since the volume of sound produced by the loud speaker depends on the amplitude of the plate current variations in the last tube, the circuits of all modern receiving sets are arranged so the varying signal voltages are applied to the grid cir-

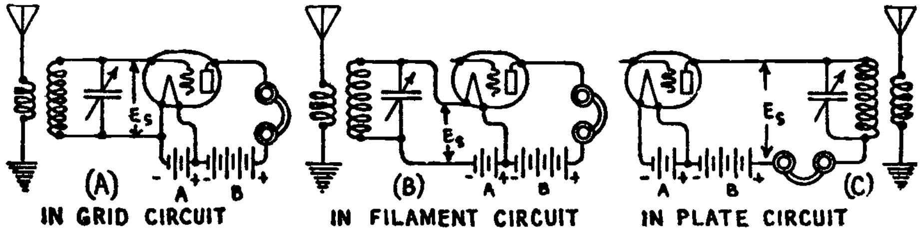


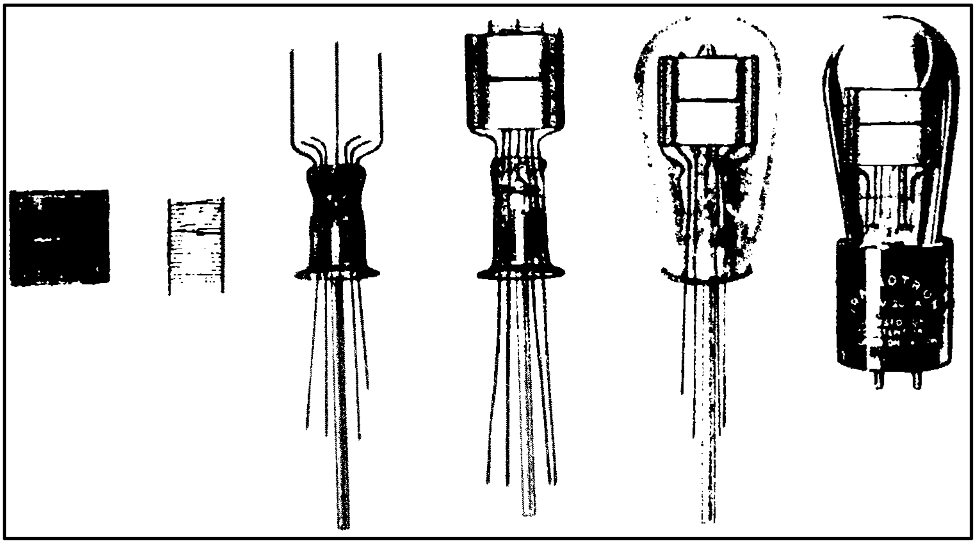
Fig. 195—A signal voltage may be applied either in the grid, filament, or plate circuits of a vacuum tube as shown. It has greatest effect on the plate current flow when it is applied in the grid circuit.

cuit (between the grid and electron emitter or cathode circuit), so as to cause corresponding variations in the grid potential and so cause similar larger variations in the plate current of the tube. The plate current variations are much greater in amplitude, but the same in wave form, as the applied signal voltage variations. This amplifying property of the three-electrode tube is one of its most valuable properties.

In Fig. 196 are shown the various parts of a typical 3-electrode tube designed for operation from batteries. Looking from left to right we have the plate, grid, mounted filament, three-electrode assembly sealed in a glass tube, and the complete tube. Notice that in the final tube the V shaped filament is in the center; around this is the spiral wire grid; and surrounding these is the metal plate. The filament in this tube is so fine that it is not visible in the illustration.

By employing an amplifier circuit with several tubes, an amplification of many thousand-fold may be obtained, since the plate current changes in the first tube act on the grid of the next tube, through the coupling device between them, and so on. The source of e.m.f. in the plate circuit (B battery or B voltage supply device) furnishes the energy which is added to that of the incoming signal by the vacuum tubes.

275. Characteristic curves: The behavior of vacuum tubes is best indicated by curves showing the relation between the various factors. The actual change in plate current due to a change in potential on the grid of an ordinary radio detector or amplifier tube is shown at the right of Fig. 197 by the characteristic curve. This can be obtained, by measuring with a milliammeter, the plate current which flows when various measured voltages are applied to the grid. The curve is important, for it is by reason of the shape of its various portions that the tube is able to perform its many different functions. The use of a "C" battery (Fig. 194), presents a



Courtesy R. C. A. Radiotron Co.
Fig. 196—Several stages in the assembly of a '01-A type 3-electrode tube.

convenient way of placing any desired steady potential on the grid. It can be made stronger or weaker by varying the battery, and can be made positive or negative by reversing the connections of the battery. The connections of simple apparatus for making a test of this kind on 3-electrode tubes, are shown at the left of Fig. 197. In Fig. 199 a more elaborate tester for obtaining the characteristics of almost any tube, is shown.

The grid voltage can be varied and the plate current measured for each step, the plate voltage and filament current remaining constant. Three curves are given, one for each plate voltage. At zero grid potential(point A on the curve), the plate current has a definite value. As the grid potential is made more and more negative, the plate current decreases. As it is made more and more positive, the plate current increases. The curve has two distinct bends, one at B and one at C. These are called the "knees" of the curve.

It is interesting to note that in the region of the negative grid potential, since there is practically no grid current flowing, we have the condition where a mere change of the *potential* applied to the grid circuit, controls the plate current or *energy* in the plate circuit.

In the practical operation of a tube, the temperature of the filament and consequent electron emission must be sufficiently high so that the normal plate and positive grid voltages do not cause saturation of the tube (see Art. 270), for if this happens, the grid cannot control the plate current and the tube becomes inoperative.

276. Types of tubes: Although the 3-electrode vacuum tube just described is perhaps the simplest type in use in present day radio equipment, we shall find that the special construction features employed in the

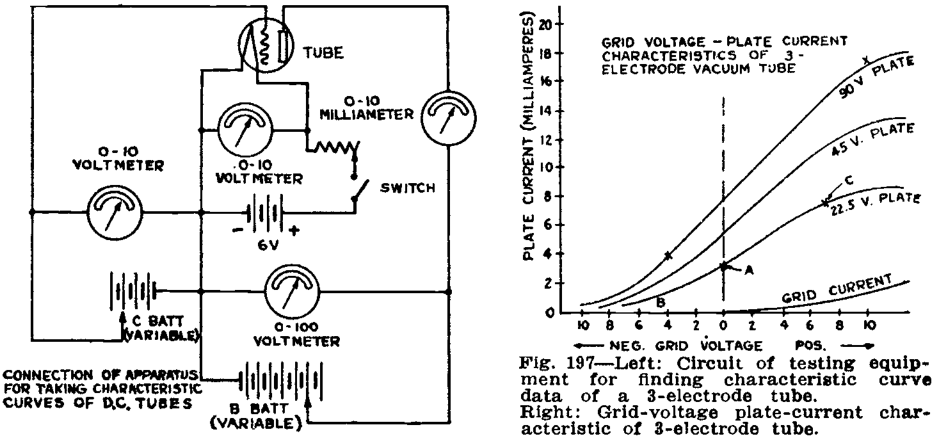


Fig. 197—Left: Circuit of testing equipment for finding characteristic curve data of a 3-electrode tube.
Right: Grid-voltage plate-current characteristic of 3-electrode tube.

many other forms of tubes now employed as amplifiers and detectors, are all attempts to adapt the basic principle of the 3-electrode tube to more convenient forms of tubes having certain desirable special characteristics for the particular purposes for which they are employed, and which this simple tube does not have. For instance, the a-c heater-type tube was simply designed to overcome the necessity for using batteries to supply the filament current of the simple 3-electrode tube. The screen grid tube was designed to overcome the objectionable grid-to-plate capacitance existing in the simple tube. The pentode tube was designed to overcome the effects of secondary emission existing in it. Each type of tube was developed for a specific reason and purpose.

In order to understand how these characteristics differ, it will be necessary for us to study in detail just what the important operating characteristics of a vacuum tube are, and how the tube design influences them. This will form the basis of our study in the next chapter.

REVIEW QUESTIONS

1. Upon what fundamental principle does the operation of all forms of thermionic vacuum tubes depend?
2. Upon what fundamental principle does the operation of photoelectric tubes depend?

3. Explain the "Edison effect".
4. What is the difference between a vacuum tube and a valve?
5. What is an electron? How is the electron related to the atom?
6. Explain the phenomenon of electron emission by the application of heat. What is the cathode; the anode or plate?
7. How is the flow of electrons in a conductor affected by the difference of electric potential across it?
8. How does increase of temperature affect the emission of electrons from a heated body?
9. Is the popular idea that electricity flows from positive to negative really correct? Explain.
10. In a vacuum tube why do electrons flow from the filament to the plate but not in the reverse direction?
11. Why must the plate in a vacuum tube be kept relatively cold?
12. What happens if the grid is made (a) more positive with respect to the filament (b) negative with respect to it?
13. Describe a 2-electrode tube and explain its operation.
14. What is the most important use of two-electrode tubes at present?
15. Describe a 3-electrode tube and explain its operation. What is it used for?
16. Why is the plate current stronger when the filament is bright than when it is dim? Does it continue to increase indefinitely as the filament current and temperature are increased? Explain why.
17. What is the space charge in a tube and how does it affect the operation of the tube? Is it desirable?
18. How does the plate current of a tube vary as the plate voltage is increased? Show this by a graph. Can the plate current be increased indefinitely by increase of plate voltage?
19. What is the function of (a) the filament; (b) the plate; (c) the grid, in a vacuum tube? Draw a diagram showing their relative positions and shapes in a 3-electrode tube.
20. Why are the elements sealed into a glass bulb from which the air has been exhausted?
21. What is meant by ionization by collision?
22. What is "secondary emission"? Explain how it is caused.
23. Suppose you had a vacuum tube with its filament lit by an "A" battery, a pair of earphones, and a B battery connected in the plate circuit; and then connected a 4.5-volt dry cell C-battery with its positive terminal to A—, and the negative terminal to the grid. What would you hear; (a) under these conditions; (b) if you reversed the connections of the C-battery; (c) if you opened and closed the grid circuit rapidly; (d) if you connected in series with the grid circuit, a source of a-c voltage varying at

an audio frequency? Draw a diagram illustrating the connections in each case and give the reasons for your answers.

24. Explain in detail with sketches, 3 ways of heating a cathode in a vacuum tube in order to make it emit electrons.
25. Describe a simple construction arrangement for a vacuum tube operating on the photo-electric principle. State 2 of the handicaps which this type of tube must work under with present photo-electric sensitive materials and sources of illumination.
26. Draw the filament current—plate current characteristic curve of a vacuum tube (at two different values of constant plate potential) and explain the reasons for its shape at low, medium and high values of filament current.
27. Do the same for the plate voltage—plate current characteristic (at two different values or constant filament current).
28. What is the difference between thermionic emission, photo-electric emission, and secondary emission? How are each produced?
29. What is meant by emission current?
30. Draw the complete circuit connections for a 3-electrode tube with its filament and plate circuit batteries connected. By means of dotted arrows show the directions of the electron flow in the filament and the plate circuit. By means of solid arrows show the direction of the current flow. Explain!

CHAPTER 18

VACUUM TUBE CHARACTERISTICS

VACUUM TUBE CHARACTERISTICS — APPARATUS FOR DETERMINING STATIC CHARACTERISTICS — GRID POTENTIAL-PLATE CURRENT CURVES — PLATE VOLTAGE — PLATE CURRENT CURVES — V. T. NOTATION — V. T. CONSTANTS WHAT AMPLIFICATION FACTOR MEANS — SIMPLIFIED EQUIVALENT TUBE CIRCUIT — D-C PLATE RESISTANCE — PLATE IMPEDANCE — MUTUAL CONDUCTANCE — TUBE CONSTANTS FROM CURVES — MEASURING TUBE CONSTANTS QUICKLY — TUBE CHECKERS — DYNAMIC CHARACTERISTICS — RESISTANCE OUTPUT LOAD — IMPEDANCE OUTPUT LOAD — VACUUM TUBE BRIDGE — TABLE OF V. T. CHARACTERISTICS — REVIEW QUESTIONS.

277. Vacuum tube characteristics: The three-electrode vacuum tube is used to perform either of four major functions; that is, it may be used as a detector, amplifier, oscillator or modulator. The four and five-electrode tubes may be employed for similar purposes. In all of these cases, however, we are concerned with producing variations in the steady plate current of the tube by means of variations in the potential difference applied between the grid and cathode.

In the ordinary 201-A type tubes etc. ,the cathode is the filament itself; in the separate-heater type tubes, the cathode which emits the electrons is independent of the heater filament. In any case, the *cathode* is the part of the tube which emits the electrons; the *anode* or plate, is the part to which these emitted electrons are attracted.

In practice, the filament (or heater) voltage of a tube is adjusted to a certain fixed value specified by the tube manufacturer, depending on the particular design of the heater of the tube. Then the correct filament current will flow. Thus the filaments of 201A, 112A and 171A tubes are designed to take 0.25 amperes at 5 volts; those of the 227, 224 and 247 tubes take 1.75 amperes at 2.5 volts, etc. Under ordinary conditions, the voltages and currents specified for the heater filaments by the manufacturers, are such as to operate the filament at a temperature which will insure an operating life of at least 1,000 hours and a sufficient supply of emitted electrons from the cathode for proper operation of the tube. Consequently, we may forget these two constants of a vacuum tube because they are fixed in value and set by the designers and manufacturer. We must remember only to supply the proper voltage at all times.

If the filament voltage and current are fixed, the plate current still depends upon two or three variable quantities. In the case of the three-electrode tube, the grid and plate voltages affect it; in the four and five electrode types (screen and pentode tubes) the screen voltage also affects it. The manner in which these variable factors affect the plate current controls the important characteristics of the tube, and may be shown best by means of graphs called *characteristic curves*, somewhat similar to those discussed in the previous chapter. Since there are several variable quantities in tube operation, the determination of the tube characteristics consists of keeping the voltage applied to the filament constant, varying the voltages applied to the other electrodes, and measuring the resulting currents which flow. We shall first consider the *static character-*

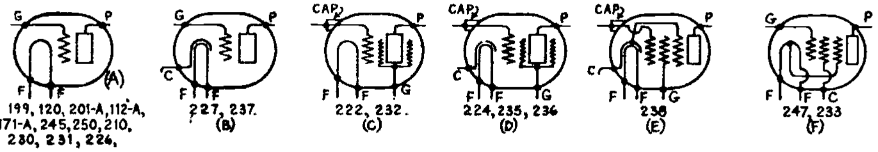


Fig. 198—Arrangement of the electrodes in standard types of vacuum tubes in use in the United States.

istics, i.e., the characteristics measured at steady values of potentials and currents. As we shall see later, these characteristics do not exactly represent the conditions under which tubes operate in most practical circuits, but they are very helpful in our study of vacuum tubes nevertheless. The characteristics which are obtained with alternating potentials applied to the grid circuit are called the *dynamic characteristics* and really represent the actual working conditions of the tube. They require more elaborate apparatus for their determination however, and for all ordinary purposes of tube study, the static characteristics are considered as representing the operating condition of the tube fairly accurately.

The dynamic characteristics differ from the static simply because in actual tube operation the varying voltage applied to the grid circuit causes the plate current to vary. This varying plate current flowing through the usual earphones, loudspeaker winding, plate coupling resistor or transformer primary connected in the plate circuit produces a varying fall of potential in it. This being subtracted from the applied steady plate voltage at every instant, causes the actual effective difference of potential between the plate and cathode of the tube to vary. The effective plate potential therefore continuously varies with the variations of grid potential and plate current. This produces a further change of plate current at every instant, which of course is not shown by the static characteristic curves.

278. Apparatus for determining static characteristics: The data for the static characteristic curves of practically all types of tubes may be obtained by means of a tube tester employing the circuit arrangement shown in Fig. 199. This is a very useful piece of apparatus for any school or home laboratory.

Since there are at present five really different terminal arrangements on standard vacuum tubes employed in the United States as shown in Fig. 198 (D and E have the same socket-terminal arrangement) this tester makes use of five separate tube sockets with their terminals suitably connected in parallel so that the proper connections are automatically made to the heater, grid, plate and screen grid electrode (if it has one) of the particular tube tested, provided that tube is placed in the proper socket as marked in the diagram. When testing tubes which do not have a screen grid, there will be no reading on the screen voltmeter and milliammeter of course. The values shown for the battery voltages and the ranges of the various instruments, will enable tests to be made on all of the types of tubes listed in the diagram. For greater accur-

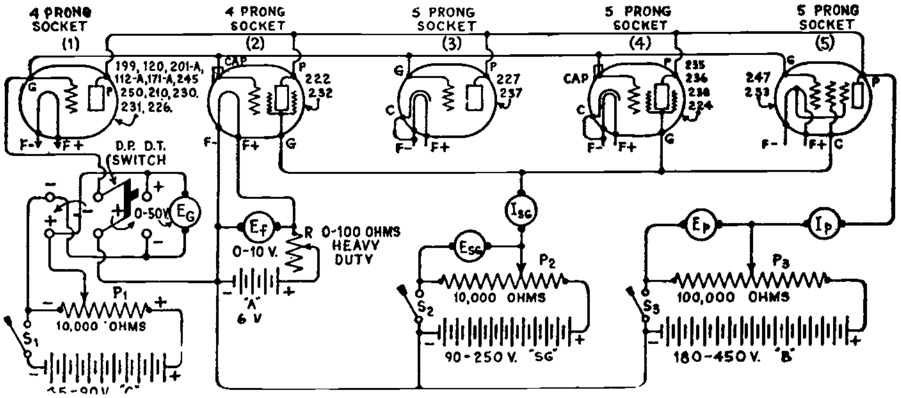


Fig. 199—Tester arrangement for obtaining static characteristics of any type of tube shown in Fig. 198.

acy when testing those types of tubes in which the voltage and currents are rather low, it is advisable to use meters of lower ranges in order to secure larger scale deflections. Meters provided with adjustable shunts or multiplier resistors are of course very valuable in this work. It will be noticed that all voltages are arranged to be supplied by batteries. This is really preferable in most laboratory work, as the voltages will be steady. If desired however, the plate and screen voltages can be supplied by a well designed standard B-eliminator connected in place of the B batteries. The proper filament voltage for the particular tube tested should always be adjusted carefully by means of the filament rheostat and read on the filament voltmeter. The recommended values for filament voltages and currents may be obtained from the general tube characteristic chart in this chapter. This chart will also supply information as to the normal voltages and corresponding currents for the other elements of the tube. This information is very helpful in selecting the proper meter ranges to be used for the particular type of tube whose characteristics are to be taken. The double-pole double-throw switch in the grid circuit makes it possible to change the polarity of the grid without the necessity for changing the meter E_g connection.

Switches S-1, S-2 and S-3 in the grid, screen and plate-battery circuits enable these circuits to be opened when the instrument is not in use, to avoid continuous discharge of the batteries through the voltage adjusting potentiometers P-1, P-2 and P-3. These may be in the form of locking push switches in order that they may be closed at the time the test is made, but may be readily released upon completion of reading of the meters. Potentiometers P-1, P-2 and P-3 should be well constructed with well designed sliding contact arms, to enable accurate grid screen and plate voltage settings to be obtained. They simply apply to the test circuits a certain definite proportion of the total fall of potential in the potentiometer resistance caused by the flow of the battery current through it ($E=I\times R$) in each case. By varying the position of the sliding contact, any voltage between zero and the maximum p.d. of the battery may be applied to the test circuit. Potentiometers are used extensively for this purpose.

In the pentode tube, since the cathode or suppressor grid is already connected to the cathode or filament inside of the tube, no external connections need be made to it.

279. Grid potential-plate current curves: The data necessary for drawing the grid potential-plate current curves of a tube may be obtained by means of the apparatus of Fig. 199 as follows:

Experiment: Arrange the apparatus as shown, making tests on several common types of tubes. Set the filament current at the proper normal value recommended by the manufacturers, (see V. T. Characteristic Chart in Fig. 214). Set the plate voltage at a fixed value of say 22.5 volts, and take readings of the plate current and grid potential for every step, as the grid potential is varied in steps of one volt, from a point where the plate current is zero, to a positive grid potential of about 10 or 15 volts. Throwing the D.P.D.T. switch to the right makes the grid *positive*. The connections of the grid voltage meter E_g do not have to be reversed. Then set the plate voltage at a higher fixed value of say 90 volts and repeat. Take the readings for several fixed plate voltage values in this way, up to the maximum rated plate voltage of the tube, and plot the readings to enable you to draw E_g — I_p (grid potential-plate current) curves, like those at (A) in Fig. 200. The student should learn the standard abbreviations and letter symbols for plate voltage, plate current, etc., used in radio work. These are listed in Appendix B at the back of this book.

The family of E_g — I_p curves shown at (A) of Fig. 200 are those for a 227 type tube. They reveal several interesting and important facts. At the large negative grid potentials, there is little or no current flowing in the plate circuit, since the strong negative charge on the grid repels almost all of the electrons back to the cathode, practically none of them getting through the spaces between the grid wires. As the negative grid potential is decreased, some of the electrons get through the openings in the grid and the space charge and the plate current begins to increase at a slow rate at first, then more rapidly, and finally in a steep straight line. If the readings were carried out with positive grid potentials large enough, the curves would finally flatten out horizontally when all of the

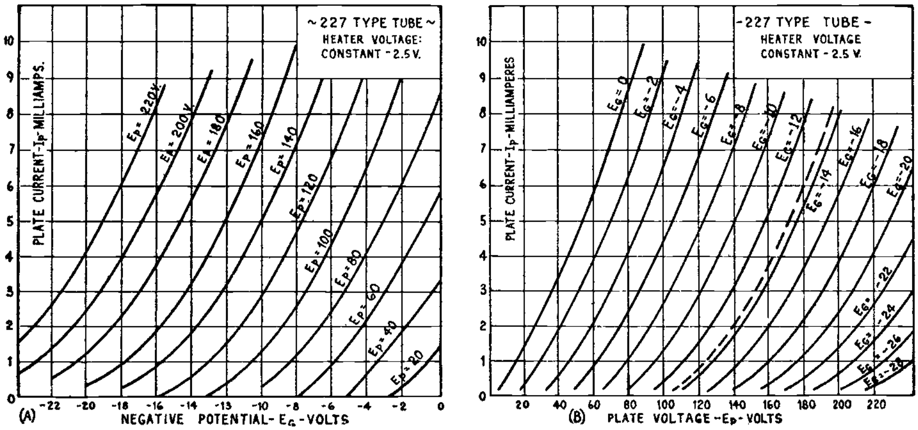


Fig. 200—Left: Family of Eg-Ip curves for a '27 type vacuum tube.
Right: Family of Ep-Ip curves for a '27 type vacuum tube.

electrons given off by the filament at that particular temperature are drawn over to the plate as fast as they are emitted (saturation).

If the plate voltage is now increased, and the test repeated with various grid potentials again, a new curve is produced which is to the left of the one just drawn, but practically parallel to it. The data for higher plate voltages will result in several other curves as shown. This is called a "family" of curves and gives us important information about the effect of the grid potential upon the plate current at various fixed values of the plate voltage.

If a microammeter were connected in the grid circuit during the test, it would show that a very small current was flowing in the grid circuit. The grid current curve for a 201A tube is shown at the lower right of Fig. 197. In all applications of the vacuum tube as an amplifier, the grid is kept at a high negative potential in order to keep the grid current as low as possible to prevent distortion as we shall see later, in Art. 340.

280. Plate voltage-plate current curves: The effect of the plate voltage upon the plate current (grid potential kept constant) may be seen from the curves at (B) of Fig. 200. The data for these is obtained as follows, by means of the same apparatus:

Experiment: Set the grid potential fixed at some value, say 4.5 volts for an ordinary receiving tube, and read and record the plate current and plate voltage for each step, as the plate voltage is increased in steps of about 20 volts at a time, from zero to the maximum rated plate voltage of the tube. Then change the grid potential to 10 volts negative and repeat the readings; then at 15, 20 volts negative, etc. The readings for a 227 type tube are plotted at (B). Note: This data may also be obtained directly from the curves at (A) by locating on the curves the proper values of plate and grid voltages and projecting across to the current scale to find the corresponding plate currents.

The E_p — I_p curves at (B) show that the plate current increases as the plate voltage is increased, and as the grid potential is increased toward positive. The curves are practically parallel over their straight parts, as shown.

The curves of (A) and (B) enable us to calculate all of the constants of the tube, and also help us to foretell the behavior of the tube when it is connected into circuits with other apparatus of known electrical constants. They are of great value, in that they tell us a great deal about the characteristics of a radio tube at a glance. The general grid voltage-plate current curves for most tubes resembles those shown in (A) of Fig. 200, although the numerical values of grid voltage and plate current will vary with the different types of tubes and different plate voltages.

281. Vacuum tube notation: A very useful shorthand method of designating the various important factors affecting the operation of vacuum tubes is in common use and the student is urged to learn and use these expressions in his work. The designation for plate voltage is E_p, for filament voltage E_f, for grid voltage E_g. Similarly, plate current is usually written as I_p, filament current is I_f, and grid current is I_g. The subscript in each case indicates whether the quantity refers to the grid, plate, or filament circuit. A complete list of these abbreviations will be found in Appendix B at the back of this book. Other abbreviations will be mentioned as we proceed with our study.

282. Vacuum tube constants: Every tube has certain constants and characteristics which indicate its value either as a detector, audio frequency amplifier, radio frequency amplifier or oscillator. The *constants* are, the amplification factor, the d-c plate resistance, plate impedance, the mutual conductance and plate-to-grid internal capacity. The important *characteristics* are, the grid voltage-plate current curve, and the plate voltage-plate current curve. We have studied how to find the important characteristics, and will now proceed to a study of how the constants are determined.

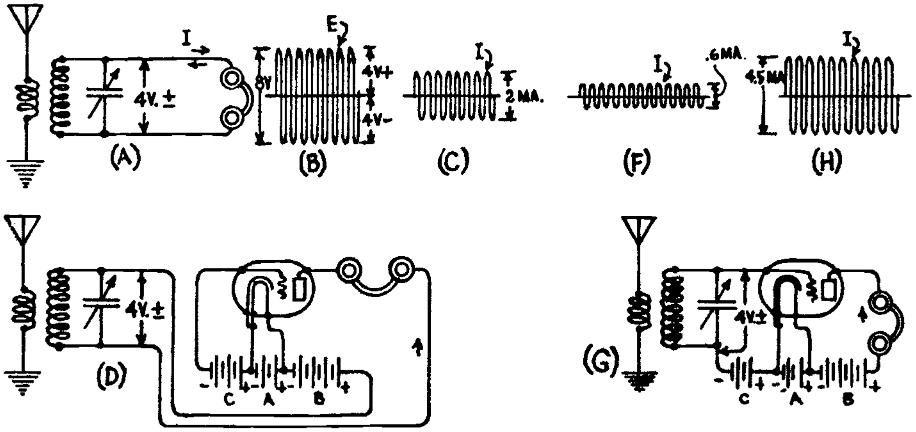


Fig. 201—Various methods of applying signal voltage to a vacuum tube circuit; variations produced in the plate current in each case.

283. What amplification factor means: The amplification factor is one of the most important constants of a tube, for the usefulness of a tube as an amplifier depends a great deal, but not entirely, on it. Let us study the action of the vacuum tube very carefully in order to see just what this important factor really means. First let us see why we use vacuum tubes as amplifiers anyway, and why we connect them as we do.

All practical forms of earphones and loud speakers in common use depend for their operation upon the fact that a varying current sent through their actuating windings produces motion of the diaphragm,—resulting in sound waves. It is the amplitude of the *variations* in the current, not the *total amplitude* of the current itself (see Article 251), which determines how great the amplitude of the vibrations of the speaker diaphragm are, and how loud the resulting sound will be. Remember this fact for it is important. Now let us refer to the simple receiving circuit shown at (A) of Fig. 201.

For simplicity in our discussion we are going to overlook several technicalities which will not affect the tube action. First, we will eliminate the detector and consider that we may feed the alternating signal voltage appearing across the terminals of the tuning circuit, directly to the winding of a pair of standard earphones or a loud speaker having an impedance of 4000 ohms. Also we will assume that the signal voltage appearing across the tuned circuit has a peak amplitude of four volts in each direction, that is, it varies from zero to four volts during each half of a r-f signal cycle, first in one direction and then in the other. Furthermore, for convenience, we will suppose it is of simple sine-wave form as shown at (B) .

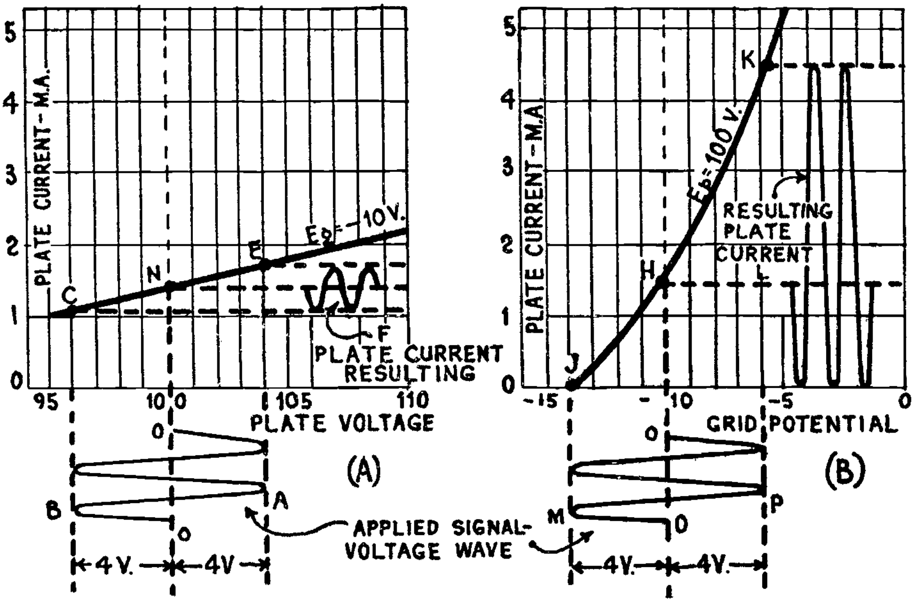


Fig. 202—Graphs showing the actual plate current variations caused by introducing the signal potential into (A) the plate circuit of a tube; (B) the grid circuit.

Under the conditions mentioned above, at the instant that the maximum peak voltage is applied to the earphone or speaker winding each cycle, the current through it will simply be equal to I=E÷Z or I=4÷4000 ohms = .001 ampere or one milliampere. The current therefore varies as shown at (C) between the values of 0 and 1 milliampere in each direction for each cycle, making a total variation of 2 m.a. The speaker diaphragm will move back and forth a certain amount due to this and a certain volume of sound will be produced. This would be one way of operating the receiver.

Now let us suppose that the signal voltage were introduced in the plate circuit of say a 3-electrode vacuum tube instead, as shown at (D), with the earphones in series so the plate current of the tube flows through them. Let us assume that the tube is being operated at normal filament voltage and that the applied steady plate voltage is 100 volts and a steady grid potential of minus 10 volts is supplied by the C battery. Then during each half cycle, the a-c signal voltage introduced will be in the same direction as that of the applied tube plate voltage and will add to it, making it 100 + 4 or 104 volts. During the next half cycle it opposes it, making the net voltage actually applied to the plate equal to 100 — 4 = 96 volts. Thus the *effective* plate voltage varies between 96 and 104 volts during each cycle. In order to see just what effect this has, let us refer to (A) of Fig. 202 which represents the single characteristic curve of this vacuum tube for the operating conditions under which it is working, i.e., a steady grid potential of minus 10 volts supplied by the C battery. The no-signal condition is represented by point N. The signal voltage curve is drawn at the bottom about the axis O—O which represents the normal plate voltage of 100 volts. When the signal voltage goes to four volts in the direction opposite to that of the plate voltage, as represented by point B, the effective plate voltage becomes 96 volts and by projectin up on the E_p — I_p curve we find that at this voltage the plate current flowing through the tu e and earphones is 1.1 milliamperes, represented by C. On the next half cycle, the signal voltage is 4 volts in the opposite direction, as at point A, adding to the plate voltage and making the effective plate voltage 104 volts as represented by point E on the curve. The plate current now flowing as represented by this point on the curve is 1.7 milliamperes. Therefore the plate current flowing through the earphones varies between 1.1 and 1.7 milliamperes about the normal value of 1.4 m.a., or a total variation of 0.6 milliamperes during each cycle, as shown at (F) of Fig. 201. The plate current flow is represented by curve F. This is constructed by projecting several points from the E_p sine wave up to the characteristic curve and then projecting over to the right. The plate current always flows in the same direction in the plate circuit, i.e., it is a unidirectional pulsating current, it merely varies up and down from the normal no-signal value of 1.4 m.a. represented by point N. The variation of the earphone current is now only 0.6 m.a. each way as against the 2 milliampere variation obtained by the arrangement of (A) of Fig. 201. Obviously, the signal will not sound as loud as before, so we have failed to gain anything by the use of the tube in this way, but have actually lost some volume.

Let us now see what happens if we introduce this same alternating signal voltage of 4 volts into the grid circuit of the vacuum tube, as shown at (G) of Fig. 201. The plate voltage now remains steady at 100 volts and the steady C bias voltage is 10 volts negative as represented by point H on the E_g — I_p characteristic curve of the tube shown at (B) of Fig. 202. This is the characteristic for a plate voltage of 100 volts. When the signal voltage is maximum in the same direction as that of the C battery voltage (point M), it adds to it and thereby swings the grid potential to $10 + 4 = 14$ volts negative. When it is maximum in the opposite direction (point P) the net grid potential is $10 - 4 = 6$ volts negative. Obviously, the a-c signal voltage results in making the potential of the grid swing alternately 4 volts above and 4 volts below the steady negative voltage of 10 volts supplied by the C battery, during each cycle, that is, the grid potential varies between minus 6 and minus 14 volts as shown by points J and K on the characteristic curve. When the grid is at minus 6 volts, the plate current is found to be 4.5 milliamperes. When it swings to minus 14 volts, the plate current is practically zero. Therefore, while the signal goes through each cycle, the plate current of the tube flowing through the earphone or loudspeaker winding now varies between 0 and 4.5 m.a. and the sound it produces is proportional to this, a total variation of 4.5 m.a. as shown at (H) of Fig. 201 and L of Fig. 202. Comparing this with the 0.6 m.a. variation produced when the same signal was introduced into the plate circuit, we can see that the signal is made much more effective by introducing it into the grid circuit. The comparitive plate current changes may be seen directly from the height of the plate current curves F and L of Fig. 202. Since the signal-voltage wave-form and the plate current scale have been drawn the same in each case, the amplitude of curves F and L may be compared directly. How much more effective this is, may be found by dividing

$$\frac{\text{plate current change produced by the given grid potential change}}{\text{plate current change produced by an equal plate voltag change.}}$$

For our case, this gives $\frac{4.5}{0.6} = 7.5$. This is called the *amplification factor* or constant of the tube.

Perhaps you now have a clear idea of the reason why we always introduce the signal voltage into the grid circuit of a vacuum tube rather than into any of the other circuits, and also, what is meant by the amplification constant or factor of a tube. If we want to consider the effect of the tube alone, we can look at amplification factor in another way as follows:

In the normal use of a vacuum tube as an amplifier, we desire to produce as large a change in plate current by means of the signals as possible. The plate circuit of a tube (A) in Fig. 203 is a complete electrical circuit as shown at (B), and somewhat similar to the ordinary electrical circuit at (C). It has in it, a source of voltage represented by the B battery or other B supply device, in series with the impedance of whatever device is connected in its plate circuit. This is analogous to the simple electrical circuit shown at (C). In this circuit, there are two ways of producing a change in the amount of current flowing,—either by increasing or decreasing the applied voltage E, or by increasing or decreasing the resistance R of the circuit. In our tube circuit at (B), we can also change the amount of current flowing in the plate circuit in either of two ways. First, we may increase or decrease the plate voltage. Second, we may increase or decrease the resistance of the path from plate to cathode, shown in dotted lines at (B), by increasing or decreasing the potential applied to the grid and thus varying the number of electrons in the space. Now either of these will cause a change in plate current, but a change of say 5 volts in the plate voltage will cause only a slight change in plate current, whereas a change of 5 volts in the potential applied to the grid of the tube will cause a very much larger change in the plate current because the grid being much nearer to the cathode (source of electrons) than the plate is, can control their flow more effectively. For instance, in a tube having an amplification factor of 9, let us suppose that a 5 volt change in the grid potential

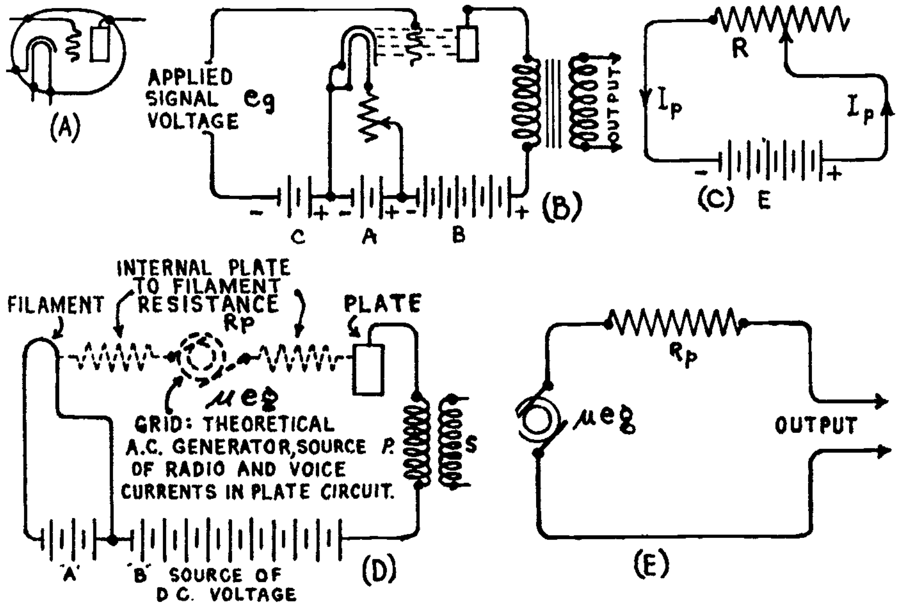


Fig. 203—The action of the plate circuit of a vacuum tube as a variable resistor.

causes a change of 10 milliamperes in the plate current. Were we to change the plate voltage sufficiently to bring about the same change of plate current (keeping the grid potential constant) we would find that it would require a $5 \times 9 = 45$ volt change of plate voltage to do it. Thus, for this tube, a change of grid potential is 9 times as effective in varying the plate current as a similar change in plate voltage is. The ratio of the two is a measure of the amplification effect or factor of the grid potential in producing plate current changes.

That is, the *amplification factor* of the tube is equal to:

$$\mu = \frac{\text{effect of grid potential in controlling the plate current}}{\text{effect of plate voltage in controlling the plate current.}}$$

Since amplification factor is a rather cumbersome word to write, the abbreviation "mu" or the Greek letter μ is commonly used as the abbreviation for it. Thus,

$$\mu = \frac{\text{plate voltage change required to produce a given plate current change}}{\text{grid potential change required to produce the same plate current change.}}$$

In the case considered in Fig. 202, the amplification factor of the 227 type of tube used is $\mu = \frac{4.5}{0.6} = 7.5$. This checks fairly well with the value of 9 given for a 227 type tube in the table of vacuum tube characteristics in Fig. 214.

The amplification factor of vacuum tubes is very important, especially if the tube is to be used as an amplifier or oscillator. In this case, it would seem that the mu should be as high as possible, but there are other considerations, such as plate impedance, etc., which determine the usefulness of a tube when used in actual circuits, as we shall see. The amplification factors of different types of tubes in common use vary between rather wide limits. Thus the mu of a 171A tube is about 3, whereas that of a 224 screen grid tube is about 420. The student should refer to the vacuum tube characteristic chart in Fig. 214 and glance down the column marked "voltage amplification factor". This will give a good idea of the values of mu for the various tubes. We shall see in the next chapter that the mu of a given tube is controlled largely by its mechanical construction, and the relative distances between the grid and cathode and the plate and cathode. A closely wound grid mounted close to the cathode produces a high amplification factor, one with a wide mesh and not so close to the filament produces a tube with a low amplification factor. Also, in screen grid tubes, mu is increased by the action of the screen grid, which neutralizes the effect of the space charge between the cathode and plate as we shall see later. The actual voltage amplification or increase of voltage realized in a practical amplifying circuit depends not only on the mu of the tube but also on the resistance, the inductance, and the capacitance in the plate circuit of the tube. The amplification factor of a given tube does not vary much under the conditions under which the tube is ordinarily used, except in the case of the variable-mu tube. The methods of measuring the mu of vacuum tubes will be considered in Articles 288 and 289.

284. Simplified equivalent tube circuit: In most all radio work, we are concerned with vacuum tubes only in connection with alternating currents or voltages of some form. Radio receivers employ tubes as amplifiers of the weak radio-frequency voltages induced in the receiving antenna circuit by the passing radio fields. Tubes are also used to amplify the low-frequency alternating voltages encountered in the audio circuits after the detector. Some tubes are utilized as rectifiers of the 60-cycle power current, while others function as rectifiers of the signal currents. The first are called rectifiers and the second, detectors. Under any circumstance, we will always be considering the applied voltages on the grid resulting from some form of alternating voltage. In other words, the grid voltages, with which we will be concerned in making a study of the "mu" of the tube, will always be alternating voltages.

To simplify the visualization of the tube action in associated electric circuits, engineers prefer to consider the schematic circuit diagram of a vacuum tube as shown at (D) of Fig. 203. Here the grid circuit is replaced by a small a-c generator directly in the plate circuit. The voltage of this schematic generator is the voltage of the a-c signal impulse on the grid multiplied by the mu of the tube, because any change in voltage in the grid circuit has the same effect on the plate current as a voltage "mu" times as large introduced directly in the plate circuit. Therefore if we are to consider our grid voltages as acting directly in the plate circuit, we must consider them as being "mu" times as large as they really are. The internal resistance of this generator is equal to the plate-to-cathode resistance of the tube. This arrangement reduces the complicated circuit of the tube shown at (B) to a simple equivalent series plate circuit with an equivalent a-c generator whose voltage is μe_g, representing the effect of the grid control on the plate current. The diagram at (D) may be further simplified as shown at (E). The tube is considered this way in all problems. The voltage of this hypothetical generator would be high in a high-mu tube and low in a low-mu tube.

285. D-C plate resistance of a tube: In the simple electrical circuit of (C) in Fig. 203 a certain direct current flows through resistor R due to the applied voltage E. Likewise in a vacuum tube a certain steady d-c plate current I_p flows across through the space between the plate and cathode (actually it is the electrons flowing in the opposite direction) and around through the circuit, due to the electrical pressure of the applied, d-c plate voltage E_p. Applying ohm's law, we find that the d-c resistance of the space between the plate and cathode is:

$$R=\frac{E_p}{I_p}$$

This is called the *d.c. plate resistance* of the tube. The electrical power used up by the flow of the plate current through the resistance of this path is $W=E_p \times I_p$ or $\frac{E_p^2}{R}$ or $I_p^2 R$.

This power is the rate at which kinetic energy is given up by the electrons when they strike the plate at their high velocity after being pulled to the plate by the attractive force of its positive charge. When each electron hits the plate, its kinetic energy due to its motion is given up, and the energy thus released at the plate by all of these electrons produces heat which may heat the plate to red heat unless it is designed to have a large enough surface to dissipate the heat. This action is similar to the heat which would be produced in a large steel plate if a shower of bullets from a machine gun were made to impinge upon its surface continuously. The kinetic energy of the motion of every bullet would be transformed into heat as soon as it was stopped suddenly by the surface of the steel plate. The heat would result in raising the temperature of the plate. We shall see later that these bombarding electrons also cause secondary emission of electrons from the plate, the secondary emission electrons interfering with the normal flow of those from the cathode. The action of electron bombardment may be seen by operating an ordinary tube for a few minutes with a plate voltage about twice as high as that recommended by the manufacturer. The plate will become red hot. The d-c plate *resistance* is not to be confused with the more important factor which is ordinarily referred to as the a-c *plate resistance* or *plate impedance* of a tube.

286. A-C plate resistance, or plate impedance of a tube: Since we are always interested in the changes produced in the plate current of a vacuum tube in actual operation, it is more important for us to know what the ratio between a *change* in plate voltage and the corresponding *change* in plate current produced by this change in plate voltage is. This is called the *a-c plate resistance* or the *plate impedance* R_p, of the tube and is numerically equal to:

$$R_p = \frac{\text{change in plate voltage}}{\text{change produced in the plate current.}}$$

The a-c plate resistance is the opposition offered to the flow of varying currents in the plate circuit and is not the same as the resistance offered to the flow of a steady d-c current from the "B" battery. The d-c plate resistance governs the steady plate current flow when no signal voltage is being applied to the grid, i.e., the grid voltage is steady. The a-c plate resistance governs the varying plate current flow when a varying signal voltage is applied to the grid, hence it is the more important of the two.

For instance, in (A) of Fig. 202, when the tube considered had a negative grid potential of 10 volts and a plate voltage of 100 volts applied (point N), the steady plate current flowing was 1.4 m.a. or .0014 amperes. Therefore the *d-c plate resistance* of this tube under these conditions is given by $R = \frac{E_p}{I_p} = \frac{100}{.0014} = 71{,}000$ ohms (approximately).

However, when the plate voltage was varied from 96 volts (point C) to 104 volts (point E), the plate current changed correspondingly from 1.1 m.a. (point C) to 1.7 m.a. (point E), a net change of 1.7 — 1.1 or 0.6 m.a. Therefore the a-c plate resistance is equal to:

$$R_p = \frac{104\text{-}96}{.0017 - .0011} = 13{,}300 \text{ ohms.} \quad \text{(approximately)}$$

(1.7 m.a. equals .0017 amperes and 1.1 m.a. equals .0011 amperes.)

The d-c plate resistance and the a-c plate resistance both change with changes in plate and grid voltages, so the values of both must be specified when these constants are considered. Thus a 227 tube has an a-c plate resistance of 11,000 ohms at a plate voltage of 90 volts and negative grid potential of 6 volts. When the plate is at 180 volts and the grid is at 13.5 volts negative, the a-c plate resistance is 9,000 ohms. At the conditions mentioned in the problem above ($E_p = 100$ volts and $E_g = -10$ volts) the a-c plate resistance was found to be 13,300 ohms. As the a-c plate resistance varies with each change in plate and grid voltage, it should be considered only for small voltage changes and at the point on the characteristic curves where the tube is actually operating. The a-c plate resistance depends on the plate-filament spacing and the plate voltage used, the grid voltage, the fineness of the grid mesh, and to a small extent on the distance between the grid and plate. The methods of obtaining and measuring these constants will be taken up in Articles 288 and 289.

287. Mutual conductance: The essential function of an amplifying tube is to produce as large an undistorted change in plate current as possible for a small change in signal potential applied to the grid circuit. As this important property of the tube depends on how much plate current change is caused by a given grid potential change, by comparing these values we obtain a figure of merit which is known as the *mutual conductance,* represented by the symbol G_m. This ratio has been called mutual because it expresses a relationship between a quantity pertaining to the plate circuit and a related quantity pertaining to the grid circuit. It is called *conductance* because it is the ratio of a current to a voltage. (The conductance of a conductor in mhos is defined as "one divided by the resistance in ohms".) Thus:

$$G_m = \frac{\text{change in plate current produced}}{\text{change in grid potential producing it.}}$$

In general, the ratio of the change in current in the circuit of an electrode to the change in the voltage in another electrode is known as the *transconductance.* The term transconductance is also commonly used in radio engineering literature to represent what we commonly refer to as mutual conductance, so it should be remembered.

Thus in the tube whose E_g - I_p curve (for a plate voltage of 100 volts) is shown at (B) of Fig. 202 a change of plate current from 0 to 4.5 milliamperes (point J to K) was produced by a change in applied grid voltage from 14 to 6 volts negative. This represents a change of 4.5 m.a. or .0045 amperes in plate current, produced by a change of 8 volts in grid potential. Thus:

$$G_m = \frac{.0045}{8} = .00056 \text{ mhos or } 560 \text{ micromhos.}$$

The mutual conductance is also defined by the ratio between the amplification factor and the plate resistance, because

$$\mu = \frac{\text{plate voltage change}}{\text{grid potential change}} \quad \text{(1)}$$

$$R_p = \frac{\text{plate voltage change}}{\text{plate current change}} \quad \text{(2)}$$

Therefore $\frac{\mu}{R_p}$ is equal to expression (1) divided by expression (2)

from which we obtain finally after cancelling out the numerators of (1) and (2) $\frac{\mu}{R_p} = \frac{\text{plate current change}}{\text{grid potential change}}$; but according to the definition given above, this expression is equal to the mutual conductance. Therefore: $G_m = \frac{\mu}{R_p}$. Also, $\mu = G_m \times R_p$, and $R_p = \frac{\mu}{G_m}$.

In general, the higher the mutual conductance of a tube, the more efficient it is considered to be as an amplifier, but comparison should only be made between tubes *designed for the same service* and having similar characteristics.

For example, the 227 type tube designed for general amplification use has a mutual conductance of 1,000 micromhos at 135 volts plate voltage, and the 120 type tube which is designed entirely for output service has a mutual conductance of 525 micromhos at the same plate voltage. The latter tube, nevertheless is capable of handling 110 milli-

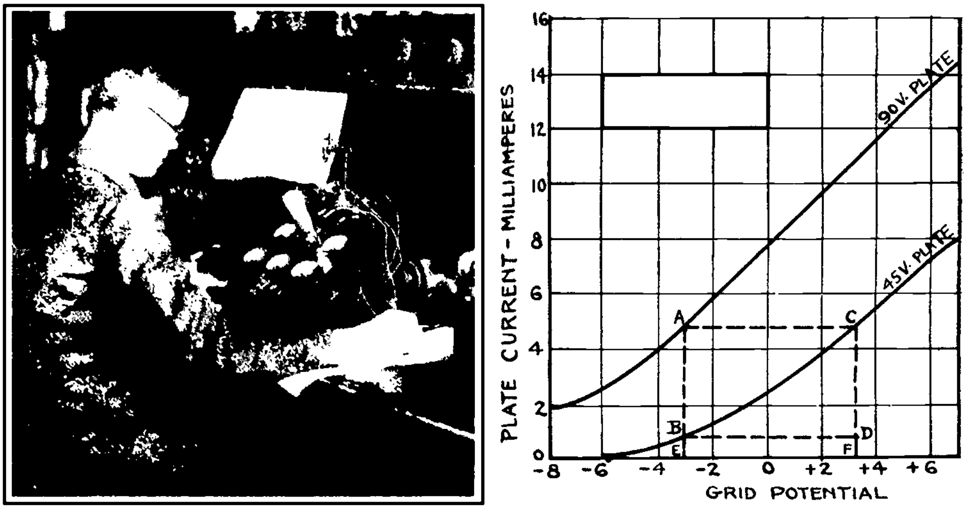


Fig. 204—**Left:** Laboratory type tube tester for taking tube characteristics.
Right: How mu is determined from the Eg-Ip characteristic curves for two values of plate voltage.

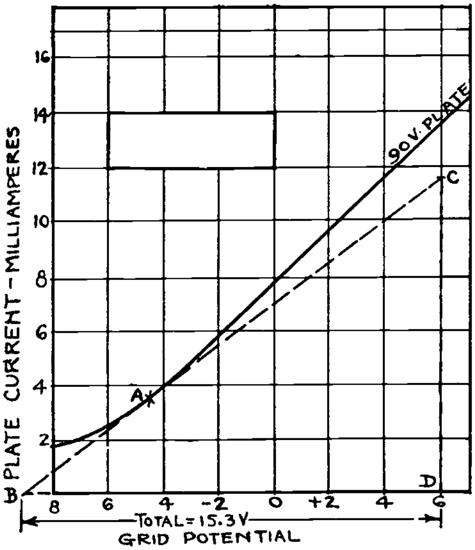
watts of undistorted power output when sufficient input voltage is available and the load is properly adjusted, against an undistorted power output of 80 milliwatts for the 227 tube.

When one is considering two tubes of the same type, the one with the higher mutual conductance is the better one, but rather large differences in mutual conductance may occur before any difference in the operation of the circuit in which the tubes are used will be noticeable. The mutual conductance is really the best tube factor on which to compare tubes which are to be used for the same purpose. Its measurement is considered in Articles 288 to 290. Since the mutual conductance depends on the plate resistance, it varies with the plate voltage, and therefore mutual conductance values are meaningless unless the voltages applied during the measurements are specified.

288. Obtaining tube constants from curves: In laboratory work where the performance of vacuum tubes is to be analyzed, the various constants may be obtained from the E_p - I_p and the E_g - I_p curves which are drawn from the readings taken on tube testing apparatus of the type shown in Fig. 199. The actual tube tester in operation is shown in the photograph at the left of Fig. 204.

To show the method employed for finding the *amplification factor* ("mu") from the E_g - I_p characteristic curves of a vacuum tube; consider the typical amplifier tube curves shown at the right of Fig. 204. One is for a steady plate voltage of 45 volts and the other is for 90 volts.

Selecting any point B on the straight portion of the 45 volt curve, drawn a vertical line A B E through this point, and a horizontal line A C, through intersection point A with the 90 volt curve, to the 45 volt curve and BD through point B. Drop a



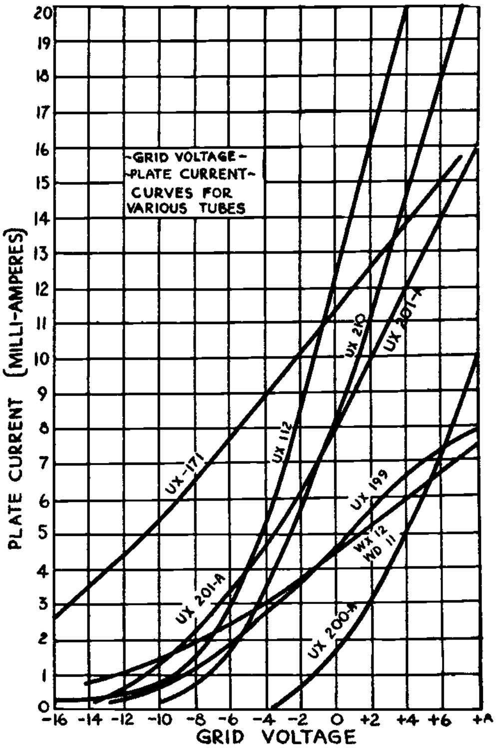


Fig. 205—**Left:** Method of finding mutual conductance from the Eg-Ip characteristic.
Right: Grid voltage-plate current characteristics of some commonly used tubes.

perpendicular line from intersection point C, to F. Now consider the tube operating at the lower plate potential of 45 volts and grid potential equivalent to point B on its characteristic curve.

If the grid potential is increased an amount equal to E F (or BD) units, the operating point moves to C, and the plate current has increased an amount C-D. This same increase C-D in plate current would also result if the grid potential were kept at value E and the plate voltage were increased from 45 to 90 volts to point A. Therefor, an increase of E-F units of grid potential has the same effect on the plate current as an increase of 45 volts in plate potential. From the foregoing definition of amplification factor, then the mu of this tube is 90 volts minus 45 volts divided by E-F (6.3 volts), or mu=7.1. That is, the grid potential exerts 7.1 times as much influence upon the plate current as does the plate voltage itself at the particular operating point B.

The methods for finding the d-c plate resistance and the a-c plate resistance for any particular operating condition have already been explained in Article 286. Since the mutual conductance is equal to the change in plate current divided by the change in grid potential producing it, it is found by merely measuring the *slope* of the E_g - I_p characteristic curve for the plate voltage at which the tube is operating. As the characteristic curve is not a straight line, its slope or "slant" changes for different values of E_g and E_p, (different points on the curve, see left of Fig. 205). Therefore, it must be taken at the point on the curve representing the particular value of grid potential applied to the tube.

Thus let it be desired to find the mutual conductance of the vacuum tube whose E_g - I_p characteristic curve is shown at the left of Fig. 205, when the tube is operating with a plate voltage of 90 volts and a negative grid potential of 4.5 volts. This operating condition is represented by point A on the curve. The slope of the curve is found by drawing a tangent line BC to it at the point considered as shown, and then forming a triangle BCD. The vertical height CD of the triangle divided by the total base line, BD (adding positive and negative grid potentials together to get the total length of BD), is equal to the slope of the curve at the point A.

Therefore to find the slope of the curve at point A, lay a straight-edge tangent to the curve at the point A, and draw tangent line B C so it cuts the horizontal axis. At any point C draw the perpendicular line C D; now measure the ordinate C D of the point of intersection (say 11.6 milliamperes or .0116 amperes). Also measure the horizontal distance B D from this latter point to the point where the tangent line intersects the horizontal axis. (Say a total of 15.3 volts.) Dividing the former distance .0116 amp. by the latter 15.3 volts, gives the slope of the curve or the mutual conductance at point A, which in this case is .00075 mhos or 750 micromhos (the micromho is the unit of conductance ordinarily used in vacuum tube work).

At the right of Fig. 205, the grid potential-plate current characteristics of various commonly used vacuum tubes are shown plotted on the same axes. The steeper the curve, the higher is the amplification constant.

The curves at the left of Fig. 206 show how the constants of a typical 3-electrode amplifier tube vary for different values of grid potential. Those at the right show how the constants vary for various values of plate voltage. Notice that the amplification factor is practically constant, but that the mutual conductance and plate impedance vary over rather wide limits. Hence the necessity for specifying the plate and grid voltages when speaking of either of these two constants for a tube. An idea of the values for various types of tubes may be obtained from inspection of the proper columns in the vacuum tube characteristic table of Fig. 214.

289. Measuring tube constants quickly: The important tube constants μ, R_p and G_m which define all of the tube's characteristics, may be found from the plotted characteristic curves of the tubes as explained in the previous article, but this is a slow laborious process since all of the readings for plotting these curves must be taken and plotted, and finally the constructions and computations just mentioned must be made. Obviously such a procedure does not lend itself to the sort of rapid testing required in production work. There are simpler methods of finding these constants by means of a simple circuit arrangement as shown at the left of Fig. 197, and there are also special testing devices for measuring them directly. The latter will be studied in Art. 295. A simplified method of measuring the *mutual conductance* is as follows:

Place the tube in the tester, set the filament voltage at the correct value and set the plate voltage at the value at which the tube will operate, say 180 volts. If the grid bias voltage under these operating conditions is to be say, 13.5 volts negative (227 type tube) set the grid voltage at minus 14 and then minus 13 and read the plate currents each time. Assuming that these plate current readings are 4.5 and 5.5 milliamperes respectively, the mutual conductance is found from:

$$G_m = \frac{\text{change in plate current (amps.)}}{\text{change in grid voltage}} = \frac{.0055 - .0045}{14 - 13} = \frac{.001}{1} = .001 \textbf{ mho. or}$$

1,000 micromhos.

Following is a simple method of measuring the a-c plate resistance (or plate impedance) of a tube:

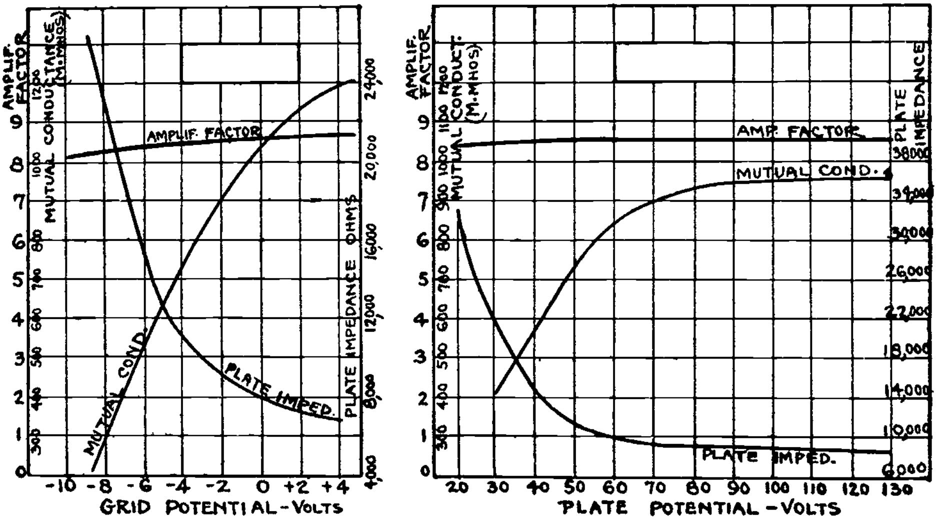


Fig. 206—**Left:** Curves showing how the mu, Gm, and Rp of a typical 3-electrode tube vary with change of grid potential.
Right: How the constants vary with change of plate potential.

Set the grid bias voltage at the value desired (for example 13.5 volts negative for a 227 type tube), and choose the value of plate voltage at which the tube will probably operate (say, 180 volts in this case). Then set the plate voltage at a value somewhat higher than this, and read the plate current. Suppose the plate voltage is set at 200 volts and the plate current reading is 8.5 m.a. Now reduce the plate voltage to a value below normal, (say 160 volts) and read the plate current again (say 4 m.a.). Then the a-c plate resistance is:

$$R_p = \frac{\text{change in plate voltage}}{\text{corresponding change in plate current (amp.)}} = \frac{200 - 160}{.0085 - .004} = 9{,}000 \text{ ohms. (approx.)}$$

This means that for this tube at a grid bias voltage of —13.5 volts, the average plate impedance between the values of E=200 and 160 volts is 9,000 ohms.

Following is a simple method for obtaining the *amplification constant.* Set the plate voltage at a certain normal value and read the corresponding plate current. Now change the plate voltage to some other value and read the plate current again. Then adjust the plate current back to the original value of the first condition by varying the grid voltage. Then the ratio of the change in plate voltage required to change the plate current this certain amount, to the change in grid voltage to produce the same plate current change, is equal to the amplification constant, or,

$$\mu = \frac{\text{first plate voltage} - \text{second plate voltage}}{\text{second grid voltage} - \text{first grid voltage.}}$$

The value of the amplification constant may be calculated directly from the values of mutual conductance and a-c plate resistance found previously, without necessity for another test. Since, $G_m = \frac{\mu}{R_p}$ then $\mu = G_m \times R_p$. Therefore, "mu" can be found simply by multiplying the mutual conductance by the a-c plate resistance.

290. Tube checkers: As explained previously, the three important electrical characteristics of a vacuum tube are its amplification constant, a-c plate resistance, and mutual conductance. It would appear that all three quantities would have to be measured in order to tell whether a tube is in good condition or not. Actually, however, this is not necessary for ordinary rapid service testing. If we can measure one of these factors, we will have a check on the other two, provided we know what the normal characteristics of the particular type of tube being tested should be. The factor usually chosen for measurement in commercial tube checkers, used by radio servicemen and dealers is the mutual conductance, for this is the most important quantity to determine. If a test indicates a tube to have a normal value of mutual conductance we can be reasonably sure that the amplification constant and a-c plate resistance are normal, since if either of these factors were incorrect, the mutual conductance would be affected. Any change due to presence of gas, low electron emission or disarrangment of a tube's electrodes will also alter the mutual conductance. Now in checking the condition of tubes we do not have to actually measure and calculate the mutual conductance—all we need is some indication that the tube has a normal characteristic. The simple relation $G_m = \frac{\text{change in plate current}}{\text{change in grid potential}}$ indicates a method of doing this. Evidently, if we change the grid voltage and note the change which this produces in the plate current, we will have in effect an indication of mutual conductance and from a chart we can determine whether the change in plate current that we noted is normal for the type of tube being tested. This is the basis for the operation of practically all the common tube checkers. The circuit of the tube checker is provided with a switch, (usually operated by a button), which when pressed will change the grid voltage on the tube by about 3 or 4.5 volts. We can calculate, or by measuring a large number of new tubes and averaging the results, determine the change in plate current which should be obtained if the tube is good. A simple chart can then be engraved on the face of the tester which will indicate the plate current readings which should be obtained with normal tubes of the various types. By using such a tube tester, it is therefore possible to obtain for all practical servicing purposes, an accurate, trustworthy indication of how good a particular tube is, and whether or not it should be replaced. Tube checkers are usually arranged to supply the proper filament, plate

and grid voltages to the tube being tested, by means of a suitable transformer operated from the 110 volt a-c electric light line.

Fig. 207 shows the circuit diagram of a tube checker which was originally devised by the E. T. Cunningham Company but which has been further simplified in order to make possible the use of a standard filament heating transformer with a single secondary winding delivering 7.5 volts This has also been altered to make it possible to check all standard types of tubes in use at the present time. A description of this checker follows:

Five sockets are provided for the various types of tubes, two being four prong sockets and the other three being of the five prong type. All of the filament terminals

TUBE TYPE	SET FILAMENT VOLTS AT
-11,-12	1.1 V.
-26	1.5 V.
-30,-31, -32,-33	2 V.
-24,-27, -35,-45, -47	2.5 V.
-00A,-01A, 112A,-71A, -40.	5 V.
-22,-99, -20	3.3 V.
-36,-37-38	6.3 V.
-10, -50	7.5 V.

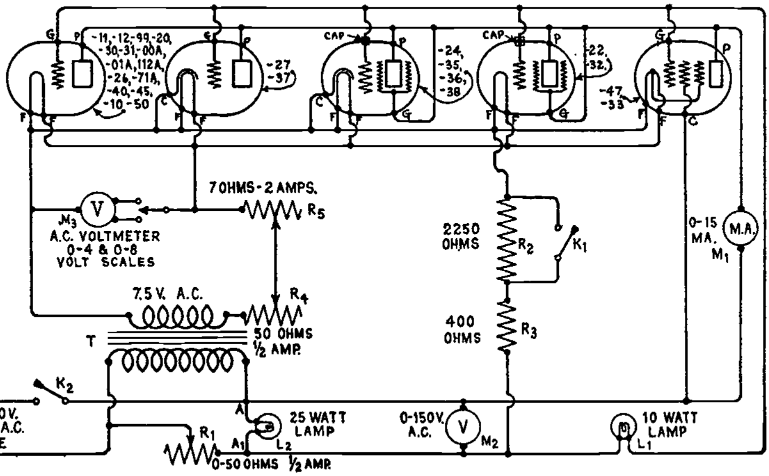


Fig. 207—An a-c operated tube checker arranged for rapid checking of the condition of tubes by a rough measurement of the mutual conductance.

of the sockets are connected in parallel across the secondary of the transformer T, having a 110 volt primary and 7.5 volt — 3 ampere secondary. The resistor R_1 in the primary circuit controls the plate voltages applied to the tubes, as read on a-c voltmeter M_2. Filament voltage control is obtained by two series filament rheostats R_4 and R_5 and read on the two-scale a-c voltmeter M_3. R_4 is a high resistance—low current rheostat for adjusting the current when testing a tube which does not require much filament voltage and current. R_5 is a low resistance—high current rheostat for adjusting the current when testing a tube which takes a high filament current. The proper filament voltage settings for the various types of tubes are listed in the table at the left. It is very important to always adjust both rheostats to maximum resistance before inserting a tube in any socket. After the tube is inserted, they may be varied to obtain the proper filament voltage. Because of the voltmeter current, the 50—ohm rheostat R_4 provides all regulation necessary—even for 60 m.a. tubes of the —99 type. Grid bias voltage is obtained from the fall of potential caused by the flow of the plate current of the tube tested through the two resistors R_2 and R_3 connected in one side of the circuit. When K_1 is pressed, it shorts R_2 out of the circuit, reducing the grid bias voltage and thereby causing a change in the plate current.

In operation, the rheostats R_4 and R_5 are first set at maximum resistance value. The tube is then inserted in the proper socket and R_4 and R_5 are adjusted to give the correct filament voltage as shown on meter M_3. Resistance R_1 is then set to make meter M_2 read 100 volts. This insures that the correct filament and plate voltage are being applied to the tube being tested. The lamp, L_2, across the transformer primary is to reduce the size of the series resistor required for some of the low-filament-consumption tubes and also serves as a pilot lamp to indicate that the checker is turned on. The plate current is then read on M_1 before and after pressing the kev K_1. A table of approximate plate current changes to be expected follows:

Tube Type	Average Plate Current Values for Tubes	
	K_1 open	K_1 closed
11	1-1.5	1-2.5
cx-12	1-1.5	2-2.5
26	1.5	4
45	3	11
24	1	2.6
27	1.5-2	3-5.5
99	1.5	3
20	2.5-3	5.5-6
22	2	4-6
01A	1.7	4.5-5.0
40	.7	1.7
71A	3.5-4	12-13
00A	1.5	3.5
10	2	6
50	3	10.5
12A	2	6.5-7.0

These should not be taken as absolute standard values, since slight variations in the values of the biasing resistors, transformer, meter calibration, etc., will cause some changes in the result. It would be best to construct the checker and obtain the plate current changes to be taken as a guide, by actually testing a set of the various types of tubes which are known to be in good operating condition.

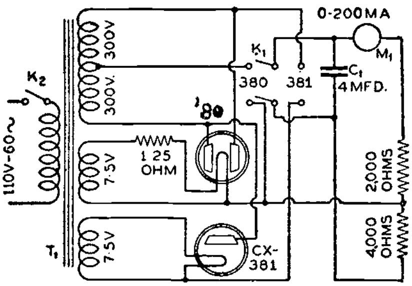
It will be found that the tube readings are dependent on the way in which A and A_1, the plate voltage supply connections, are made to the a-c supply and filament transformers.

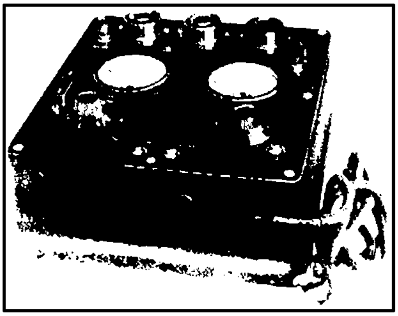
These leads should be reversed until the highest readings are obtained, in order to obtain results comparable to this table. The difference is especially noticeable in the case of tubes with a 7.5-volt filament. It is seen that for the screen-grid tubes the screen grid is connected to the plate, making it a three-element tube for purposes of this test. For this reason it is necessary to use a separate socket for screen-grid tubes since on them the control-grid connection is on top and the screen grid is connected to the usual grid terminal of the socket. Clips are provided for connecting to the caps on screen grid tubes. Of course, a-c meters must be used in the checker. The 10-watt 110 volt lamp L_1 used as a protective resistor is included in the circuit to protect the meter in case a shorted tube is accidentally inserted in the socket. A plate-filament or grid-plate short in a tube inserted in this tester will cause the 10-watt lamp L_1, to light and the needle of meter M_1 to vibrate slightly about the zero adjustment, the needle following the 60-cycle current passing through the meter.

A simple checker for quickly checking the condition of half-wave or full-wave rectifier tubes is shown in Fig. 208. If the transformer T used in the tube checker just described also has a 600 volt center-tapped winding and two additional 7.5 volt windings, the rectifier tube checker may be built as part of the former unit using the single transformer to supply all voltages. The rectifier is arranged to operate in a standard rectifier circuit, using the rectifier tube to deliver a current to a fixed load resistance. A low current through this resistance indicates a defective tube.

The circuit shown at the left of Fig. 208 is arranged to use a standard power transformer delivering 600 to 700 volts from a center-tapped high voltage winding and two 7.5 volt windings. A resistance of 1.25 ohms is connected in series with one winding, so that 5 volts appears across the filament of the type '80 rectifier. As can be seen from the circuit diagram, a double-pole, double-throw switch is provided to change from one type of tube to the other. When a type -80 is being tested, it is supplied with 300 volts per plate and it supplies current to a four mfd. condenser and a 2,000 ohm load resistance. When a type -81 tube is to be tested, the switch is thrown to the proper side and this alters the connections so that the tube is supplied with 600 volts on the plate and it feeds into a 4-mfd. condenser and a 6,000-ohm load resistance.

The test is made by simply throwing the switch to the proper position, placing the tube in the proper socket, closing the line switch and reading the milliammeter connected in series with the load resistance. The milliammeter should read 100 ma. or more for a type -80 tube and 60 ma. or more for a type -81 tube. If the power transformer supplies 700 volts across the high voltage secondary, both the readings will be about 10 ma. greater. It is preferable to keep the tube socket terminals beneath





Courtesy Weston Elect. Inst. Co.

Fig. 208—Left: An a-c operated tube checker for checking half-wave or full-wave rectifier tubes.
Right: A typical tube checker for rapidly checking tubes by making a rough measurement of the mutual conductance.

the panel to avoid shocks. A conventional double-pole double-throw tumbler switch should be employed. The 4-mfd. condenser must be a good one capable of working continuously at 1000 volts, d-c. The load resistor must have a high current-carrying capacity.

At the right of Fig. 208 is shown a typical tube checker designed to operate directly from the 110 volt 60 cycle lighting circuit. Variations in line voltage from 90 to 130 volts are compensated by means of the line voltage adjuster mounted on the panel. All a-c or d-c tubes can be tested, including both single and full-wave rectifiers. Both plates of the type 280 tube can be tested by placing the tube in the socket, noting the meter reading and then pressing a button which gives the reading of the other plate. To operate the tester it is necessary to adjust the line voltage regulator until the pointer on the line voltage meter is opposite the arrow. Then the selector switch is set for the proper voltage and the tube inserted in the correct socket. Pressing the button marked "Press for Grid Test" causes the plate current meter reading to change and whether or not the tube is good can then be determined by checking these plate current readings against a chart supplied with the tester.

Set analyzers (which will be described in the chapter on radio set testing and servicing) are also employed for checking the condition of tubes directly in the radio receiver itself, employing the filament and plate voltages from the receiver. By inserting a plug in a given socket and taking the tube out of that socket and inserting it in the set analyzer socket, the tube is tested under its own circuit conditions. Provision is also made in these, for changing the value of grid bias in order to change the plate current and obtain a check on the mutual conductance of the tube.

292. Dynamic characteristics of tubes: All of the characteristic curves and methods of measuring tube constants considered up to this point have been *static characteristics*, that is, they have been based on a steady grid potential and the voltage actually effective on the plate was assumed to be constant. However, this is not what actually happens when tubes are in actual operation, for as vacuum tubes are used in practice in transmitting and receiving circuits, as alternating or pulsating signal e.m.f. is impressed on the grid circuit and results in a pulsating plate current. When some form of coupling device having impedance is connected in the plate circuit of the tube in order to couple it to the next one in an amplifier, the characteristic curve is altered as we shall see. Since vacuum tubes are used mostly in this way, it is necessary for an exact analysis of the tube action to know the shape of the characteristic that obtains when varying signal potentials are impressed on the grid; that is, it is necessary to know the shape of the *dynamic characteristics*. There are three different conditions of operation (1) the dynamic characteristic of the tube itself; (2) that of the plate circuit containing the tube and a non-inductive resistance; (3) that of the circuit containing the tube and an impedance. For the first case the dynamic characteristic coincides with the static characteristic for a range of frequencies up to several hundred thousand cycles per second, so this need not be considered.

293. Tube with resistance output load: In the case where a non-inductive resistance is connected in the plate circuit of a tube, as in the case of a resistance-coupled amplifier, the dynamic characteristic is altered from the static characteristic. Let us refer to the fundamental amplifier circuit shown at (A) of Fig. 209. The source of steady plate voltage supplies a voltage E_b. The plate current I_p flowing through the plate load resistor R_L causes a fall of potential in it equal to $I_p R_L$ volts. As a result, terminal 1 of this resistor is at a lower potential than terminal 2, since the current flows from 2 to 1. Therefore the effective voltage E_p actually existing between the cathode and the plate is less than the applied voltage E_b by an amount equal to the voltage drop in the resistor, or

$$E_p = E_b - (I_p \times R_L)$$

For example, let $R_L = .5$ megohms (500,000 ohms), $E_b = 250$ volts, $I_p = 0.2$ milliampere. Then, $I_p \times R_L = .0002 \times 500{,}000 = 100$ volts and $E_p = 250 - 100 = 150$ volts actually applied to the plate.

Experiment: Connect up a 201-A type tube in the tube tester shown in Fig. 197 with a fixed value of applied "B" voltage of 180 volts and normal filament current. Now measure and plot the plate current as the grid voltage is varied from about 5 volts plus, to 15 volts minus. Repeat this with values of 1,000, 4,000, 10,000, 50,000 ohms connected in series with the plate.

Any variation in the plate current will cause a variation in the I × R drop across R_L and hence the effective plate voltage E_p will also change according to the equation above. Therefore, any change in the potential on the grid will cause not only a change in plate current, but a variation in effective plate voltage as well, and if the plate load resistor and plate current are large, the effective plate voltage will be quite different from the applied plate voltage. (The values specified for plate voltages in vacuum tube characteristic tables always refer to the actual effective voltage between the cathode and the plate itself.) Therefore the voltage drop

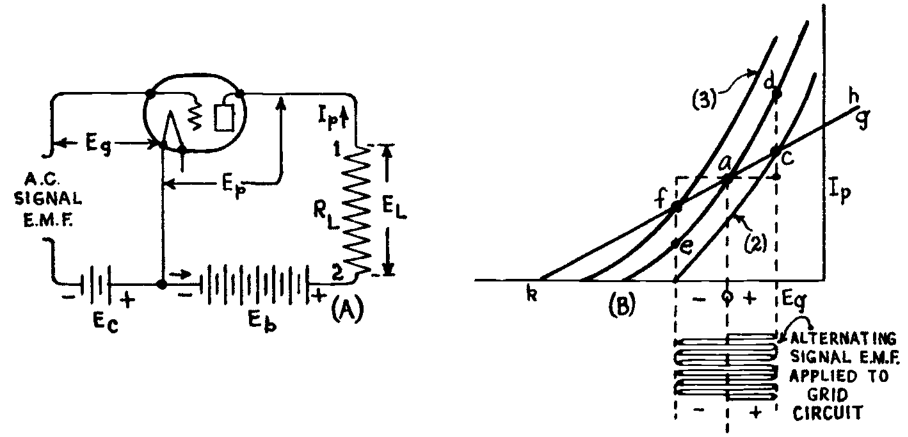


Fig. 209—(A) Vacuum tube with resistance load in plate circuit.
(B) Why the dynamic characteristics of a vacuum tube differ from the static characteristics.

existing across resistor R_L, (which is the useful voltage to be passed on to the next stage) cannot be determined from the static E_g - I_p characteristic curve, because actually, the effective plate voltage is not constant but changes in instantaneous value with every change of grid potential. Hence the corresponding plate current changes are not exactly what we would expect them to be from a consideration of the static characteristics where the effective voltage actually applied to the plate remains absolutely constant and the plate current changes are due to the grid potential changes alone.

In order to see exactly what happens due to this voltage drop in the plate load resistor, let us consider (B) of Fig. 209. Here the E_g - I_p characteristic curves for three values of effective plate voltage E_p are drawn. These might be simply three of the curves from (A) of Fig. 200. Consider the middle curve to be the characteristic for the condition when the tube has a definite value of effective voltage E_p applied to its plate. The other two are the characteristics for higher and lower values of effective plate voltage. Let the constant grid battery voltage E_c be so adjusted that the direct current in the plate circuit is *oa*. Then, on account of the voltage drop in R_L due to the current *oa* in it the actual effective plate-cathode voltage is

$E_p = E_b - I_p R_L$. If I_p be varied by impressing an alternating potential on the grid, E_p varies accordingly, since the plate-supply voltage E_b is constant. Thus, if a positive wave of signal e.m.f. is applied, the grid potential is shifted toward positive and the plate current increases. This causes E_p to decrease in value, due to the increased voltage drop in R_L, say to the corresponding point on the lower characteristic curve (2) and the current instead of increasing to *d* as it would if E_p remained constant, increases only to *c*. Likewise, when a negative wave of signal e.m.f. is applied, the negative grid potential is made more negative, the plate current decreases only to *f* instead of to *e* as it would if E_p remained constant. The characteristic therefore straightens out and takes the shape given by *fac* instead of *ead*.

The *dynamic characteristic* curves for a typical vacuum tube are shown at (A) of Fig. 210. As the voltage drop through R_L depends on the

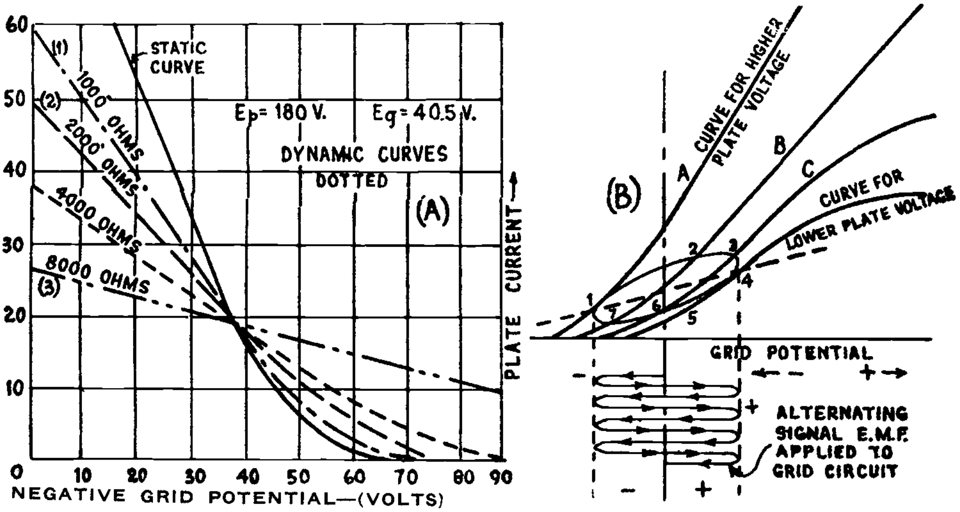


Fig. 210—(A) Static and dynamic Eg-Ip characteristic curves for a typical vacuum tube with various values of resistance load connected in the plate circuit.
(B) Dynamic Eg-Ip characteristics for a tube with an impedance load in the plate circuit.

value of R_L, a different curve will result for each value of R_L employed, as shown: One curve labeled "static" is the static characteristic curve, all the rest are the dynamic curves. These are published here by courtesy of Radio Broadcast Magazine.

The dynamic characteristic is, as its name implies, a curve indicating how the tube will function under actual operating conditions. The static characteristic curve, although valuable in giving an idea of the general characteristics of a tube, gives no indication at all of the tube's actual performance. Under actual operating conditions, a tube always operates with a certain load in its plate circuit and consequently a curve taken to indicate the tube's performance should be made with some load in the plate circuit. One curve marked "dynamic" was taken when the tube had 4000 ohms resistance in its plate circuit. The difference between the static and the dynamic curves is considerable, as will be seen. The curves were taken with an applied B voltage (E_b) of 180 volts and the grid voltage (E_g) was varied in steps, the plate current being measured at each step.

The other curves are dynamic characteristics taken with different resistances in the plate circuit. Curve No. 1 was made with 1000 ohms resistance, No. 2 with 2000 ohms, and No. 3 with 8000 ohms. It will be noticed that with the higher plate load resistances, the curves have longer straight portions. The curves all cross at about 40 volts because this grid voltage represents the initial d-c potential placed on the grid and the curves are made by increasing and decreasing the grid voltage about this average value. It is necessary in taking the curves to adjust the plate voltage each time so that with the different resistances the same plate current is obtained at 40.5 volts on the grid.

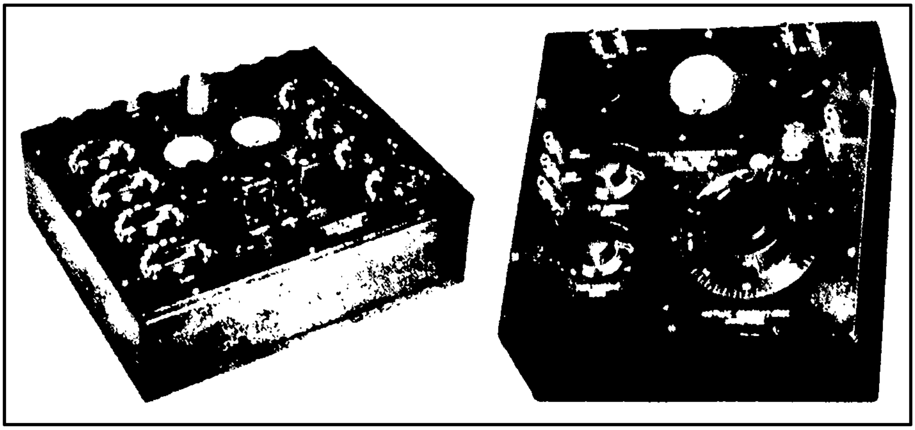
It will be seen that the dynamic curves are much flatter and longer than the static curve. Therefore, the plate current variations for a given grid potential variation, are smaller in magnitude. The mutual conductance of the circuit is no longer as high as the value for the tube alone. The slope of the curve tells us how much plate current will flow through the resistor when a given potential is applied to the grid, under actual circuit conditions, and it is therefore very useful. Of course what we are ultimately interested in are the dynamic characteristics, but if we find that the static characteristics are normal, we can be fairly certain that the tube will operate properly.

294. Tube with impedance plate load: When the plate circuit load is an impedance, that is, contains reactance as well as resistance, the dynamic characteristic curves are somewhat different. A case of this kind would occur if the primary winding of a coupling-transformer, or an impedance coil, were connected in the plate circuit as in the case of transformer or impedance coupled r-f and a-f amplifiers. In this case, on account of the reactance in the plate circuit, the phase difference between the plate and grid potentials may differ from 180 degrees, and the dynamic characteristic of the plate circuit takes the form of a loop as shown at (B) of Fig. 210.

The tube starts working at conditions represented by say, point 1 on a certain characteristic curve A, when the signal voltage is at the lowest value in its negative half cycle, as shown by the wave on the signal e.m.f. curve below. As the signal e.m.f. becomes positive during the next half cycle of the signal e.m.f. curve, the action of the grid of the tube moves over to point 2 on curve B representing a lower effective plate voltage, due to the fact that the effective plate voltage has dropped because of increased drop in voltage in the load impedance. In this way, as the positive half of the cycle of the signal wave goes to maximum, the tube works successively at points 1, 2, 3 and 4. Then as the grid potential becomes more negative due to the signal e.m.f., the action of the tube returns back to point 1, but along a different path 4 - 5 - 6 - 7; since, due to the fact that the entire plate circuit consists of the resistance from plate to cathode in series with the load impedance, the circuit is a reactive one and the plate current changes are not exactly in step with the grid potential changes (see Figs. 109 and 110), whereas if the plate load were pure resistance and the plate current changes were in step with the grid potential changes, the successive operating points would go back along the straight line 4-1. Actually since the plate current reductions and the reduction in the voltage drop in the load impedance lag behind the grid potential changes, the plate current is lower at each instant than it would otherwise be, so the action of the tube returns along points 4 - 5 - 6 - 7 to 1. The curve 1 - 2 - 3 - 4 is above the straight line 1 - 4 for the converse reason, i.e., the variations in voltage drop lag behind the variations in the grid potentials so the plate current at each instant is a little bit higher than it would be if they were in step, so points 1 - 2 - 3 lie above the straight line 1 - 4. As we shall see later, in order to obtain distortionless amplification it is necessary to make the operating characteristics 1 - 2 - 3 - 4 - 5 - 6 - 7 - 1 approach the straight line 1 - 4, since unless this is a straight line, the output plate current variations are not an enlarged reproduction of the input signal voltage variations impressed on the grid circuit. This can be done by making the external load impedance larger than the plate resistance of the tube. Thus the static characteristic curves may be quite different from the dynamic curves.

This does not mean that the static characteristic curves of a vacuum tube are of no value. They are a great help in understanding the dynamic characteristics and they also show many important facts regarding vacuum tubes. They simply must be used with a full understanding that they do not show the exact conditions existing when the tube is in actual operation in practical circuits.

295. Bridge methods of finding dynamic characteristics: The determination of the actual tube constants under the dynamic circuit conditions just described, i.e., with varying grid potentials, is usually accomplished with some form of bridge circuit. An a-c potential from some source such as a 1,000 cycle oscillator or buzzer is usually applied to the



Courtesy General Radio Co.

Fig. 211—**Left:** Vacuum tube bridge for laboratory measurement of dynamic or static characteristics of vacuum tubes. See Fig. 212.
Right: Meter for rapid measurement of mutual conductance.

grid circuit of the tube under test. A 1,000 cycle e.m.f. source is usually employed as a signal voltage since the minimum sound in the earphones may be more easily detected on account of the great sensitivity of the ear to sounds of 1,000 cycles. A bridge for measuring the tube constants is not the ordinary type of impedance network. It depends upon the balancing of the amplified signal voltage in the plate circuit by an opposing voltage so that no sound is heard in the earphones connected in the plate circuit (after the manner of the ordinary impedance bridge). A typical laboratory type of vacuum tube bridge designed for rapid measurements is shown at the left of Fig. 211. By means of several switches provided, it is possible to obtain the circuit arrangements shown in Fig. 212, in order to make various measurements. A bridge of this type may be used for easy and rapid measurement of filament characteristics of amplification constant, a-c plate resistance and mutual conductance. Either static or dynamic characteristics may be measured with it. As complete instructions for operating the bridge are furnished by the manufacturer, they are not given here.

The bridge is designed to combine accuracy with great ease and speed of manipulation. All changes in the bridge to obtain the different circuits used, are made by the use of throw switches. The balancing adjustments are on a dial decade scheme. There is no necessity for removing plugs or changing connections.

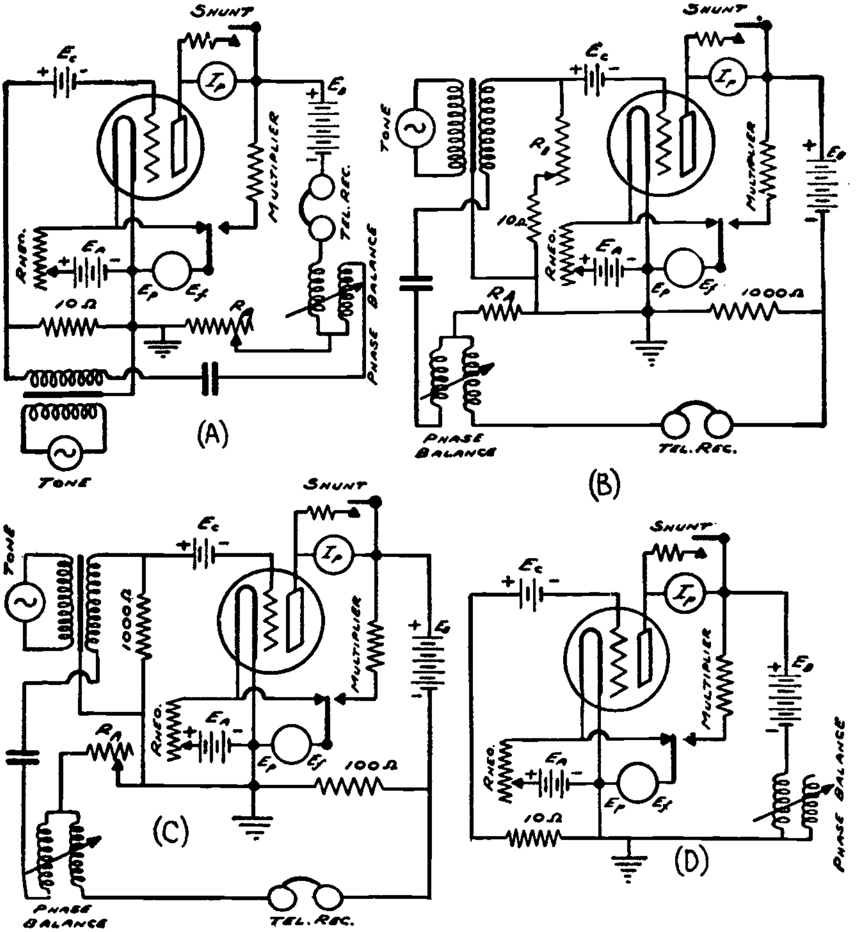


Fig. 212—Circuit arrangements which may be obtained by means of the key switches provided in the vacuum tube bridge of Fig. 211.
(A) circuit for measuring amplification constant. (B) circuit for measuring the a-c plate resistance. (C) circuit for measuring mutual conductance. (D) circuit for taking the static characteristics.

Of the three fundamental dynamic constants of a tube, the mutual conductance gives the most positive indication of the tube behavior, since it involves the ratio of the other two constants. While it is not a complete indication of the comparative merit of tubes of differing types, it is a positive indication among tubes of the same type. If a tube fails to meet the standard specifications of its type, either through faulty filament emission or an incorrect spacing of the elements, the mutual conductance always will be lowered and it may be detected. Since the mutual conductance is very easily measured, this constant is the one most suited for use as an acceptance standard for purchasers, and for use in factory, store or laboratory for rapid checking of tubes against a standard value. A mutual conductance meter designed to measure this constant rapidly, is shown at the right of Fig. 211. This device should not be confused with the vacuum tube bridge just described, which is a laboratory instrument designed to give accurate measurement of all three constants.

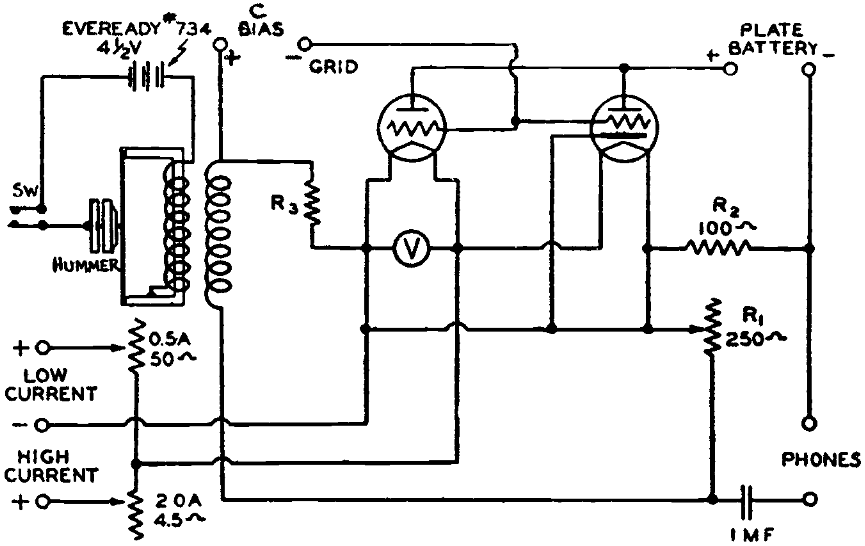


Fig. 213—Circuit diagram of the mutual conductance meter shown at the right of Fig. 211.

A commercial type of mutual conductance meter is shown at the right of Fig. 211. Its circuit diagram is shown in Fig. 213. This is a null-point bridge instrument excited by a 1,000 cycle e.m.f. produced by a self contained microphone hummer and battery. A standard four-prong socket is provided, as well as a 5-prong socket for five-prong separate-heater tubes. All tube batteries are to be connected externally, and any desired plate voltage may be applied to the tube as well as any desired grid biasing voltage. The instrument is equipped with a voltmeter for indicating the voltage across the filament. A low-resistance high-current, and a high-resistance low-current rheostat are provided for filament voltage adjustment of all types of tubes. By the use of one or the other of the rheostats it is possible to adjust the filament voltage to the correct value for any standard tube. A pair of earphones is used to indicate when the bridge is balanced. If the bridge is operated in a noisy environment, an external stage of amplification should be employed to bring up the sound level in the earphones.

Values of mutual conductance having a precision of within 5 per cent are quickly obtained by the manipulation of the single dial to give silence in the phones. This is calibrated to read the mutual conductance in micromhos directly. When testing screen grid tubes, the negative terminal of the C battery is connected directly to the control grid cap on the screen grid tube by means of a wire and a clip. A screen grid battery is connected with its negative terminal to A- and its positive terminal to the

DETECTORS AND AMPLIFIERS

TYPE	PURPOSE	BASE	DIMENSIONS MAX. OVERALL: LENGTH	DIAM.	CATHODE TYPE	RATING: FILAMENT (OR HEATER) VOLTS	AMPERES	SUPPLY	PLATE MAX VOLTS	SCREEN MAX VOLTS	PLATE SUPPLY VOLTS	NEGATIVE GRID BIAS VOLTS: D C ON FIL.	A C ON FIL.	SCREEN VOLTS	PLATE CURRENT MILLI-AMP.	A C PLATE RESISTANCE OHMS	MUTUAL CONDUCTANCE MICRO-MHOS	VOLTAGE AMPLIFICATION FACTOR	OHMS LOAD FOR STATED POWER OUTPUT	POWER OUTPUT MILLI-WATTS
WD-11	DETECTOR or AMPLIFIER	WD 11	4¼"	1 3/16"	FILAMENT	1.1	0.25	D C	135	—	90 135	4.5 10.5	—	—	2.5 3.0	15500 15000	425 440	6.6 6.6	15500 18000	7 35
WX-12	DETECTOR or AMPLIFIER	UX	4¼"	1 3/16"	FILAMENT	1.1	0.25	D C	135	—	90 135	4.5 10.5	—	—	2.5 3.0	15500 15000	425 440	6.6 6.6	15500 18000	7 35
UX-112-A	DETECTOR or AMPLIFIER	UX	4 11/16"	1 13/16"	FILAMENT	5.0	0.25	D C	180	—	90 135	4.5 9.0	—	—	5.2 6.2	5600 5300	1500 1600	8.5 8.5	5600 8700	30 115
UV-199	DETECTOR or AMPLIFIER	UV 199	3½"	1 3/16"	FILAMENT	3.3	0.063	D C	90	—	90	4.5	—	—	2.5	15500	425	6.6	15500	7
UX-199	DETECTOR or AMPLIFIER	UX	4¼"	1 3/16"	FILAMENT	3.3	0.06	D C	90	—	90	4.5	—	—	2.5	15500	425	6.6	15500	7
UX-200-A	DETECTOR	UX	4 11/16"	1 13/16"	FILAMENT	5.0	0.25	D C	45	—	45	Grid Return to −1 Filament		—	1.5	30000	666	20	—	—
UX-201-A	DETECTOR or AMPLIFIER	UX	4 11/16"	1 13/16"	FILAMENT	5.0	0.25	D C	135	—	90 135	4.5 9.0	—	—	2.5 3.0	11000 10000	725 800	8.0 8.0	11000 20000	15 55
UX-222	RADIO FREQ. AMPLIFIER	UX	5½"	1 13/16"	FILAMENT	3.3	0.132	D C	135	67.5	135 135	1.5 1.5	—	45 67.5	1.5 3.3	850000 600000	350 480	300 290	—	—
UX-222	AUDIO FREQ AMPLIFIER	UX	5½"	1 13/16"	FILAMENT	3.3	0.132	D C	135	67.5	180†	1.5	—	22.5	0.3	2000000	175	350	—	—
UT-224	RADIO FREQ AMPLIFIER	UY	5½"	1 13/16"	HEATER	2.5	1.75	A C or D C	275	90	180 180 250	1.5 3.0 3.0	1.5 3.0 3.0	75 90 90	4.0 4.0 4.0	400000 400000 600000	1050 1000 1025	420 400 615	—	—
UY-224	BIASED DETECTOR	UY	5½"	1 13/16"	HEATER	2.5	1.75	A C or D C	275	90	275‡	5 approx.	5 approx.	20 to 45	Plate Current to be adjusted to 0.1 ma with no Input Signal			—	—	—
UY-224	AUDIO FREQ AMPLIFIER	UY	5½"	1 13/16"	HEATER	2.5	1.75	A C or D C	275	90	250*	1.0	1.0	25	0.5	2000000	500	1000	—	—
UX-226	AMPLIFIER	UX	4 11/16"	1 13/16"	FILAMENT	1.5	1.05	A C or D C	180	—	90 135 180	5.0 8.0 12.5	6.0 9.0 13.5	—	3.8 6.3 7.4	8600 7200 7000	855 1135 1170	8.2 8.2 8.2	9000 8000 10500	30 90 180
UT-227	DETECTOR or AMPLIFIER	UY	4 5/16"	1 13/16"	HEATER	2.5	1.75	A C or D C	275	—	90 135 180 250	6.0 9.0 13.5 21.0	6.0 9.0 13.5 21.0	—	2.7 4.5 5.0 5.2	11000 9000 9000 9250	820 1000 1000 975	9.0 9.0 9.0 9.0	14000 13000 18700 24000	30 80 165 300
UY-227	BIASED DETECTOR	UY	4 5/16"	1 13/16"	HEATER	2.5	1.75	A C or D C	275	—	275	30.0 approx.	30.0 approx.	—	Plate Current to be adjusted to 0.2 ma with no Input Signal			—	—	—
RCA-230	DETECTOR or AMPLIFIER	UX	4½"	1 3/16"	FILAMENT	2.0	0.06	D C	90	—	90	4.5	—	—	1.8	13000	700	9.3	15000	16
RCA-232	RADIO FREQ AMPLIFIER	UX	5½"	1 13/16"	FILAMENT	2.0	0.06	D C	180	67.5	135	3.0	—	67.5	1.4	150000	505	580	—	—
RCA-232	BIASED DETECTOR	UX	5½"	1 13/16"	FILAMENT	2.0	0.06	D C	180	67.5	174¶	6 approx.	—	67.5	Plate Current to be adjusted to 0.2 ma. with no Input Signal			—	—	—
RCA-232	AUDIO FREQ AMPLIFIER	UX	5½"	1 13/16"	FILAMENT	2.0	0.06	D C	180	67.5	180†	1.0	—	22.5	0.25	—	—	—	—	—
RCA-235	RADIO FREQ AMPLIFIER	UY	5½"	1 13/16"	HEATER	2.5	1.75	A C or D C	275	90	180 250	1.5 3.0	1.5 3.0	75 90	5.8 6.5	350000 350000	1100 1050	385 370	—	—
RCA-236	RADIO FREQ AMPLIFIER	UY	4 11/16"	1 9/16"	HEATER	6.3	0.3	D C	135	75	90 135	1.5 1.5	—	55 67.5	1.8 3.0	200000 300000	850 1050	170 315	—	—
RCA-237	DETECTOR or AMPLIFIER	UY	4¼"	1 9/16"	HEATER	6.3	0.3	D C	135	—	90 135	6.0 9.0	—	—	2.6 4.3	11500 10000	780 900	9.0 9.0	17500 14000	30 80
UX-240	VOLTAGE AMPLIFIER	UX	4 11/16"	1 13/16"	FILAMENT	5.0	0.25	D C	180		135‡ 180†	1.5 3.0	—	—	0.2 0.2	150000 150000	200 200	30 30	—	—

*For Grid-leak Detection—plate volts 45, grid return to + filament or to cathode.
†Applied through plate coupling resistor of 250000 ohms.
'Applied through plate coupling resistor of 200000 ohms.
‡Applied through plate coupling resistor of 10000 ohms.
‡Applied through plate coupling resistor of 250000 ohms or 500 henry choke shunted by 0.25 megohm resistor.
¶Applied through plate coupling resistor of 100000 ohms.

POWER AMPLIFIERS

TYPE	PURPOSE	BASE	LENGTH	DIAM.	CATHODE TYPE	FILAMENT VOLTS	AMPERES	SUPPLY	PLATE MAX VOLTS	SCREEN MAX VOLTS	PLATE SUPPLY VOLTS	NEG. GRID BIAS D C ON FIL.	A C ON FIL.	SCREEN VOLTS	PLATE CURRENT MILLI-AMP.	A C PLATE RESISTANCE OHMS	MUTUAL CONDUCTANCE MICRO-MHOS	VOLTAGE AMPLIFICATION FACTOR	OHMS LOAD FOR STATED POWER OUTPUT	POWER OUTPUT MILLI-WATTS
UX-112-A	POWER AMPLIFIER	UX	4 11/16"	1 13/16"	FILAMENT	5.0	0.25	A C or D C	180	—	135 180	9.0 13.5	11.5 16.0	—	6.2 7.6	5000 5000	1600 1700	8.5 8.5	8700 10800	115 260
UX-120	POWER AMPLIFIER	UX	4¼"	1 3/16"	FILAMENT	3.3	0.132	D C	135	—	90 135	16.5 22.5	—	—	3.0 6.5	8000 6300	415 525	3.3 3.3	9600 6500	45 110
UX-171-A	POWER AMPLIFIER	UX	4 11/16"	1 13/16"	FILAMENT	5.0	0.25	A C or D C	180	—	90 135 180	16.5 27.0 40.5	19.0 29.5 43.0	—	12.0 17.5 20.0	2250 1960 1850	1330 1520 1620	3.0 3.0 3.0	3200 3500 5350	125 370 700
UX-210	POWER AMPLIFIER	UX	5½"	2 3/16"	FILAMENT	7.5	1.25	A C or D C	425	—	250 350 425	18.0 27.0 35.0	22.0 31.0 39.0	—	10.0 16.0 18.0	6000 5150 5000	1330 1550 1600	8.0 8.0 8.0	13000 11000 10200	400 900 1600
RCA-231	POWER AMPLIFIER	UX	4½"	1 3/16"	FILAMENT	2.0	0.130	D C	135	—	135	22.5	—	—	8.0	4050	760	3.8	9000	150
RCA-233	POWER AMPLIFIER	UY	4 11/16"	1 13/16"	FILAMENT	2.0	0.26	D C	135	135	135	13.5	—	135+	14.0	50000	1500	75	7000	700
RCA-238	POWER AMPLIFIER	UY	4 11/16"	1 9/16"	HEATER	6.3	0.3	D C	135	135	135	13.5	—	135++	9.0	102000	975	100	13500	525
UX-245	POWER AMPLIFIER	UX	5½"	2 3/16"	FILAMENT	2.5	1.5	A C or D C	275	—	180 250 275	33.0 48.5 54.5	34.5 50.0 56.0	—	27.0 34.0 36.0	1900 1750 1670	1850 2000 2100	3.5 3.5 3.5	3500 3900 4600	780 1600 2000
RCA-247	POWER AMPLIFIER	UY	5½"	2 3/16"	FILAMENT	2.5	1.75	A C or D C	250	250	250	15.0	16.5	250+++	32.0	35000	2500	90	7000	2500
UX-250	POWER AMPLIFIER	UX	6¼"	2 11/16"	FILAMENT	7.5	1.25	A C or D C	450	—	250 350 400 450	41.0 59.0 66.0 80.0	45.0 63.0 70.0 84.0	—	28.0 45.0 55.0 55.0	2100 1900 1800 1800	1800 2000 2100 2100	3.8 3.8 3.8 3.8	4300 4100 3670 4350	1000 2400 3400 4600

+Screen Current 3.5 Milliamperes. ++Screen Current 2.5 Milliamperes. +++Screen Current 7.5 Milliamperes.

RECTIFIERS

TYPE	PURPOSE	BASE	LENGTH	DIAM.	CATHODE TYPE	FILAMENT VOLTS	AMPERES	SUPPLY	RATINGS	NOTES
UX-280	FULL-WAVE RECTIFIER	UX	5½"	2 3/16"	FILAMENT	5.0	2.0	A C	1 {A C Voltage per Plate (Volts RMS) ... 350; D C Output Current (Maximum MA.) ... 125 2 {A C Voltage per Plate (Maximum Volts RMS) ... 400; D C Output Current (Maximum MA.) ... 110 3 {A C Voltage per Plate (Maximum Volts RMS) 550; D C Output Current (Maximum MA.) ... *135 (This rating is permissible only with filter circuits having an input choke of at least 20 henries.	For d-c output voltage delivered to filter of typical rectifier circuit, refer to curves in Technical Bulletin.
UX-281	HALF-WAVE RECTIFIER	UX	6¼"	2 3/16"	FILAMENT	7.5	1.25	A C	A C Plate Voltage (Maximum Volts RMS) ... 700 D C Output Current (Maximum MA.) ... 85	For d-c output voltage delivered to filter of typical rectifier circuit, refer to curves in Technical Bulletin.

TYPES FOR AMATEUR AND EXPERIMENTAL RADIO USES

TYPE	PURPOSE	BASE	DIMENSIONS MAXIMUM OVERALL: LENGTH	DIAM.	CATHODE TYPE	FILAMENT: VOLTS	AMPS	SUPPLY	NORMAL PLATE VOLTS	VOLTAGE AMPLIFICATION FACTOR	NEGATIVE GRID BIAS: CLASS B APPROXIMATE VOLTS	CLASS C APPROXIMATE VOLTS	SCREEN VOLTAGE: CLASS B APPROXIMATE VOLTS	CLASS C APPROXIMATE VOLTS	PLATE CURRENT: CLASS B MAXIMUM MA.	CLASS C MAXIMUM MA.	PLATE DISSIPATION: CLASS B MAXIMUM WATTS	CLASS C MAXIMUM WATTS	POWER OUTPUT: CLASS B PEAK WATTS	CLASS B CARRIER WATTS	CLASS C WATTS
UX-852	OSCILLATOR or R.F. POWER AMPLIFIER	UX	8½"	6 1/16"	FILAMENT	10.0	3.25	A C	2000	12	150	250	—	—	85	100	100	100	120	30	100
UX-865	OSCILLATOR R.F. POWER AMPLIFIER	UX	6¼"	2 3/16"	FILAMENT	7.5	2.0	A C	500	150	40	75	125	125	30	60	15	15	7.5	1.9	7.5
RCA-866	HALF-WAVE RECTIFIER	UX	6¼"	2 3/16"	FILAMENT	2.5	5.0		Maximum Peak Inverse Voltage 7500 Volts; Maximum Peak Plate Current 0.6 Ampere; Approximate Tube Voltage Drop 15 Volts												

Courtesy R.C.A. Radiotron Co

Fig. 214—Table of average characteristics of the various types of vacuum tubes.

C-terminal of the tester, for the screen grid of the tube connects to the normal G terminal of the tube socket.

It is desirable that tubes be tested for short-circuited elements before being placed in the mutual conductance meter. A glance at the schematic diagram will show that when any of the elements in the tubes are shorted, the entire plate battery is impressed across R2, and although R2 will carry 250 milliamperes, it will not withstand the heavy short-circuit current from the plate battery. If it is not practical to make a preliminary test for short-circuited elements, a protective relay or a fuse may be inserted in series with the plate battery.

296. Table of vacuum tube characteristics. As there are many different types of tubes for various special applications, and designed to operate from various sources and values of voltages and currents, it is convenient to have all of their important constants and operating characteristics arranged in a chart or table for convenience. A table of this kind is shown in Fig. 214. This is reproduced here by courtesy of the R.C.A. Radiotron Co., Inc. The student should learn to look up values from this chart and he should spend some time acquainting himself with the different general type numbers of the various tubes as well as the operating filament, grid and plate voltages recommended for them, and the values of mu, mutual conductance, a-c plate resistance, and undistorted power output resulting. A good working knowledge of the data contained in this table will be of great assistance in all work concerning the use of vacuum tubes.

For instance, referring to the 227 tube and reading over to the various columns at the right, we find that this tube may be used either as a detector or an amplifier, has a UY type base, may obtain its filament supply of 1.75 amperes at 2.5 volts either from an a-c or d-c source, will operate as a detector with a plate voltage of 45 volts, etc. We find that when used as an amplifier, with an effective plate voltage of 90 volts, and a C-bias of 6 volts, the plate current is 2.7 milliamperes, the a-c plate resistance is 11,000 ohms, the mutual conductance is 820 micromhos, the mu is 9, the ohms load for maximum undistorted output is 14,000 ohms, and the maximum undistorted output is 30 milliwatts. For other values of plate and C bias voltages, these values are different as shown. In this way, this table can be used to supply a great deal of valuable operating data about all of the types of tubes listed.

REVIEW QUESTIONS

1. What are the three important constants of a vacuum tube?
2. Of what use are vacuum tube characteristic curves?
3. Why does a certain electric potential on the grid have a greater influence over the space charge and plate current flow in a tube than an equal potential applied to the plate?
4. For a given tube the same change in plate current is produced whether the plate voltage is changed by 50 volts or the grid potential is changed by 5 volts. What is the amplification factor of this tube?
5. Draw an E_g - I_p characteristic curve for a tube operating with 90 volts applied to the plate, using the following values of E_g - I_p; —10 volts, .2 m.a.; —8 volts, 0.5 m.a.; +6 volts, 12 m.a. Find the amplification factor, of the tube at some point on this curve, assuming that the E_g - I_p characteristic for a plate voltage of say 80 volts may be drawn parallel to and near this one.

6. Find the mutual conductance of the tube in problem (5), from the curve.
7. Find the d-c plate resistance of the tube in problem (5) at a grid potential of —4 volts. Find the a-c plate resistance.
8. Define (a) amplification constant, (b) mutual conductance, (c) d-c plate resistance, (d) a-c plate resistance of a tube.
9. Why do the mutual conductance and the a-c plate resistance of a tube vary if the plate and grid voltages are varied?
10. Why is the plate current always larger than the grid current? Under what conditions may current flow in the grid circuit of a vacuum tube?
11. The power output of a vacuum tube is greater than the power input. Does this mean that the tube creates power? Explain just where the extra power comes from.
12. One tube has an amplification factor of 200, another type has a value of 5. Does this mean that the first tube is a better tube to use in any type of amplifier than the latter is? Explain in detail.
13. Explain in detail why the signal voltage to be amplified is always impressed across the grid circuit of a vacuum tube rather than into, or across, any of the other circuits.
14. What tube constant do most commercial tube checkers measure? Why?
15. Draw a simple circuit diagram of a tube checker designed to check the mutual conductance of a simple 3-electrode tube. Explain its operation.
16. What is the difference between the static and dynamic characteristic curves of vacuum tubes? Why are they different? Which gives more accurate information concerning the characteristics of a vacuum tube under actual operating conditions? Why?
17. If you were interested merely in finding out whether various tubes in a batch were in good operating condition, what test would you apply to them?
18. If you wanted to find out the exact characteristics of the tubes in question 17, how would you test them? Why?
19. A 90 volt B battery is connected in the plate circuit of a vacuum tube in which there is also a 0.1 megohm resistor. The plate current flowing is 0.2 milliampere. What is the effective voltage being applied to the plate of the tube? What voltage appears across the resistor? Draw a sketch with all of the circuit conditions and values marked on it and explain.
20. Would a tube whose E_g - I_p characteristic curve was very steep have a higher or lower amplification constant than one whose curve is not so steep? Why?
21. What is meant by the term "transconductance"?

CHAPTER 19

CONSTRUCTION FEATURES OF VACUUM TUBES

MANY TYPES OF TUBES — ELECTRON EMITTING FILAMENTS — THORIATED TUNGSTEN FILAMENT — REACTIVATING THORIATED TUNGSTEN FILAMENTS — OXIDE COATED FILAMENTS — INDIRECTLY HEATED CATHODES — CATHODES FOR A-C FILAMENT OPERATION — QUICK HEATER TUBES — THREE-ELECTRODE INDIRECT HEATER TUBE — PARALLEL AND SERIES OPERATION OF HEATER FILAMENTS — WHAT SCREEN GRID TUBE DOES — FEEDBACK IN R. F. AMPLIFIER — ELECTRODE ARRANGEMENT IN S. G. TUBE — TYPES OF S. G. TUBES — CHARACTERISTICS OF S. G. TUBES — SPACE-CHARGE GRID TUBE — VARIABLE MU S. G. TUBE — POWER TUBES — HEATING OF THE PLATE; SECONDARY EMISSION AND SPACE CHARGE — POWER PENTODE TUBE — SCREEN GRID PENTODE — POWER SENSITIVITY — GRID BIAS FOR DIRECT HEATER AND INDIRECT HEATER TUBES, AND FOR SEVERAL TUBES — VACUUM TUBE CONSTRUCTION AND MANUFACTURE — EFFECT OF GAS — REVIEW QUESTIONS.

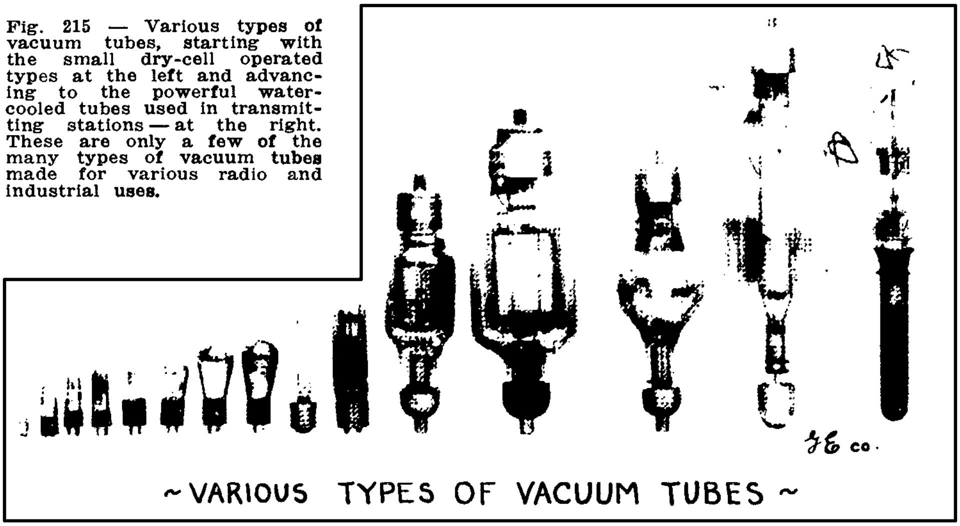
297. Many types of tubes: Vacuum tubes are made in many forms with electrodes of various sizes, shapes and arrangements, each designed to give the tube certain special desired characteristics.

The receiving types vary in filament rating, electron emitting characteristics, mutual conductance, a-c plate resistance and amplification constant. They also vary in detector sensitiveness, power output and overload capacity. Various types of vacuum tubes are shown in Fig. 215. This is only a part of the list of the many types of tubes made. The filaments may be designed to be operated from dry cells, storage batteries or raw alternating current. The tubes can be constructed to handle from one or two milliwatts to several thousand watts of power. The filaments may be either of the thoriated tungsten type or coated with the oxides of barium or calcium to increase the electron emission for a given temperature. In many tubes, the filament does not emit electrons at all, the electron emission being obtained from a separate cathode heated by the filament. Filaments may be made in the form of round wires, or flat ribbons; arranged in the form of a straight wire, an inverted V, a double V, etc.

The plates are usually plain, box shaped, or nearly cylindrical, with the grids corresponding. The relative spacing of grid, filament, and plate, as well as the fineness of the mesh in the grid, also depends on the type of tube. Some tubes have been designed with a multiplicity of filaments, grids and plates. Some types of tubes have even been designed with multiple elements so as to contain within the glass bulb all the necessary parts for one or two amplifier stages. These have attained some popularity in the United States. While a large number of types of tubes are manufactured, we will now see that they all possess generally similar construction features. We will also see how the special characteristics are obtained.

298. Electron-emitting filaments: As explained in Article 264, all practical vacuum tubes in use at the present time obtain a supply of electrons for their operation by means of some body called the *cathode* which is heated by an electric current flowing through a filament wire. The student is advised to refer again to Fig. 189 for a review of the various methods of obtaining an electron emission. The question is often asked as to whether radium could be used as the electron emitter in vacuum tubes.

Fig. 215 — Various types of vacuum tubes, starting with the small dry-cell operated types at the left and advancing to the powerful water-cooled tubes used in transmitting stations—at the right. These are only a few of the many types of vacuum tubes made for various radio and industrial uses.



Radium gives out, among other things, a continuous stream of electrons. A filament of metallic radium in a vacuum tube would produce electrons continuously, whether it were hot or cold, for thousands of years. It would avoid, therefore, any necessity for heating the filament. The heating battery could be dispensed with and the filament would never wear out or burn out.

This would be very pleasant, but filaments of metallic radium are impossible if for no other reason than because one of them would cost some half-million dollars. What is actually proposed, and has been many times attempted, is to construct a tube in which the hot filament as a source of electrons is replaced by a preparation containing very little radium but which is still capable of giving off a continuous stream of electrons. A familiar example is the material used on the face figures of the so-called radium watches. This material really does contain a little radium. The activity of the radium produces light from another constituent of the material causing the figures to shine in the dark.

Now similar compositions containing radium can be made so that they will produce electrons instead of light and they can be put into vacuum tubes instead of the filament. A radium tube is, therefore, possible in theory. Whether it would be really useful is another matter, since there would be no practical way of controlling the electron emission in order to produce tubes with desired characteristics easily controlled during manufacture.

We will first consider the filaments used in those tubes in which the electrons are emitted directly from the heated filament itself, i.e., the filament is the *cathode*, as shown at (B) and (C) of Fig. 189. Since the purpose of the filament is to produce heat, it makes no difference so far as the emission of electrons by heating is concerned, whether the filament is heated to red heat by current from dry cells, a storage battery or an electric light line, provided the proper voltage is supplied to it. Any of these sources of voltage supply may be used, but the ordinary electric light line is probably the most widespread and convenient source of filament voltage commonly employed.

Some substances emit electrons readily at rather low temperatures, while most materials give off very few even though heated to extremely high temperatures. It has been found that the oxides of the rare earth metals, thorium, barium, calcium and strontium, give off a more abundant supply at easily obtained temperatures than any other materials of reasonable cost thus far produced, so they are used in vacuum tubes for producing the electron emission. As these materials are not mechanically strong enough to be made into self-supporting filaments and do not conduct electric current very well anyway, a filament of some wire such as tungsten, nickel or platinum, capable of being operated continuously at high temperatures without melting, is employed to carry the current and act as a rigid structure for supporting the electron-emitting material. Two types of cathodes of this form are in general use today, the thoriated tungsten filament and the oxide-coated filament. The use of the latter is rapidly increasing and it is being employed in all of the new types of tubes, but since the thoriated tungsten filament is still being used in the tubes which are listed in the reactivation table of Article 300 as being capable of being reactivated, a short description of it will be given here.

Since the function of the filament in the type of tube now being considered, is to emit electrons, it is evident that it is desirable from the point of view of life of the filament wire, and electrical power consumed in the filament circuit, to use an electron-emitting material which will emit the greatest quantity of electrons at the lowest operating temperature. Pure tungsten wire is not a very good electron emitter, thoriated tungsten wire is better and barium and strontium oxides are still better. For instance, for the same amount of power in watts used in the filament circuit (same normal operating temperature), when the plain tungsten has an emission represented by 1, the thorium's emission is represented by about 20, and the emission of the oxide coated filament is about 120. The advantage of the oxide coated filament is apparent. Under normal operating conditions, thoriated tungsten filaments are operated at a white heat at about 1700 degrees Centigrade in order to secure sufficient emission, whereas oxide-coated filaments give sufficient emission when operated at a dull red heat at about 750 degrees Centigrade, with corresponding longer life. For a given emission current, the thoriated tungsten filament takes one-fourth the electrical heating power required by a pure tungsten filament. An oxide-coated filament requires less than one-half that required by a thoriated filament.

299. Thoriated tungsten filament: At the present time, some commercial types of tubes still use the thoriated tungsten filament. These are the ones listed as being capable of reactivation in the table in Article 300.

The thoriated tungsten filament is really a tungsten filament having thorium distributed throughout its mass, and a very thin layer of the metal thorium on its surface. The tungsten serves merely to heat the thorium and to renew the thorium layer as it is used up, the electron emission coming wholly from the thorium layer. The raw filament wire is made of tungsten impregnated with from one-half to one per cent of thorium oxide and some carbon. (Tungsten is the metal also used for the filaments of incandescent lamp bulbs because of its ability to withstand high temperature without melting.)

When such a filament is heated, two important actions take place. As the temperature is increased to about 2,500 degrees Centigrade, some of the thorium oxide is reduced to metallic thorium, and then this gradually works its way to the surface of the filament. At this temperature, the thorium which diffuses to the surface of the filament vaporizes immediately, leaving only pure tungsten at the surface. If the temperature is then lowered to about 1,800 degrees Centigrade for a few minutes, the thorium wanders or diffuses through the filament and when it reaches the surface (provided the vacuum is about perfect) remains there and gradually forms a layer of metallic thorium atoms which never exceeds a single atom in depth. It is this almost inconceivably thin layer which inereases the emission over a hundred thousand times. When more thorium atoms work their way to the surface and come up under other thorium atoms already there, the latter at once evaporate, thus maintaining the layer only one atom thick. If the temperature is raised a few hundred degrees, the metallic thorium is formed from the oxide more rapidly and comes to the surface more abundantly, but it does not stay on the surface. It evaporates at once, leaving a tungsten surface.

This film is very sensitive and must not be heated to too high a temperature, or it will evaporate. It is necessary to operate such a filament within a narrow range of temperature close to 1,700 degrees Centigrade, where the ratio of evaporation is small and the temperature is high enough for the thorium to diffuse gradually to the surface and continually replenish the layer as it is used up by the normal operation of the tube. In the UX-201 A tube which uses this type of filament for instance, this condition obtains approximately when five volts is applied to the filament, sending a current of 0.25 amperes through it.

The electron emission of tubes employing this type of filament depends upon the presence of a thin layer of thorium atoms on the outer surface of the filament. During the normal operation of the tubes, the thorium on the outer surface gradually evaporates. This is constantly replenished by diffusion of the thorium from the inside of the filament. As long as the filament voltage is normal and is not raised over ten per cent above the rated value, the evaporation and replenishing continues at an equilibrium rate, so that a constant layer of thorium is maintained on the surface.

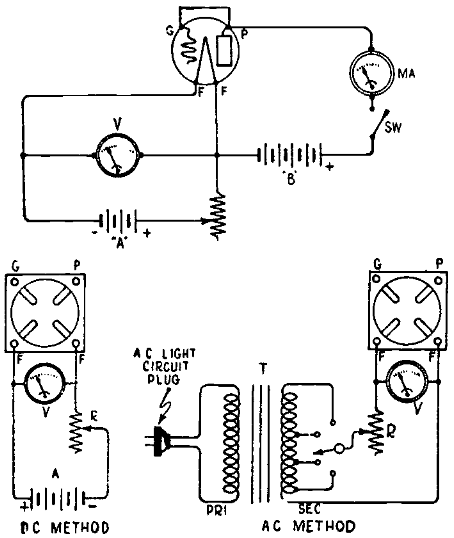
If too high a filament voltage is used, the rate of evaporation of thorium is increased more rapidly than the rate of diffusion of the thorium to the surface, the thorium surface layer is partially or totally destroyed, and the emission drops to that of pure tungsten (which is practically zero at these temperatures) and the tube operation is impaired. If the tubes are operated at very low voltages, the filament temperature is so low that the process of boiling out the thorium from the interior of the filament becomes abnormally retarded, and the layer is slowly used up.

The great majority of thoriated tubes die a natural death, in that their life continues until all of the thorium in the filament is used up. Obviously nothing further can be done with them. Tubes which decrease in operating efficiency after having suffered some of the abuses mentioned above can usually have their thorium layer and full efficiency restored by the simple process of "reactivation" or "rejuvenation". Reactivation consists of cleaning the surface and reducing some of the thorium oxide in the wire to metallic thorium by heating the filament of the tube (with plate and grid circuit disconnected) to a higher temperature than normal, for a short time, by the application of specified high voltages. This is known as "flashing". Then it is operated for a longer time at a lower temperature. This boils out additional thorium atoms from the interior of the filament and a new active layer is formed on the surface. This is known as "ageing". The plate and grid circuits are left disconnected to prevent them from attracting the thorium electrons to themselves during the process.

300. Reactivating thoriated tungsten filaments: The process of reactivation of thoriated tungsten filaments may be carried out as follows:

All tubes not listed in the table of Fig. 216 as being capable of reactivation have oxide-coated filaments.

Before reactivating a suspected tube, the condition of its filament should be tested by testing its electron emission to see if it is actually below normal. This is done by connecting the grid and plate together as shown at the upper left hand diagram of Fig. 216 and connecting them to the plus terminal of a "B" battery through a milliammeter of suitable range (see table in Fig. 216). The remaining connections are shown. The voltage across the filament, read on V, should first be adjusted to the values specified in the table, for the particular type tube being tested. This also gives the proper "B" voltage to use. Close the switch *just long enough to obtain a reading of the emission current on MA.* If the reading is *less* than that specified in the table, the tube can usually be improved by reactivation. If the emission is above the minimum specified, the tube is in good condition, and does not need reactivation.



TYPE OF TUBE	EMISSION TEST			REACTIVATION PROCESS			
	FIL. VOLTS	PLATE VOLTS	MINIMUM EMISSION ALLOWABLE	FLASHING FIL. VOLTS	FLASHING TIME	AGEING FIL. VOLTS	AGEING TIME
WD-11 WX-12 C-11 CX-12	1.1	50	6 M.A.	CANNOT BE REACTIVATED			
UX-199 CX-299	3.3	50	6 M.A.	12	10–15 SEC.	4	30 MIN.
UX-120 CX-220	3.3	50	15 M.A.	12	10–15 SEC.	4	30 MIN.
UX-201A CX-301A	5.0	50	20 M.A.	16	10–15 SEC.	7	30 MIN.
UX-200A CX-300A	5.0	50	14 M.A.	16	10–15 SEC.	7	30 MIN.
UX-240 CX-340	5.0	50	14 M.A.	16	10–15 SEC.	7	30 MIN.
UX-112A CX-112A	EMISSION READING CANNOT BE TAKEN			CANNOT BE			
UX-171A CX-371A	5.0	50	50 M.A.	REACTIVATED			
UX-210 CX-310	6.0	100	85 M.A.	NO FLASHING		9	30 MIN.
UX-226 CX-326	1.5	50	35 M.A.	CANNOT BE			
UX-227 CX-327	2.5	50	35 M.A.	REACTIVATED			
UX-216B CX-316B	6.0	125	85 M.A.	NO FLASHING		9	30 MIN.
UX-280 CX-380	5.0	80	100 M.A.	CANNOT			
UX-281 CX-381	7.5	150	200 M.A.	BE			
UX-250 CX-350	7.5	250	560 M.A.	REACTIVATED			

Fig. 216—Upper left: Circuit for testing emission.
Lower Left: Circuits for reactivation.
Right: Voltages and other data for reactivation.

Reactivation may be done in either of two ways, depending on the condition of the tube. For a tube which is operating fairly satisfactorily, but which is to be pepped up to maximum, it is only necessary to disconnect all "B" batteries (or the "B" power unit) from the set and keep the tubes lit up at *normal voltage* for two or three hours, using the rheostats on the set to regulate the brilliancy. The storage "A" battery usually used with the set can be employed to supply the filament current. It is very important that the filament voltage be kept exactly at its proper value, as shown by a good voltmeter.

For the bad cases where the tube gives little or no emission, the more elaborate method must be employed. This consists of two steps: first, operating the filament for a very short time at a specified high voltage (called "flashing"), then operating it at specified lower voltages for a longer period (called "ageing or cooking"), all of this with grid and plate disconnected. During this process the tube is operated without plate voltage, since under normal conditions with the plate voltage on, the electrons would be attracted to the plate as soon as they are brought to the surface of the filament; but by leaving the plate circuit open, they are allowed to accumulate on the filament and are therefore available in the required quantities when operation is resumed.

Reactivation may be carried on either with direct or alternating current. At the lower left of Fig. 216 are shown the connections for the direct current method. A is a battery capable of furnishing at least 15 volts. R is a rheostat, GPFF is an ordinary tube socket, and V is a good voltmeter. The resistance R is adjusted until the filament voltage is as shown in the "flashing voltage" column in the table, depending on the particular type of tube. This voltage is applied for the length of time specified. Then it is decreased to the value specified as "ageing", for the time shown. It is absolutely necessary that these voltages and times be strictly adhered to, since they are the values which have been found to give best results, after a long series of investigations.

The alternating current from the lighting socket can also be used for reactivation. For the alternating current method it is necessary to use a step-down transformer T, to step down the 110 volts to that necessary for the test. Any transformer giving the desired voltage can be used. This can be one of the small type used for operating door bells or electric toys. The voltage tap nearest the voltage specified should be selected and a rheostat in series with the filament used to adjust the exact voltage as read by the a-c voltmeter. The table gives the necessary data for those tubes which can be rejuvenated. The connections are shown at the lower center of Fig. 216.

A tube can, on the average, be reactivated about six or eight times without any apparent injury to the filament. The emission of various oxide-coated tubes can be tested by the process given, but obviously they *cannot* be reactivated, as will be seen presently from a study of this type of filament

If the tube will not return to normal after proper reactivation treatment, it is proof that the tube has either served its normal life and the supply of thorium in the filament has been used up; or it has been so heavily overloaded that the thorium content has been exhausted or the vacuum impaired. Obviously nothing can be done with such a tube.

301. Oxide coated filaments: Very early work on vacuum tube filaments showed the value of coating the filament with certain oxides to greatly increase the electron emission at low operating temperatures. Tubes used in telephone work have employed oxide-coated filaments of platinum for many years. All of the latest tubes designed for radio receiving, employ either an oxide-coated metal filament or an oxide-coated cathode with a separate-heater filament operating at a dull red heat. The former construction is used in battery-operated tubes and power tubes. The latter type will be described later.

The *oxide-coated* filament is usually made with a very thin ribbon of metal which serves to conduct the current and heat the electron-emitting oxide. Often the ribbon is twisted on itself in such a way as to expose everywhere a sharply curved surface to make the oxide coating stick better. The reader should examine the filaments in some of the larger tubes such as the 245, 280 and 281 types. Several metals have been used for the filament wire or core. All early forms of oxide-coated filaments used a platinum or platinum-iridium filament core. The use of the large quantities of this valuable metal required for the millions of vacuum tubes manufactured, threatened to exhaust all available sources of supply and led to the search for cheaper substitutes. As a result, an alloy called Konel, several alloys of platinum, pure nickel, and alloys of nickel such as silico nickel, titanium nickel, chromium nickel, etc., are being used for filament wire by various tube manufacturers. Pure nickel, heretofore used extensively for filaments, is rapidly being abandoned in favor of these other metals on account of its chemical interaction with the carbonates used for the preliminary coating. The wire used must offer the necessary high electrical resistance, so as to be economical in operation. The best wires are those with a cold resistance several times that of nickel, and with the resistance rising rapidly as they warm up, so as to provide some measure of automatic current regulation. The wire must not stretch unduly when heated, to sag and "short" with the near-by grid. A high melting point is necessary, for the carbonates require about 750 deg. C to provide the necessary emission.

A mixture of barium and strontium carbonates and a binder of nitrates, ordinary water glass, or alcoholic suspensions of barium and strontium oxides, is applied to the filament wire either by successive dippings and bakings in a continuous operation, or by spraying by means of an air brush as in the case of the independently heated cathodes, the applications being repeated until the desired amount of coating material has been deposited. The mixture is baked on to the filament wire in special ovens. When the filament is assembled with the other elements in the glass bulbs, and the bulb is being exhausted, it is lit up to red heat by a source of current. This high temperature breaks down the carbonate coating and the reaction with the air in the tube forms an oxide coating and carbon dioxide gas, the latter being drawn off by the vacuum pump. The coating left on the filament wire core is a combination of barium and strontium oxides which adhere to the filament wire due to friction at the interface together with a certain rigidity of the mass as a whole that results from the interlocking particles. This coating when heated to a dull red heat of about 750° C. by the heat produced in the filament wire due to the current flowing through it, will emit electrons freely. The same electron emission may be obtained from oxide coated platinum at 950° C. Considerable research work is being carried on to determine the exact nature of the effect of the core metal on the emission and whether the real source of electron emission is a layer of metallic barium on the surface of the *core* or whether it takes place from a film of barium of atomic thickness on the surface of the *coating*. It is expected that the results of this work will lead to the development of even more efficient coated filaments than we now have.

Of course, oxide-coated filaments cannot be reactivated as thoriated tungsten filaments can, since all of the active material is on the surface of the filament wire or cathode, and when this is once used up, it cannot be replaced. When the active coating is all used up, the electron emission of the tube drops to a point where it is insufficient to keep the tube operating satisfactorily.

This loss of electron emission may cause impaired set performance in a number of ways. For example, in the case of rectifier tubes the loss of emission means that the rectified voltage supplied by the tube is reduced to a point which reduces the sensitivity of the set, introduces distortion in the output, and limits the volume at which the set can be operated.

In the case of output tubes, the maximum obtainable volume is reduced. If this reduction in volume is carried to an extreme, the set develops an extremely harsh and rasping quality.

In the case of the detector and audio stages, somewhat similar effect in quality is obtained as the tubes wear out.

In the radio frequency stages, a loss of sensitivity and corresponding loss of volume results. The supply of electrons from the cathode should be adequate to supply at least twice the normal plate current, otherwise the tube will be overloaded on strong signals and the quality of the set response is impaired.

The normal operating filament temperature of the usual oxide-coated filament is 750 degrees Centigrade, and this is greatly exceeded when the voltage overload surpasses the 5 per cent limit or allowance specified by the tube manufacturer. The main advantages of the oxide-coated filament or cathode over the thoriated filament, is the lower operating temperature (about 950 degrees Centigrade lower) with consequent increase in filament life and reduced filament power consumption and higher saturation currents. Improved oxide-coated filaments have made possible the construction of tubes designed to obtain their filament current economically from 2-volt batteries of the dry-cell or air-cell type. These filaments are thinner than a human hair and consume .06 ampere at 2 volts. This is a filament power consumption of only .12 watts per tube. Compare this with the old 201 type of tube used several years ago. This required 1 ampere at 5 volts, (5 watts) or 40 times as much power to heat its tungsten filament sufficiently to give off a rather limited supply of electrons.

302. Indirectly heated cathodes: In some cases a more mechanically rugged filament unit consuming a small supply of heating power is required, than is found in the ordinary direct-heated cathode types of filaments just described. Examples of this are in the use of radio receivers on automobiles and airplanes where the tubes are subjected to considerable vibration unless elaborate and costly shock-absorbing mounting schemes are resorted to. The tubes in these receivers must usually obtain their filament current from a battery and economical operation is essential. Also, in those radio receivers in which the filaments are heated by low voltage alternating current supplied by the 110 volt a-c electric light line by a suitable step-down *filament heating* transformer as shown at (D) of Fig. 189, the use of the ordinary type of electron emitter consisting of a coated filament has not proved satisfactory, due to the fact that the varying current causes the filament temperature, the associated fields, the electron emission and plate current to vary, resulting in an annoying hum heard in the loud speaker. For vacuum tube applications of this general class, the indirectly-heated cathode has been developed and is used in many types of standard tubes. The construction of the heater element, insulating bushing and oxide-coated metal cathode thimble proper, were described in Article 264 (which should now be reviewed carefully) and shown in elementary form at (D) of Fig. 189. In this construction the filament simply serves the purpose of producing heat. The electron emission is due to the barium and strontium oxide coating on the cathode surface. General purpose tubes such as the 227, 224, 235, etc., having this type of electron emitter have filaments rated at 2.5 volts and either 1.5 or 1.75 amperes. Special types of tubes such as the 236, 237 and 238 types, designed especially for d-c use in automobile and airplane receivers, or in sets operated directly from the direct current house supply lines, have filaments rated at 6.3 volts and 0.3 amperes. The 2.5-volt heater-type tubes can be operated with either a-c or d-c filament current of the proper voltage. Some 6.3 volt tubes are designed to be operated only with d-c filament current.

303. Cathodes for a.c. filament operation: Instead of employing batteries for supplying the filament heater current for vacuum tubes, it is much more convenient where possible, to use the ordinary 110 volt house electric light supply line as a source of current. If the current available is a-c, it can be stepped down to the proper voltage for the operation of the tube filaments by means of a suitable step-down transformer. However, if alternating current is used to heat the filaments of ordinary "direct-heater" type tubes such as the 201-A type, several very objectional actions occur.

Alternating current starts from zero, rises to a positive value and drops to zero again then reverses its direction and repeats the process over and over 60 times every second (for a 60 cycle e. m. f.) as shown at (A) of Fig. 111 and (A) of Fig. 217. Twice during each cycle the current is actually zero and at other instants it has various values between zero and its peak value. Since the heat produced at each instant by the flow of current through the resistance of the filament wire is proportional to the square of the current flowing at that instant multiplied by the resistance of the wire ($W = I^2 R$), it is evident that the heat set up in the wire will also increase and decrease 120 times a second. Since the filament in this type of tube is finer than a human hair and therefore does not contain much metal, it cannot hold much heat, and twice every cycle when the current drops to zero, the temperature of the filament and its electron emitting substance also drops as shown at (B) of Fig. 217. This variation in temperature results in a corresponding variation in electrons emitted and in the electron and current flow between the plate and the filament. These variations in the plate current 120 times a second, cause the earphone or loudspeaker diaphragm to vibrate 120 times a second, resulting in a 120-cycle sound wave which sounds as a very objectionable low-pitched hum.

Experiment: Connect up the proper A, B and C batteries and loud speaker to an ordinary radio receiver designed for battery operation with 201-A type tubes and tune in a station. Now disconnect the A battery and connect the terminals of the 5 volt secondary winding of a filament transformer to the A+ and A— terminals of the set. Connect the primary to the 110 volt a-c line, and turn on the a-c current and the set. A loud low-pitched hum will be heard, which drowns out the program being received due to the fact that it modulates the incoming signals at 120 cycles due to the 120 cycle variation in electron emission caused by the unsteady heating of the electron emitters.

Another cause of hum in tubes of this type may be understood by assuming that we have a tube requiring 6 volts for its filament and 45 volts potential on its plate, as shown at (C) of Fig. 217. (The grid can be omitted from this discussion for the present.) The electrons given off by the heated filament are negative charges and since the plate is positive, the electrons will be attracted over from the filament to the plate. But the attracting power of the plate depends upon how positive it is with respect to the filament.

On the diagram we note that 45 volts is the difference in potential existing between the end of the filament "F" and the plate. This is true because the resistance of the heavy wires is negligible. The difference in potential between "D" and the plate, however, cannot be 45 volts, on account of the 6 volt "A" battery. Point "D" is 6 volts positive with respect to point F on the filament and hence the potential difference be-

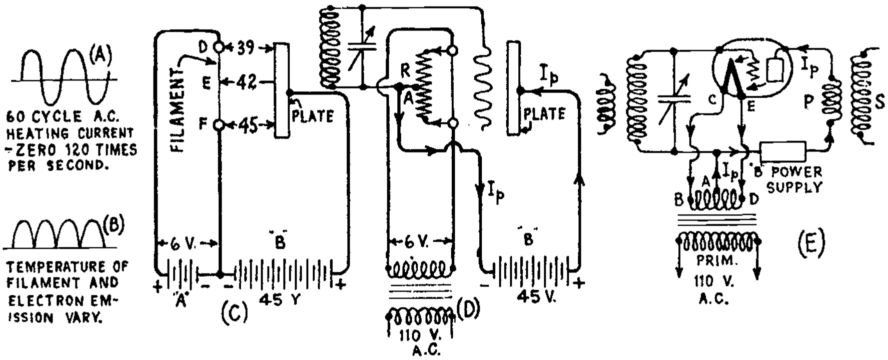


Fig. 217—Effects of alternating current for filament heating.

tween D and the plate is only 39 volts. Between the center point "E" and the plate, the difference is only 42 volts. If the filament is heated by steady direct current, this condition is not objectionable, but if alternating current is used, the voltage of the filament is continually changing; during one half cycle one end is positive with respect to the other, and during the next half cycle it is negative. Since the attractive force of the plate for emitted electrons depends on how positive it is with respect to the part of the filament the electrons came from, it is evident that more electrons will be drawn from the end D of the filament than the end F during one half cycle and more will be drawn from end F than from D during the next half cycle, etc. In he interval between these times, slightly different quantities of electrons are attracted, etc.

The same action takes place in the grid circuit if it is returned to either end of the filament. The fact that the potential of each end of the filament is alternately increasing 3 volts above and then decreasing 3 volts below, that of the center point (for the 6 volt type filament considered for convenience), makes the grid potential vary likewise. If the plate and grid circuits are returned to either end of the filament carrying 60 cycle a-c, then the effect is the same as though a 120 cycle signal voltage were applied in the grid circuit—producing a 120 cycle variation in plate current and resulting in a 120-cycle sound from the speaker (a low-pitched hum).

To reduce this hum in tubes of this type which are to be heated by a-c, a low voltage 1.5 v. filament is used in place of the ordinary 5 volt filament, so that the potential of the ends of the filament only alternates plus and minus .75 volt above that of the center of the filament, and the grid and plate return circuits are returned to a point which is *electrically* midway between the terminals of the filament, that is, a point whose potential is always at the same value as that of the center point of the filament wire, which value does not change. This condition may be likened to that in a see-saw pivoted at the center. The ends of the see-saw alternately move up and down but the center point remains always on the same level.

The electrical center of the filament circuit may be obtained either by means of a center-tapped resistor connected directly across the filament terminals as at (*D*) or by constructing the filament-heating winding with a tap at its electrical center as at (*E*). The former method is preferable, since the resistor can be connected directly at the filament terminals thus insuring a correct center. The contact A may be even made adjustable by using a potentiometer for the purpose in order to obtain the exact and best operating point for minimum hum in the loud speaker. The method of using a center tap on the transformer winding has one serious objection in that the heating transformer is usually some distance away from the tube and therefore connecting wires BC and DE may be quite long and may not be of exactly the same length and resistance. In this case even though the center tap of the transformer winding is located accurately, it would not represent the accurate electrical center of the filament circuit of the tube since the resistance from the filament *center* to the winding center tap on side CBA is different from that on the other side EDA.

The path of the plate current I_p is from the positive terminal of the "B" voltage supply, through the plate load, across from the plate to the filament of the tube and then back through the filament-heating winding and out of the center-tap A, back to the negative terminal of the "B" voltage supply as shown by the arrows in (E). If a center-tapped resistor is used, as at (D), the plate current flows from the filament, through the resistor and out of the center tap A, to B minus, as shown by the arrows in (D). In most of the diagrams in this book, the use of the center-tapped resistor will be shown, but the student should remember that the center-tapped filament transformer winding may also be employed provided proper care is taken to keep the connecting wires short and equal in length. Most manufacturers now employ the center-tapped resistor arrangement on account of its advantages of simplicity and cheapness, but there are thousands of old radio receivers in use which have the tapped transformer winding. It should also be remembered that the center-tapped resistor should be located near and *connected directly* to the filament terminals of the tube socket, for if it is placed some distance from it and connected by long wires, the same unbalancing due to unsymmetrical wiring and resulting unequal resistances in the two sides of the circuit may result, and the same objectionable hum as in the case just explained for the transformer winding will be present.

The *total* resistance of the center-tapped resistor used, should be high enough so it does not draw too much current from the filament-supply source. Resistor values used for this purpose have become fairly well standardized; the various values used across filaments of various voltage ratings being approximately as follows. These values are not critical of course:

Filament Voltage	Total resistance of Center-Tapped Resistor—Ohms.
1.5	10
2.5	20
5.0	50
6.3	50 or 75
7.5	75 or 100

Two typical types of center-tapped resistors for this purpose are shown in Fig. 218. The illustration at the left shows the resistance wire wound on the form, with the center-tap connection visible. In the unit at the right, the resistor element is encased in Bakelite to keep out all moisture, etc., and to prevent mechanical damage to the thin resistance wire. Three metal terminals are brought out for connecting it.

There is also a magnetic field surrounding the filament when there is current flowing. If direct current is employed, this field is fixed and although it deflects some of the electrons leaving the filament and forces them to travel much longer paths than others, it has practically no noticeable effect on the operation of the tube.

However, in the case of a-c this magnetic field will be periodically reversed and if the field changes, the paths of the electrons will be changed with the frequency of the a-c. This will result in fluctuations in the plate current, resulting in "hum."

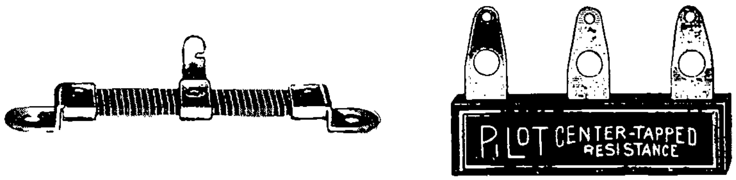


Fig. 218—**Left:** Center-tapped resistor showing resistance wire wound on supporting frame. **Right:** Center-tapped resistor enclosed in moisture-proof Bakelite.

In the 226 type a-c tube, the oxide-coated filament was made very heavy and short and designed to operate with a low voltage of 1.5 volts—across it at a current of 1.05 amperes. It was made round in order to have the greatest thermal inertia for a given mass of filament material. The fact that it was thick enabled it to store a comparatively large quantity of heat during each half cycle, so its temperature did not drop so much during the intervals of zero current, that is, it had a high thermal inertia. Thus a steadier electron emission and plate current resulted. It was possible to obtain a good balance between the electromagnetic and electrostatic fields at the value of plate current desired, by returning the grid and plate circuits to the electrical center of the filament circuit by means of a center-tapped resistor connected across it as at (D) or by a center-tap on the filament winding of the supply transformer. The former method is preferable. Even though its thermal inertia is high and it has rather low hum output, it has been supplanted entirely by the independently heated equi-potential cathode used in the 227, 224, 235, etc., types of tubes. The 226 tube could not be used as a detector due to the hum it would produce.

In the equi-potential cathode construction, already described previously and shown in simple form (without the grid) at (D) of Fig. 189, the heater circuit is entirely independent of the plate and grid circuits. The cathode which emits the electrons is at a constant electrical potential and the direction of the plate current flow is from plate to cathode and back to B minus as shown. The cathode is heated, receiving its heat by conduction and radiation from the filament proper. The thermal inertia of the metal of the cathode, and the insulating bushing (see (D) of Fig. 189) is so great that fluctuations in the a-c current and heat of the filament do not affect the electron emission and plate current. This type of construction is suitable for both detector and amplifier tubes. In the usual type of separate-heater tube there are five prongs, the additional one attached to the cathode being known as the "Cathode" prong. Direct-heater tubes of the 226 type are no longer used in a-c electric radio receivers of recent design.

If the current for the filaments of vacuum tubes in a receiver is to be obtained from a 110 volt d-c electric light line, it is also advisable to use separate-heater type tubes because the d-c current obtained from commercial d-c generators is not absolutely smooth but contains slight ripples due to the rectification by the commutator as shown at (B) and (C)

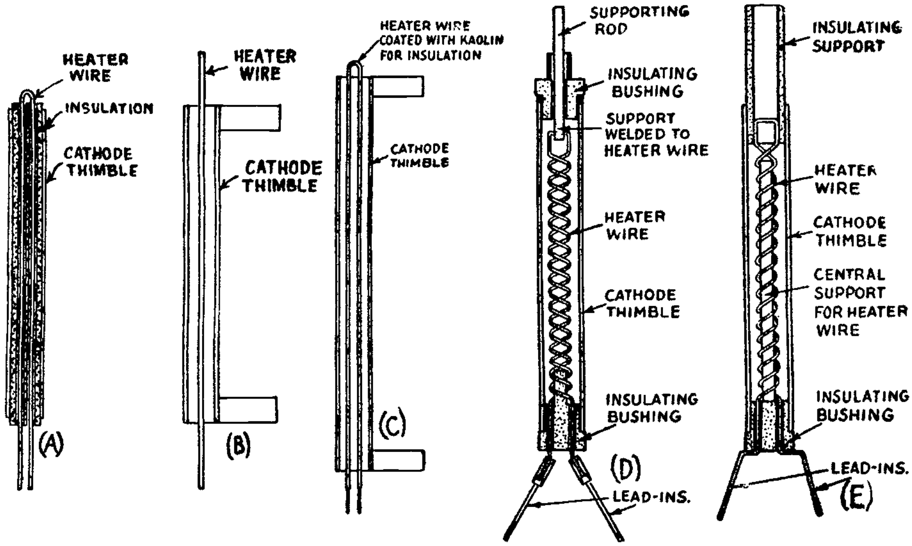


Fig. 219—Various types of filament and cathode arrangements in indirectly heated cathode type tubes.

of Fig. 68, which will cause hum due to varying filament-heating and electron emission when tubes with ordinary thin filaments are employed.

304. Quick-heater tubes: Filament and cathode arrangements in indirect-heater tubes have undergone a series of changes in order to achieve quick-heating of the cathode when the filament current is turned on. Quick heating has been achieved in various ways, either by a marked reduction in the mass of insulating material between the filament and cathode, by the use of new synthetic ceramic insulators having very good heat conductivity, or by the total elimination of the insulating material, merely relying on the mechanical separation between filament and cathode to prevent electrical contact and possible short-circuiting.

An early type of indirectly-heated cathode is shown at (A) of Fig. 219. The cathode itself is a hollow, oxide-coated nickel thimble or cylinder. The filament is in the form of a hairpin loop of wire usually threaded through a bushing of ceramic material so e-what like porcelain, within the cathode thimble. This insulates the cathode from the filament, and the two heater wires are placed close to one another so that the alternating current fields set up around the two wires will largely neutralize one another because the currents in the two wires are of opposite phase, with the result that the external field around the heater will be very weak and the resulting hum therefore low. The great disadvantage of this cathode is the time required for the tube to begin functioning. Under the operating conditions obtaining in the average radio receiver, it generally takes from 15 to 30 seconds for the set to begin playing after being turned on.

In an endeavor to reduce this heating time, some tube manufacturers developed the cathode shown at (B). This type of structure resulted in a quick heating cathode but it introduced many serious disadvantages. In the first place, the a-c heater is of the "straight through" type in which the field of the a-c heater current is not made to neutralize itself, with the result that this type of cathode produces entirely too much hum for use in the modern highly sensitive broadcast receiver. It will be evident also that the heater wire must be centered within the cathode thimble by the factory worker; an operation that cannot be accomplished satisfactorily in quantity production. In the second place, the heater wire is supported by long wires in glass beads which are not integral with the cathode. Since the heater wire is not covered with an insulator, the rough handling which a tube gets in shipment and the constant vibration which it receives in use often produces short-circuits of the heater to the cathode, with resulting greatly increased hum and unsatisfactory operation of the tube.

(C) shows a type of cathode construction which was developed in an endeavor to eliminate the serious limitations of the previous cathode. As will be noted, an insulated hairpin is always centered within the cathode thimble. The kaolin insulation employed is a very hard and brittle substance, however, with the result that the repeated heating and cooling of the a-c heater, as the set is turned on and off in use, tends to crack off the insulation from the heater, thereby affording an opportunity for the heater to short circuit against the cathode thimble. It also will be noted that the hairpin heater is hand spaced and supported within the cathode as in the previous construction, and hence is subject to the same trouble. (D) shows a quick-heater, low-hum cathode used in modern high sensitivity receivers. It employs a heater of tungsten wire, coiled into a tight double spiral, which makes it act like a spring. This springy heater is mounted under tension between two insulating plugs in the ends of the cathode. When the wire expands in heating, the springiness of the coiled construction takes up the slack, keeping the heater tight and in the exact center of the cathode. When jolted and jarred, the coil can deflect sideways without breaking, but instantly snaps back into position. The bottom insulating bushing is provided with a short projection which extends up into the heater coil for about two turns. This keeps the end turns from being short-circuited against each other as the operator threads the lead-in wires through the two holes in the bushing and thus assures a good rugged construction at this point.

An improved type of cathode construction is shown at (E). The projection on the bottom insulating bushing has been lengthened to extend the full length of the heater coil. This stiff, hard rod, running the full length of the coil makes it difficult to pull or twist it out of shape when assembling and no strain need be put on the coil to keep it stretched when it heats up.

305. Three-electrode indirect-heater tube: The construction of a general purpose three-electrode 227 type tube with independent heater construction is shown at Fig. 220. Starting at the left, the various parts are shown in the order of their assembly, working up to the completed tube at the right. The grid is in the form of a round spiral wire of molybdenum, wound with spaced turns to allow the electrons to pass through the openings. This fits around the cathode assembly. Around this is the metal plate, usually of nickel. The parts are mounted on a glass stem and sealed in a glass bulb from which all of the air is later exhausted. The plates of many tubes of this type are made of a close-mesh wire screen or a perforated sheet instead of a solid sheet of metal, in order to reduce secondary emission and provide greater heat radiation. This will be considered later.

The arrangement of the elements and terminal markings in a tube of this type are shown in the cut-away view at (A) of Fig. 221, and the common symbol for the tube is shown at (B). The arrangement of the terminals in the five-prong socket required for this type of tube is shown at (C). Notice that the two filament terminals are arranged together, at the left is the cathode and at the right is the plate terminal. The grid terminal is at the rear and separated from all the rest in order to reduce the capacitance between it and the other prongs and contact pieces. This view is drawn looking down on top of the socket. An illustration of a socket of this kind is also shown at the left of Fig. 222. This tube can be

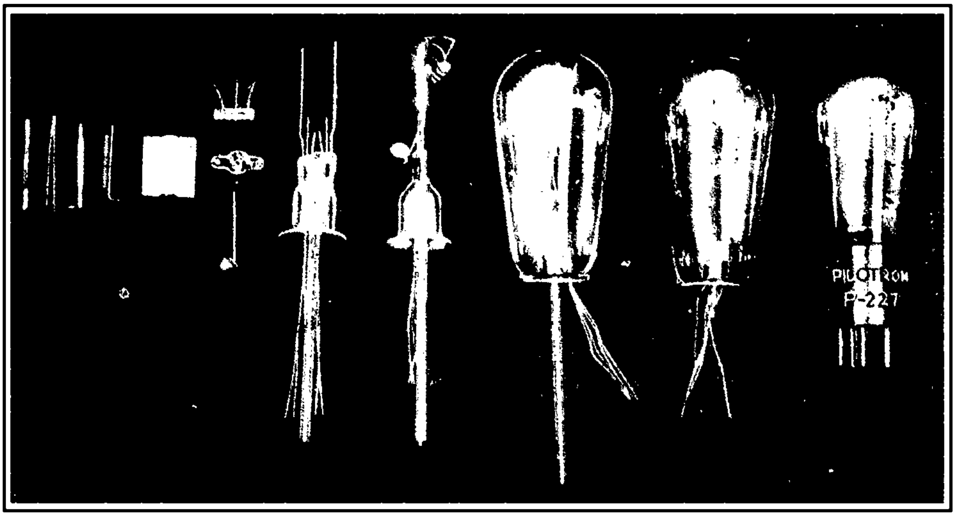


Fig. 220—Elements, and steps in the construction of a 3-electrode indirect heater type tube. At the left are the filament, cathode, grid and plate.

employed as a detector, or amplifier and possesses operating characteristics somewhat similar to the 201-A tube which was the standard general purpose tube for many years. Its characteristic curves are shown in Fig. 200. The filament is designed to operate with 2.5 volts at 1.75 amperes, and of course may be heated either with a-c or d-c current, but it is commonly employed with a. c. heating current since other tubes with more desirable heater characteristics are available for d-c filament current operation.

306. Parallel and series operation of heater filaments: When several vacuum tubes of the type just described are operated together, their heater filaments may be connected either in parallel or in series. The parallel arrangement will be considered first since it is most commonly used. At (D) of Fig. 221, the filaments of four separate-heater type tubes are shown connected to the low voltage secondary winding of the filament heating transformer T. With this type of connection, the secondary winding S of the transformer must deliver a voltage equal to that required by the filaments of the particular types of tubes employed. The current supplied by the transformer winding is equal to the sum of the filament currents taken by all the tubes, so the winding must be of wire having ample cross-section area to carry this current without undue heating or voltage drop. The wiring from the transformer to the tube sockets must also be of ample size to carry the current without excessive voltage

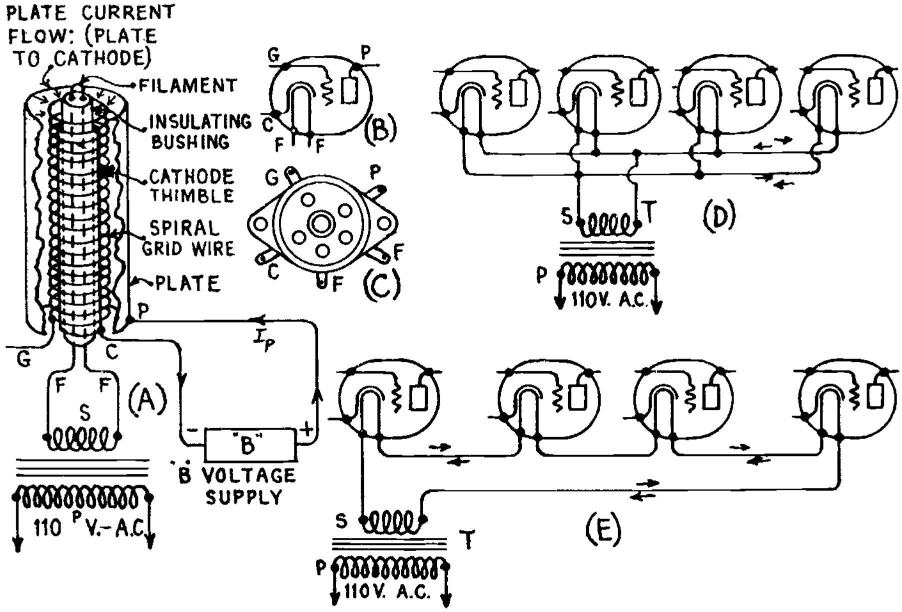


Fig. 221—(A) Construction and arrangement of the elements in a 3-electrode tube of the indirect heater type. (C) 5-prong socket terminal arrangement for the tube. (D) Parallel filament connection. (E) Series filament connection.

drop, in order that the voltage existing at the tube filament terminals shall be of the proper value. Since the corresponding wires carry alternating current, the wires in each pair should always be run close together in order to prevent inducing 60 cycle a-c voltages by electromagnetic induction into other circuits which may run near them. As explained in Article 124, the wires may also be twisted together to prevent induction effects but this is rarely necessary if they are kept close together and at some distance from all other circuits which they might affect. A 5-prong tube socket suitable for tubes of this type is shown at the left of Fig. 222. Sockets of this kind usually contain flexible metal contact springs which press firmly against the tube prongs when it is inserted, thereby making good electrical contact with them. A small step-down transformer designed to furnish low voltage a-c current for the filaments of a-c type tubes is shown at the right. Transformers of this kind are designed to operate from the a-c house lighting circuit. They are usually of shell-type construction as shown at (D) of Fig. 71. As we shall see later, the filament current in most radio receivers is obtained from the separate low-voltage windings on the same power transformer that is used in the B-power supply unit. A transformer of this type is shown at the left of Fig. 72. A large number of radio receivers manufactured several years ago and still in use, employed types 226, 227, 224, 171-A, 245 and 280 tubes so that four different low voltages are supplied by separate windings on the same core of the transformer. Modern practice is definitely toward the use of tubes having similar filament voltage ratings (2.5 volts in the

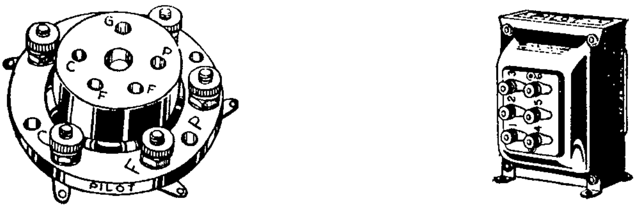


Fig. 222—Left: A 5-prong socket for separate heater type tubes. Right: A small transformer designed to deliver low-voltage a-c current for the filaments of a-c operated tubes.

U. S.) so that the filament transformer construction and filament circuit wiring is simplified and cheapened.

If the filaments are connected in series as shown at (E) of Fig. 221, the transformer winding must supply a voltage equal to that taken by one tube, multiplied by the number of tubes. The current in the circuit is simply equal to that taken by a single tube. This arrangement is not used to any extent in a-c operated receivers because it has several disadvantages. If the filament of one tube burns out, all the tubes go out and they must all be tested in order to locate the defective one. Also each filament is at a different potential than the rest. As we shall see, the series filament connection is used in receivers operated from d-c house lighting circuits due to the fact that with this arrangement the total filament current drain is lower than with the parallel arrangement. This makes the series voltage-reducing resistor cheaper to build, since it must not dissipate so much power.

Problem: A radio receiver contains six 235 type tubes connected with their filaments in parallel. The filament of each tube is rated at 2.5 volts and 1.75 amperes. What must be the voltage and current carrying capacity of the secondary winding of the transformer used to supply the current? If the power factor is 1, how many watts of electrical power does the transformer supply to the filaments?

Solution: (a) The voltage delivered by the transformer winding is the same as that required by one tube, i.e., 2.5 volts since it is a parallel circuit. (b) The total current is equal to $1.75 \times 6 = 10.5$ amperes. The winding must be designed to carry this current without undue heating. (c) Since this is an a-c circuit the power is given by

$$W = E \times I \times \text{power factor} = 2.5 \times 10.5 \times 1 = 26.25 \text{ Watts. Ans.}$$

Problem: Find the same quantities if the filaments of the tubes are connected in series.
Solution: (a) The total voltage to be supplied by transformer$=2.5\times6=15$ volts. (b) Total current$=1.75$ amperes (same as for one tube). (c) Watts$=E\times I\times$power factor$=15\times1.75\times1=26.25$ Watts. Ans.

Although many types of tubes are employed in radio receivers at the present time, all of those used as detectors and amplifiers (excepting the last stage audio or "power amplifier" tube) in late type receivers operated from the d-c or a-c electric house lighting circuit, are of the separately-heated cathode type on account of their superior characteristics as regards hum-free operation. They are also used in automobile and aircraft receivers where the more fragile filaments in the directly heated type would break due to the excessive vibration.

307. What the screen-grid tube does: One of the most serious factors which for many years retarded the development of real high-gain vacuum tube amplifiers for amplifying the weak high-frequency (radio frequency) signal voltages set up in receiving antenna circuits, was the fact that in the three-electrode tube, which was the only type commercially available at the time, an excessive capacitance existed between the grid and plate. This caused a feedback of energy from the inductive plate circuit to the tuned grid circuit, with the resulting oscillation and "peanut-stand whistle" so characteristic of the receivers of several years ago. Since the voltage amplification factor of the 201-A type tubes employed in those days is only 8, it was necessary to use several stages of amplification in order to boost the signal voltages up to a reasonable strength. However, as the number of radio frequency stages was increased above about 2, serious difficulties due to oscillation were encountered, and all sorts of circuit arrangements and "oscillation suppression" devices were developed to enable satisfactory operation of 3 and 4 stage r-f amplifiers with a reasonable amount of amplification. The popular neutrodyne circuit of old was one of those designed particularly at this stage of radio history, to neutralize the feedback of energy which would otherwise cause oscillation. The development of the screen-grid tube eliminated the necessity for these various oscillation preventatives by simply removing the source of the trouble, in reducing the grid-to-plate capacitance to a very low value, and at the same time made it possible to obtain more amplification per stage due to its higher amplification factor. The fact that the screen-grid principle accomplishes these two important results makes it an exceedingly useful tube. At the present time, the screen-grid tube in one form or another has practically entirely supplanted the older form of 3-electrode tube in radio-frequency and intermediate-frequency amplification, simply because of these important advantages.

308. Feedback in r-f amplifier: In order to understand just how the screen-grid tube greatly reduces the oscillation tendency when used in r-f amplifiers employing tuned-grid and inductive-plate circuits, we must leave our study of vacuum tube construction for a few moments to study the action of an r-f amplifier stage and the way in which a feedback of energy from the plate to the grid circuit can take place due to the grid-plate capacitance of the tube. Feedback may also take place via other routes but these will be considered in another chapter; at this time we are merely interested in the reason for the particular type of construction employed in the screen-grid tube. In Fig. 223 is shown the fundamental circuit of a tuned radio frequency amplifier stage employing a simple 3-electrode vacuum tube.

L_2C_2 is the tuned input to the amplifier tube, L_3 is the primary and L_4 the secondary of the coupling transformer, which, when tuned by condenser C_4 impresses a voltage E_4 on the grid-filament circuit of the following tube. The small series voltage impressed on the input of the first stage, represented by "e," is impressed magnetically through mutual induction from the primary coil L_1. The circuit L_2C_2 is tuned to resonance with the frequency of this input voltage "e," and when in this condition, presents the minimum impedance to the flow of current circulating through it, indicated by the arrows in the L_2C_2 circuit. The strength of this current at resonance is determined by Ohm's law and is therefore equal to the impressed signal voltage

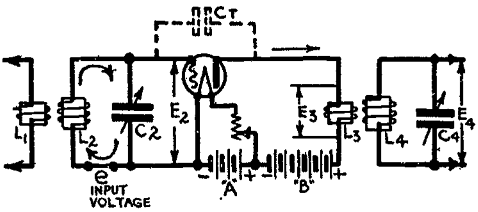


Fig. 223—Fundamental circuit of T.R.F. amplifier stage using 3-electrode tube.

divided by the resistance of the tuned circuit, or e/R. This current in circulating through the inductance L_2, builds up a voltage E_2 across the L_2C_2 circuit, which is the a-c grid potential applied to the tube, and controls the electron flow of the tube. (The voltage E_2 is usually much larger than "e," depending on the size of the inductance L_2 and its resistance.) This important fact has already been discussed in our study of resonance and "gain" in Articles 174 and 249.

The a-c signal voltage E_2 applied to the grid circuit, causes the plate current through L_3 to fluctuate in accordance with the changes it produces in the grid potential. These plate current fluctuations are rather large due to the strong control which the grid has on the electron flow and plate current. The fluctuating plate current flows through the primary of the transformer L_3, which transfers energy to its secondary circuit L_4 by electromagnetic induction, giving rise to voltage E_4 of the same frequency as E_2 but of greater magnitude. This is fed to the grid circuit of the following tube, etc. Since the action in each of the stages in a multi-stage amplifier is similar, we will consider only this one stage. The ratio of E_4 to E_2 is called the voltage "gain per stage" and may be any value between about 2 and 20 (with ordinary 3-electrode tubes), depending upon the efficiency of the design. With screen-grid tubes and properly designed apparatus it is possible to obtain much more gain than this.

Referring to (A) of Fig. 193 and (A) of Fig. 221 it is evident that since the plate, grid and filament are mounted concentrically with each other within the vacuum tube, and since the lead-in wires, tube prongs, and tube socket prongs are close together, some capacitance exists between the elements since they are all at different potentials. Considering a simple 3-electrode tube as shown at (A) of Fig. 224, we find that the grid and plate form a small condenser represented by C_{gp}, the grid and filament form a small condenser represented by C_{gf} and the plate and filament form a condenser C_{pf}. The former one is usually the largest, due to the large exposed area of the grid and the plate, and is the most important one. In a 201-A type 3-electrode tube, the plate-grid capacitance is 10 mmf. In a 227 type separate-heater tube, the capacitances are as follows: grid to plate 3.3 mmf.; grid to cathode, 3.6 mmf.; plate to cathode 2.8 mmf.

None of the internal tube capacitances cause as much trouble as that between the plate and grid. That between the grid and filament or cathode, has the effect of affecting the constants of the grid circuit. Since the value of this capacitance is small, its effect is usually negligible.

The plate-to-filament (or cathode) capacitance is not detrimental since it serves as a very small by-pass for the radio frequency currents to the plate return or negative filament circuit. The presence of the grid-plate capacitance is very objectionable, since it permits the transfer of energy through the tube in the direction opposite to that desired, as we shall now see. The resulting *feed-back* as it is called, is objectionable.

Consider the amplifier stage drawn in simplified form at (B) of Fig. 224. The plate circuit load is inductive. The capacitance between the grid and plate is represented by the condenser and dotted lines above them. Consider an instant when the signal input voltage is in such a direction that it causes a flow of current around the tuned circuit in the direction shown by the solid arrows into the upper condenser plate, making this the positive end of the tuned circuit and driving the grid potential toward positive. This will cause the plate current through L_3 to increase momentarily. The increase of current through L_3 gives rise to a momentary inductive voltage in a direction tending to oppose this increase of current (Lenz's Law) i.e., tending to make the bottom end of L_3 positive with respect to the top end. Since the entire circuit from the grid around to the plate is exactly the same as the simple condenser circuit shown at (C), this voltage impulse is transferred around through the B, A and C batteries and coil L_2, to the grid, causing a small current impulse to flow around to the grid through the circuit as shown by the dotted arrows. (The grid, we must remember, is one plate of the condenser, and therefore this is just the same as the current impulse which would flow in the condenser circuit at (C) from the right hand plate around through the circuit to the left hand plate, if a voltage were set up in L_3 with the polarity shown.) The result then of this current impulse fed back to the grid circuit, is to drive the grid further positive (since it is in the same direction as the original signal current in the tuned circuit and therefore aids it). This added voltage impulse on the grid is amplified by the tube again so as to produce a larger change in the plate current than would otherwise have resulted. Thus we see that the feed-back in the case of an inductive plate load really strengthens the signal impulses and therefore increases their effect on producing changes in the plate current.

A limited amount of feedback is beneficial from the standpoint of amplification, since it tends to increase it. When the next signal impulse takes place a fraction of a

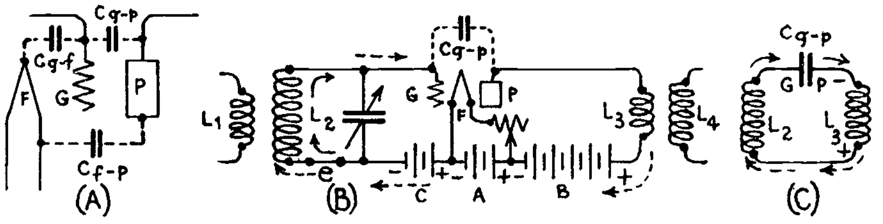


Fig. 224—Analyses of feedback in tuned-grid amplifier stage with inductive plate load.

second later, the current flows in the tuned circuit in the opposite direction, the grid is driven more negative, causing the plate current to decrease momentarily. The induced voltage in L_3 is now in the opposite direction and a momentary transfer of current takes place from the grid around the circuit to the plate, thus aiding the signal voltage impulse again. If the grid-plate capacitance is large enough, and the resistance of the circuit through which the energy flows is low so that little of it is dissipated in the form of heat, considerable energy is transferred back and forth through the circuit between the grid and plate during each signal impulse, and the tube will act as a generator or *oscillator,* since each voltage impulse fed back to the grid circuit from the plate circuit is amplified by the tube and fed back again to be amplified again, etc.

If at this time, the input signal voltage due to the primary L_1 were removed, a-c currents would still flow in the tube circuit, because whatever energy came from L_1 originally, has been amplified by the tube and fed back to the grid circuit where it is amplified again, and again and returns to the input. In other words, the tube oscillates, enough energy being supplied from the B battery to make up for all losses of power in the circuit. The frequency of this local feedback energy is determined by the frequency of resonance to which the tuned circuit L_2C_2 is adjusted. If this is varied or adjusted so it is slightly above or below that of the incoming signal, the result is a combination of the incoming signal impulses with the feedback impulses generated in the tube circuit, to produce a third audible frequency impulse whose frequency is equal to the difference between the two, and which sounds like a high pitched whistle; a fourth impulse whose frequency is equal to the sum of the two is also produced. This is too high in frequency to be audible. The former is the whistle heard while an oscillating receiver is being tuned to an incoming signal or when its tuning condensers are not adjusted so as to be exactly in tune with the frequency of the incoming signal impulses. If the load in the plate circuit is either capacitive or a pure resistance, the voltage impulse fed back from the plate circuit to the grid circuit due to the plate-grid capacitance of the tube, is just opposite in phase to the signal impulse applied to the grid circuit. Therefore the circuit cannot oscillate, and the signal output from the tube will be weakened by the feedback. In this case the action is one of *degeneration.*

The remedy for this is obviously either to neutralize this feedback current by an equal feedback current in the opposite direction or phase at every instant; to reduce this current by connecting resistance in the circuit so as to introduce losses, or to alter the internal structure of the vacuum tube so as to greatly reduce or eliminate entirely the capacitance between the grid and the plate. The former method is the basis of the *neutrodyne* system which is no longer used extensively in receiving circuits (since there is no need for it now that screen-grid tubes are available) ; the next is the basis of the so-called *losser* system, and the last is the method used in the screen-grid tube.

Of course, the grid-plate capacity has a fixed value in any type of tube, whether it is used as an audio or radio amplifier, but the higher frequencies in a radio circuit cause this capacity to be much more effective and troublesome when the tube is used as a radio amplifier. This last trouble alone has probably resulted in the development of more radio circuits and inventions than any other known factor.

309. Electrode arrangement in screen-grid tube: Referring now to (A) of Fig. 225 we have the arrangement employed in the screen-grid tube. This type of tube is made in two forms, one with a directly heated cathode for battery operation, and the other with a separately heated cathode for a-c operation. The construction of both are the same, with the exception of the electron emitter, and for simplicity the former will be considered first. The actions of both in an amplifier or detector circuit are similar, the difference being merely in the arrangement used to obtain the electron emission.

The elimination of the plate-grid capacitance may be understood by reference to the simple condenser circuit at (A) of Fig. 225. G and P represent the two plates of a condenser (we may imagine them to be the grid and plate of a vacuum tube). An a-c generator G is connected in the circuit together with an ammeter A and a voltmeter V as shown. Due to the alternating e. m. f. of the generator, a current (flow of electrons) will circulate around through the circuit, alternately from one plate to the other as shown by the arrows, the current which flows being proportional to the capacitance of the condenser and the voltage V. This becomes evident when we remember that a condenser stores in the plate which is negative, the excess electrons which have been transferred around through the circuit (flow of electric current) by the applied e. m. f. The larger the capacitance of the condenser, the more electrons it can store due to a given e. m. f., and therefore the larger is the electron flow (current flow) through the circuit between the plates. If another plate were placed between these and connected as shown at (B), the effect is now of two condensers in series, but since there is no varying e. m. f. in the circuit between plate S and plate P, and they are connected together by a wire, they will both be at the same potential and consequently, no current will flow between them, current only flowing in the circuit between G and S where the source of voltage is connected. Consequently, the capacitance

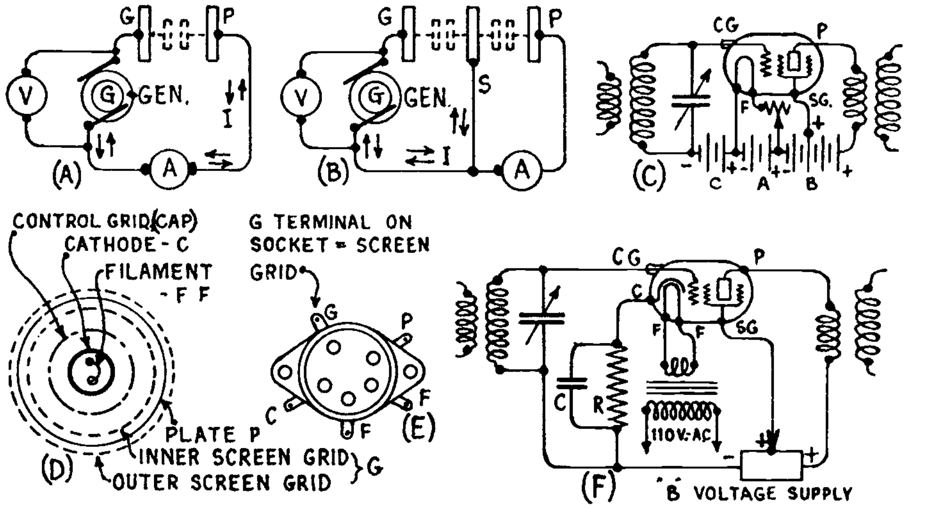


Fig. 225—How the plate-grid capacitance in the screen-grid tube is reduced to almost zero by the screen-grid placed between the control grid and the plate. (D) Electrode arrangement in a screen-grid tube. (E) Terminal arrangement. (F) Connection of a-c screen-grid tube in an amplifier circuit.

between S and P has really been shorted out of the circuit and the current indicated by the ammeter drops to zero. We may then say that the effective capacitance between S and P has been reduced to zero by the *electrostatic shield or screen* S, connected as shown. It may be said that P is *shielded* or *screened* from G by S.

In the *screen-grid* type of tube, this method of reducing the capacitance between the plate and grid is employed, by introducing a fourth electrode called the *screen* or *screen-grid*, placed between the ordinary grid and the plate, as shown diagrammatically at (C). The "screen-grid" electrically shields the control-grid from the plate. This form of tube is called a *four-electrode* tube. The ordinary grid, in whose circuit the signal e. m. f. is applied is now called the *control grid* since it controls the flow of electrons between the cathode and plate. Since it is obviously impossible to place a solid sheet of metal between the control grid and plate because it would stop the flow of electrons, a grid-like screen consisting of many turns of fine wire is used, as shown in the cut-open view of the screen-grid tube in Fig. 226, and at (D) of Fig. 227. This is practically as effective in acting as an electrostatic shield and in reducing the capacitance, as a solid sheet would be. The plate-grid capacitance is not affected by the introduction of the grid bias voltage connected as at (C) of Fig. 225, since the screen is still grounded as regards an impressed a-c signal voltage, that

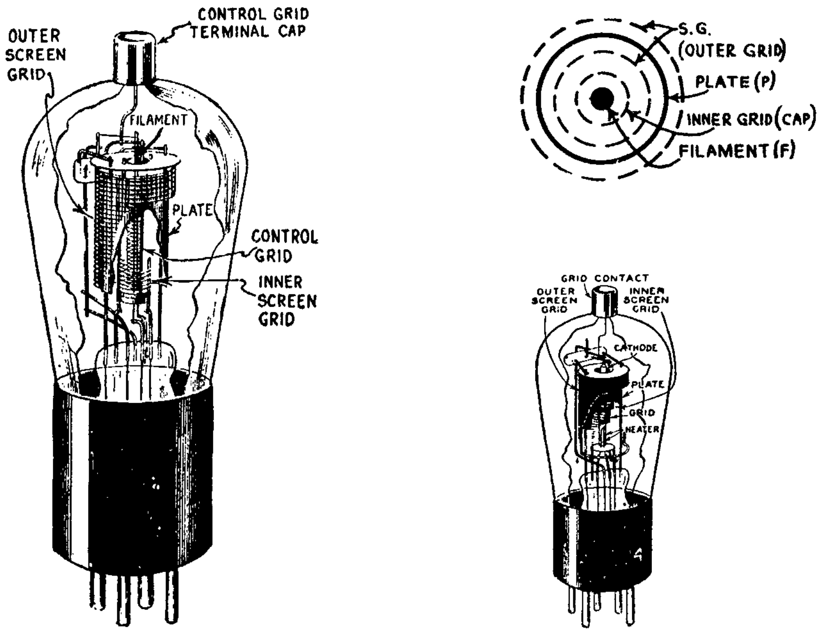


Fig. 226—**Left:** Arrangement of the elements in a battery operated type screen-grid tube. **Upper Right:** Top view of the elements in the tube. **Lower Right:** Arrangement of the elements in a separate heater type of screen-grid tube designed for a-c filament operation.

is, the potential difference between the negative terminal of the C-battery and the screen-grid lead remains steady in value. In addition to the screen directly between the plate and control grid, the outer surface and ends of the plate are screened from the control grid and its lead by a close wire-mesh circular screen as shown in Fig. 226 and at (F) of Fig. 227. The solid sheet metal plate is shown at (E), and the control grid is at (C). To make this construction possible, the control grid lead is brought out to a metal cap sealed into the top of the glass bulb as shown. So effective is this screening, that the direct grid-plate capacitance of the battery type 232 screen-grid tube is .02 mmf., and that of the a-c type 224 tube is .01 mmf., as compared to 10 mmf. for that of the 201-A and 3.3 mmf. for the 227 type of 3-electrode tubes. Of course this very low value of grid-plate capacitance in these tubes reduces practically to zero the feedback due to grid to plate capacitance when they are used as r-f amplifiers. Consequently, there is no instability from this source to hamper the radio-frequency amplifier performance. However, the other sources of feedback such as magnetic coupling between the plate and grid coils, coupling in the "B" voltage supply, etc., must also be eliminated in order to entirely eliminate feedback in the amplifier stages, even if screen-grid tubes are employed.

In order to avoid any detrimental action by the screen grid on the flow of electrons through the open spaces in it on their way to the plate, it is maintained at a potential about equal to the stream potential at the point in which it is inserted in the electron stream. This is accomplished by connecting the screen grid to a low voltage tap on the B voltage supply device, usually 50 to 90 volts. The screen voltage may also be made variable by connecting it to the movable arm on a potentiometer connected across the "B" voltage supply. As the voltage applied to the screen is reduced by adjustment of the potentiometer, the mutual conductance of the tube is decreased, with consequent decrease in volume. This arrangement has been used as a volume control for receivers, but it is not entirely satisfactory however, since it may also greatly decrease the selectivity of the receiver.

Since the screen-grid tube consists of the usual 3-electrodes, (grid, plate and cathode), and an additional one, the screen-grid, it is called a four-electrode tube. As the screen grid is maintained at a positive poten-

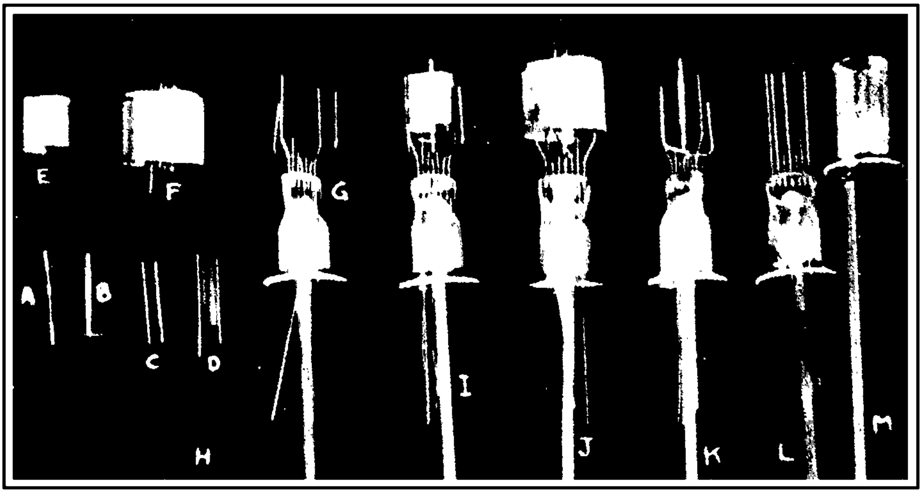


Fig. 227—Various stages in the assembly of the main parts of a separate-heater type screen-grid tube.

tial with respect to the heater or filament, it thereby tends to neutralize and decrease the space charge between the filament and plate. This helps to increase the controlling effect of the control grid on the electron and plate current flow, that is, it increases the amplification factor of the tube. Thus, while the 3-electrode 227 type tube has a mu of 9, the 224 screen-grid tube has a mu of about 400, although it is only possible to obtain an effective amplification of about 40 or 50 in practical circuits. Because of this high voltage-amplification, the wire to the control-grid cap must be shielded from all other wires and circuits if it is long or near them. This is accomplished by using a wire with a copper braid or shield covering connected to ground. The entire tube is also covered usually with a metal tube shield connected to ground. This prevents all stray voltages from reaching the control grid. Also the screen-grid circuit must be well filtered by means of r-f chokes and by-pass condensers, to prevent coupling in the "B" voltage supply.

The electrons from the filament proceed toward the plate and screen-grid at considerable speed, and most of them go through it and are collected by the plate, provided it is kept at a higher positive potential than the screen. Because the screen grid is between the plate and the control grid, the rate at which electrons go across the space is not controlled so much by the plate voltage as it is by the voltages on the two grids, that is, the plate current is more or less independent of the plate voltage within the operating zone of the tube, as shown by the fact that the E_p - I_p curves at (A) of Fig. 228 are almost horizontal, and the a-c plate resistance (which is the ratio between changes in plate voltage and the corresponding changes produced in the plate current), is very high, being 250,000 ohms in the 236 battery type tube and 400,000 ohms for a 224 a-c type of screen-grid tube. Since the plate resistance is almost invariably higher than the load impedance, the plate current is determined mostly by the plate resistance.

310. Types of screen-grid tubes: Screen-grid tubes such as the type 222, 232, and 236 are designed with a thin filament which is heated directly by the d-c current flowing through it. The general construction of this type of tube is shown at the left of Fig. 226. The elements are arranged as already described and as shown at (C) of Fig. 225. At the upper right of Fig. 226 is shown a plan view of the element arrangement looking down on top of the tube. These tubes have four prongs in the base, two for the filament, one for the plate and one for the screen grid. The control grid connection is the cap at the top of the glass bulb as shown.

The elements in the screen-grid tubes such as the 224, 235, 236, etc. designed for a-c operation are arranged in the same way as shown at (D) and (F) of Fig. 225 and the lower right of Fig. 226, excepting that a standard separately heated cathode arrangement similar to that already described and shown in Fig. 219 is employed. The base of the tube has 5 prongs as shown at (E) of Fig. 225. Two prongs connect to the filament, one to the cathode, one to the plate, and the remaining prong which is marked G on the socket, connects to the screen-grid of the tube. The "control grid" terminal is the cap on top of the glass bulb. The heater filaments of several tubes of this type may be operated in parallel from a single transformer winding in the same way, as shown at (D) of Fig. 221.

At Fig. 227 are shown the various elements of a 224 a-c type screen-grid tube during the stages of assembly. A is the filament with small ceramic spacing sleeves, B is the cathode, C is the spiral-wire control grid, D is the spiral wire inside part of the screen grid, E is the plate, F is the metal mesh outside part of the screen grid. At I, the plate, control grid, and cathode assembly are mounted on the stem. At J, the outer and inner parts of the screen-grid have been slipped over the plate. The various detector and radio and audio frequency amplifier circuits in which screen-grid tubes may be used will be studied later.

311. Characteristics of screen-grid tubes: Some of the static characteristic curves of an a-c screen-grid tube are shown at (A) of Fig. 228. It will be noticed that over the normal operating range of plate voltage down to about 90 volts, changes of plate voltage have little effect on the plate current. At low plate voltages, the current actually decreases instead of increasing, that is, an *increase* in plate voltage causes a *decrease* in plate current. The tube then has a *negative* resistance characteristic. This is very important in the action of the tube as a "Dynatron". At plate voltages lower than the screen-grid voltages, electrons may get through the screen-grid, but when they strike the plate they dislodge electrons (secondary emission) and both are attracted back to the screen-grid, because of its greater positive potential. This backward flow of electrons opposes the normal flow of electrons in the tube, thereby causing the plate current to decrease.

When used as an amplifier, the plate, grid-bias and screen-grid voltages are adjusted so that the tube is operated on some portion of the almost flat part of its plate-voltage plate-current curve. The sum of the currents in the screen-grid circuit and the plate circuit are almost constant. The 232 and 224 types of screen-grid tubes may be operated either as amplifiers or detectors as we shall see later.

312. Space-charge grid arrangement: The amplifying effect of a tube is due to the fact that since the grid is closer to the filament than the plate, a slight grid potential change, causes a greater plate current change than an equal plate potential change would. The amplification factor of an ordinary 201-A type tube is about 8.

The space around the filament is filled with a cloud of negative electrons, which constitute a space charge. This negative cloud repels the negative electrons attempting to shoot out from the filament, and being closer to the filament than is the grid, it has a greater effect than the grid. The space-charge produces two effects on the operation of the tube:

The space charge constitutes a constant opposition to the attraction of the positive charge of the plate for the negative electrons from the filament. To overcome this constant repulsion, nearly 85 per cent of the plate potential applied to the ordinary 3-electrode tube is used up (this part of the plate potential being practically useless as far as amplification goes), leaving about 15 per cent for direct action on the filament to establish the plate current and produce amplification. It is evident then that if the space charge could be entirely eliminated, for equal results, the plate voltages necessary for tube operation would be only about 15 per cent of what they are with 3 electrode tubes, and the plate supply voltage unit would be very much simplified and cheapened.

The second effect of the space charge is to lower the amplification constant of the tube, since the grid does not have perfect freedom in controlling the plate current flow. In practice, the tube is always operated with the grid negative. As the repelling effect of a negative grid is added to the existing repelling effect of the space charge, any small change in grid potential is only a small percentage of the total repelling potential. That is, if the space charge were eliminated, the grid effect would be many times what it is with the space charge present, and (with nothing else happening) the amplification factor of the tube would be raised from eight up to 30 or 40, without any change in plate impedance.

Of course, the amplification factor can be increased as is done in ordinary high-mu tubes by increasing the fineness of the grid mesh and placing the grid relatively nearer

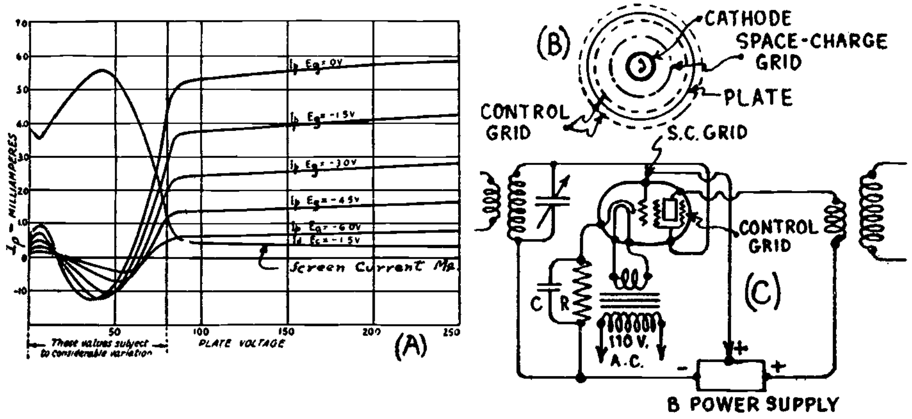


Fig. 228—(A) Average static characteristics of a '24 type screen grid tube.
(B) Arrangement of elements when the space-charge connection is used.
(C) Connection of an ordinary screen-grid type tube as a space-charge grid tube in a circuit.

to the filament than the plate. But this increases the plate to grid capacity enormously and increases the plate impedance, thus making these tubes usable only in audio-frequency circuits, due to the difficulties brought about by excessive feedback when used at the high frequencies existing in radio-frequency circuits, and the difficulty in securing the proper high impedance load necessary in the plate circuit of the interstage coupling device to obtain any appreciable gain. If an ordinary 3-electrode high-mu tube such as the type 240 were to be constructed to have a mu of 200, the plate impedance would be about "*six million*" ohms! The effect of the space charge in ordinary three-electrode tubes is far greater than the effect of the grid, and is a constant factor unaffected by the incoming signal, and tending always to reduce the amplification of the tube.

The space charge effect can be overcome, or at least reduced partially, by putting a *positive charge at or near the region where the negative space charge accumulates.* This is done by introducing a positively charged fourth electrode into the tube, whose purpose it is to assist the work of the plate in attracting electrons and do this efficiently because of its being nearer the troublesome cause. It is evident that this fourth electrode must surround the filament, can be placed either between grid and filament or between grid and plate, and must be of open construction to permit the electrons to fly through it. It can be in the form of another grid, an open winding or a network. If this electrode is placed around the filament, between it and the ordinary control grid as shown at (B) and (C) of Fig. 228, the tube is known as a space-charge grid tube.

The ordinary screen-grid tube can be connected up as a space-charge grid tube as shown at (B) and (C) of Fig. 228. The inner or control grid of the screen-grid tube now becomes the space-charge grid and the screen-grid of the screen-grid tube now becomes the control grid as shown. The space-charge grid is maintained at a positive potential by connecting it to a low voltage tap on the "B" power supply unit.

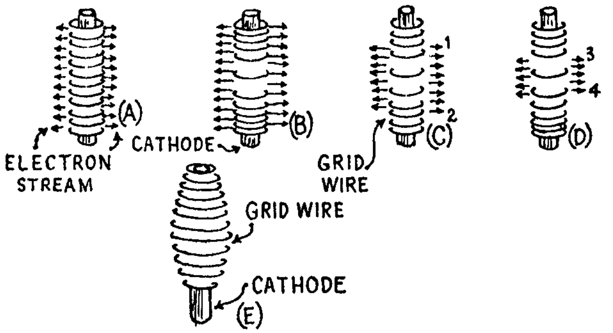
The practical results of the space-charge grid connection are, that the plate current for a given plate voltage is much increased and the mutual conductance of the tube is also increased. Since the screening effect of protecting the grid from potential variations in the plate circuit is lost by this arrangement, the grid-plate capacitance has reappeared, and therefore the tube is of no use as a radio-frequency amplifier. It is in audio-amplifier circuits that the space-charge grid tube finds its field of usefulness and a very high amplification per stage can be obtained at audio frequencies. However, because of the rather high internal tube capacitances resulting from this connection, the space-charge grid tube tends to discriminate against the high-frequency audio tones when used as an amplifier. Audio amplifier circuits for the space-charge grid tube will be considered later.

313. Variable-mu (super-control) tube: A detailed study of the uses and fields of application of the variable-mu tube will not be presented at this point since we have not yet progressed sufficiently in our study of radio-frequency amplification to appreciate the full significance and importance of what it accomplishes. This phase of the study will be considered later when dealing with radio-frequency amplification. At this time we will consider merely the constructional f atures which enable us to build a vacuum tube whose amplification factor and mutual conductance may be made to vary in any desired steps when the control grid potential is varied.

In the ordinary screen-grid form of vacuum tube already described in Articles 309 to 312, the control grid is composed of a small spiral-wound coil of wire of uniform diameter with uniform spacing between the turns as shown at (A) of Fig. 229. Obviously, every portion of a control grid of this kind has an equal effect on the control of the flow of electrons through the open spaces, when it is placed around a cathode emitting electrons uniformly from its surface as shown. The E_g - I_p characteristic curve of such a tube is shown by curve K at (A) of Fig. 230. It is evident that the characteristic is practically a straight line for the normal control grid potential working range from points *o* to *a* (from o to about —5 volts). Therefore, over this range the plate current changes are substantially proportional to the changes of control grid potential. (We need not consider the part of the characteristic for *positive* control-grid potentials, since amplifier tubes are never operated with positive grid potentials.) As the control-grid potential is made more negative toward points *c* and *b*, the plate current changes are no longer quite proportional to control-grid potential changes, as shown by the fact that the characteristic becomes somewhat curved. When the control grid potential is about 11 volts negative, (point *b*) the electron flow through it is entirely stopped by its negative charge, so the plate current drops to zero as shown. The curve L in (B) of Fig. 230 represents the control grid potential—mutual conductance curve for the 224 tube operated at normal filament, plate and screen-grid voltages. It will be seen that the mutual conductance also drops to zero when a negative grid potential of about 11 volts is reached. It will be remembered from our previous study in Article 287, that the *mutual conductance* of a vacuum tube is defined as the change in plate current produced, divided by the change in grid potential producing it.

If any of the electrodes of the tubes are not arranged symmetrically with each other, the operating characteristics may become quite different. For instance, in the variable-mu screen grid tube developed by Stuart Ballantine and H. A. Snow, the individual turns of wire on the control grid are not uniformly spaced as at (A) of Fig. 229, but are more widely spaced at the middle than at the two ends, as shown at (B). It is evident that with this construction, the more closely spaced end portions will exert a greater controlling action on the flow of electrons through them than the more openly spaced center part will.

At low negative grid bias voltage, the effects of a non-uniform turn-spacing on the electron flow and the tube characteristics are practically similar to those obtained when a uniform grid structure is employed. Electrons get through uniformly all along its entire length, as shown at (B). The screen grid and plate are not shown in these sketches in order to avoid confusion. It should be remembered that the positive plate surrounds the control grid, tending to draw the negative electrons through it. As the grid bias voltage is made more negative however, the electron flow from those areas



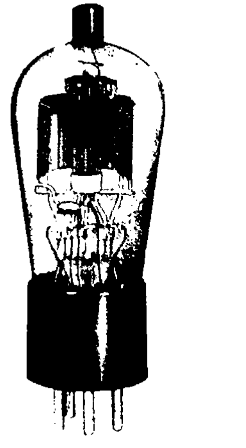


Fig. 229—How the non-uniformly spaced control grid wires in the variable-mu tube passes electrons at the widely spaced portion and acts as an impassable barrier at the closely wound portions. (E): A possible control-grid shape which gives the same results but which is not practical to manufacture. Right: An open view of a variable mu tube.

Courtesy R.C.A. Radiotron Co.

of the cathode covered by the closely-wound portion of the grid is gradually cut off, since the negative charge of these grid wires form an impassible barrier for the negative electrons. When this condition occurs, only the smaller area of the cathode around the more widely spaced turns between points 1 and 2 is effective as shown at (C), since electrons can get through the more open mesh there. Therefore, the amplification factor and mutual conductance of the tube are decreased rather abruptly at this point since given changes in grid potential now produce smaller changes in the electron flow and plate current than when the entire grid is acting on the electron flow; because the ends of the grid are already cutting off the flow of electrons, so no change in electron flow results there. For greater negative grid potentials, the electron stream is still further reduced, until a point is finally reached where the entire plate current flow is reduced to zero.

The variations in plate current of the commercial 235 variable-mu screen-grid tube of this type for various grid potentials is shown by curve V, at (A) of Fig. 230. The mutual conductance is found to vary similarly as shown by curve M at (B) of Fig. 230. Notice that both the plate current and the mutual conductance (transconductance) increase rather abruptly after a certain point is reached in each case. This is the reason for the name *variable-mu* or *multi-mu* tube. Referring to curve V at (A) it is seen that the slope of the E_g - I_p curve is rather steep from point *z* to point *m*. Since the slope of this curve is a measure of the amplification factor of the tube (see Article 288) the amplification factor is high for a grid potential range represented by this portion of the characteristic. From point *z* to point *x*, the characteristic is very curved so the slope and the mu is changing rapidly. From *x* to *e* the characteristic is practically a straight line again, with a much smaller slope than before. Thus the mu for the grid potential range represented by this part is very much smaller than before. Consequently, if the normal operating potential of the grid of this tube is shifted from say, -6 volts to -24 volts by the application of a greater negative grid biasing voltage, the amplification factor and mutual conductance would drop considerably. For instance, in the 235 type variable-mu tube with a fixed plate voltage of 250 volts and a fixed screen-grid voltage of 90 volts, the mutual conductance is 1 micromho at a control grid potential of -50 volts, 15 micromhos when it is -40 volts, and 1050 micromhos when it is -3 volts (see curve M at (B) of Fig. 230).

This important characteristic of being able to greatly vary the *mutual conductance* and *amplification factor* of a variable-mu tube simply by changing the control-grid bias voltage (either by a "manually-operated volume control" or by an "automatic volume control"), makes it possible for the tube to handle a larger range of signal strength or voltage without distortion due to cross-talk and cross-modulation (see Art. 362), than an ordinary screen grid tube can. When a weak signal is being received,

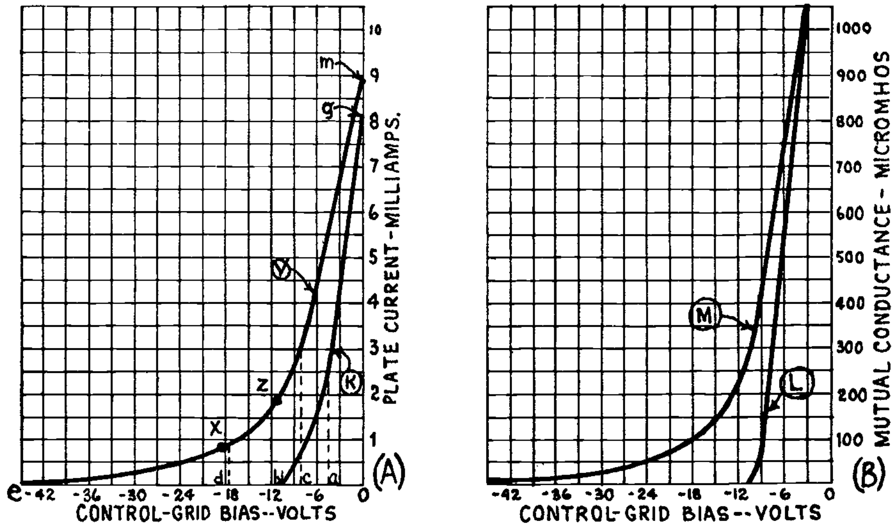


Fig. 230—(A): Eg-Ip characteristics of a '24 type screen grid tube (K) and a variable-mu (or "super-control") type of tube (V).
(B): Eg-Gm characteristics of the same tubes. Curve (M) is for the variable-mu tube and curve (L) is for the ordinary screen grid tube.

high amplification is desired, and the volume control of the receiver is adjusted so as to apply a reduced negative bias to the control-grid, thus permitting the tube to work over the high-amplification region between *z* and *m* on characteristic (V) of (A) of Fig. 230. When a powerful signal is being received, the volume control is adjusted so as to make the grid bias voltage more negative, thus shifting the operating region toward *x* and *e* on the characteristic. This higher negative bias causes the electron flow from the sections of the cathode enclosed by the ends of the control-grid to be cut off (see (D) of Fig. 229), thus greatly reducing the control effect of the grid on the electron flow, that is, reducing the "amplification factor".

In addition to this convenient variable amplification feature, the variable-mu tube is also important because as will be seen from the curves in (A) of Fig. 230, it can handle a much larger range of signal strengths or voltages applied to its control-grid than can an ordinary screen grid tube. For these reasons, variable-mu tubes are often called *super-control* amplifier tubes. They are particularly suitable for use in sets having "automatic volume control" (see Art. 376).

The 235 type variable-mu tube shown in Fig. 229 is of the screen-grid separate-heater type, since it is designed to be used in the r-f or intermediate frequency amplifiers of a-c operated receivers or as the "mixer" tube in super-heterodyne receivers. The wide spacing of the control grid at the center and the closer spacing at the ends may be seen from this illustration, since the outer screen-grid and plate have been partly broken away to show the inner screen grid and control grid. Otherwise the construction of the tube is exactly similar to that of the screen-grid 224 type. The special applications of the variable-mu tube will be considered in connection with cross modulation in Art. 362, and radio-frequency amplifiers. It is important to note that the change in the characteristic of the tube can be made to take place at any pre-determined operating condition merely by proper design and spacing of the electrodes.

314. Power tubes: In all the amplifying tubes except the last one in the audio amplifier, the object desired is an amplification or increase of the *signal voltage* applied to the input circuit. The varying signal voltage acts upon the grid of the tube to control the plate current. The varying plate current flowing through a resistance or inductive load produces varying potential difference or voltage drop across the load. The variations in voltage appearing across the load are greater than the variations in signal voltage applied to the grid, i.e., the applied voltage variations are amplified.

In the output circuit of the amplifying tube in the last audio amplifier stage (the tube that feeds energy to the loud speaker), it is electrical *power* (watts) that is desired, since actual electrical power is required to operate the speaker and cause motion of its diaphragm. Therefore, it is desirable that the last tube not only have a high amplification factor, but that it also have a large plate current and low plate impedance so that only a small part of the energy supplied to its plate circuit by the "B" power supply device be used up in the tube itself, and most of it be transferred to the loud speaker coupling device connected in its plate circuit. If a large portion of the applied plate circuit voltage is used up inside of the tube to overcome the impedance of the plate—cathode path, then very little will be left for use in supplying power to the loud speaker circuit since ($W = E \times I$). Also since the signal voltage set up in the antenna circuit has been amplified many thousand times by the various amplifying stages of the receiver before it reaches the grid circuit of the last tube in the receiver, this tube must be capable of handling without distortion, quite large variations of signal voltage applied to its grid circuit (as high as 50 volts or more in home radio receivers and even more in high power audio amplifiers), that is, its E_g - I_p characteristic curve must be straight over a large range of grid potential.

Since in the power tube it is desired to obtain as much power output as possible due to a given applied signal voltage, the term *power sensitivity* is commonly used when comparing power tubes. The "power sensitivity" is a measure of the power controlled in the plate circuit by a given input grid voltage change. Thus in a tube with a large "power sensitivity" small changes of grid potential handle large changes in output power. Obviously this property is very desirable in a power output tube. Power sensitivity will be discussed more in detail in Article 319 in connection with the power pentode tube. Since these special requirements are somewhat different from those desired for interstage amplifier tubes, the tubes used in the last audio stage of radio receivers and audio amplifiers are constructed somewhat differently from the ordinary general-purpose amplifying tubes, and since their function is to deliver as much undistorted power to the loud-speaker as possible, they are called *power tubes*. If we study the methods by which these characteristics must be obtained in an ordinary 3-electrode type of tube, we will see that the requirements conflict so that it is not possible to attain all of them, but that a compromise in the resulting characteristics must be accepted.

First, in order to obtain a low plate impedance, the plate must be mounted rather near to the cathode (electron emitter) so as to make the length of the plate current path short, and the plate area may be made quite large so as to make the cross-section area of the electron stream large. Also, the cathode must be designed to provide a plentiful supply of electrons. Second, in order to obtain a high amplification factor, the grid wires may be very closely spaced as shown at (A) of Fig. 231 and the grid

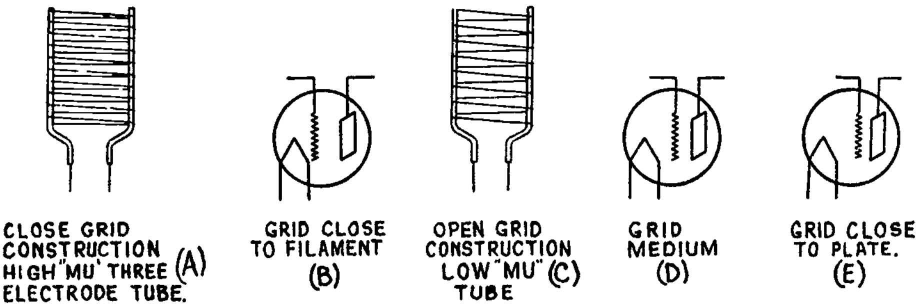


Fig. 231—Effect of grid position and structure on the amplification factor and plate impedance of a 3-electrode tube.

should be mounted much nearer to the filament than the plate is, as shown at (B), so that a given change in grid potential will have a greater control on the electron flow than an equal change in plate potential would. It can be seen that these two requirements conflict, since if the plate is mounted close to the filament to reduce the plate impedance then the grid would have to be mounted practically on the filament to produce a high amplification factor. This would be undesirable due to the possibility of short circuits. Also if the grid wires were of very close mesh, the grid would entirely cut off the flow of electrons for rather small values of negative grid potential and the E_g - I_p characteristic would quickly drop down to zero plate current and therefore would not be straight for a very long portion, i.e., only rather small input signal voltages could be applied to the grid circuit without distortion.

As a result of these considerations, our 3-electrode power tubes such as the 171-A, 245 and 250 types are compromises between the desired characteristics. In order to secure the desirable low plate impedance in the neighborhood of 2,000 to 6,000 ohms, together with a grid characteristic such that the E_g - I_p characteristic is practically a straight line over rather a large swing of grid potential, the grids of such tubes must be wound rather openly as shown at (C) and must be placed quite far relatively, from the filament as shown at (D). If the grid is too near to the plate, as at (E) the grid will have no greater effect on the plate current flow than the plate has, and the amplification factor will be low. The result is, that such tubes have a rather low voltage amplification factor as will be seen from the following figures for some common American 3-electrode power tubes.

Tube Type	Permissible signal grid-voltage swing (volts)	Maximum undistorted output (milliwatts)	Plate impedance in ohms	Plate current (M. A.)	Voltage amplification factor
120	22.5	110	6,300	6.5	3.3
231	22.5	170	4,000	8	3.5
112-A	15	260	5,000	7.6	8.5
171-A	40.5	700	1,850	20	3.0
245	48.5	1600	1,750	34	3.5
210	35	1600	5,000	18	8.0
250	38	4600	1,800	55	3.8

Note: These figures are those for the condition where the tube is operated at maximum plate voltage and correspondingly proper negative grid bias voltage. They are taken from the table of Fig. 214.

Examination of these values shows that in general, those power tubes having the lower plate impedances and larger power output values have the lower amplification factors. It is also evident that the larger tubes such as the 245, 210 and 250 types can handle a larger signal voltage swing and deliver more undistorted power output than the smaller types. As their plate currents are quite large and they employ quite high plate voltages, considerable power is dissipated in the plate-filament circuit of such tubes.

315. Filament current supply for power tubes: The filaments of all 3-electrode type power tubes, with the exception of the 120 and 210 types (which are no longer used to any great extent), are of the oxide-coated ribbon type. The filaments of the larger power tubes such as the 171-A, 245, 210 and 250 types are rather thick and consequently if they are heated with alternating current, their temperature will not vary to any great extent over each a-c cycle since they retain considerable heat. They are therefore heated with a-c of the proper voltage supplied by a step-down transformer, and a center-tapped resistor is connected across the filament for obtaining the electrical center of the filament as explained in Article 303. The method of obtaining the grid-bias voltage automatically will be explained later. Heating the filament of a power tube with a-c produces some 120-cycle ripple in the plate current, as in the case of any of the other tubes in the receiver. A slight ripple in the plate current will produce a slight hum in the loudspeaker, but this will not be audible a foot or two away from the loud speaker. Of course, the power tubes designed for use in battery-operated receivers have their filaments heated from the "A" battery.

316. Heating of the plate: The electrons which are travelling from the filament to the plate are moving at the rate of thousands of miles per second when they hit the plate. When electrons moving at such a high velocity are suddenly stopped by the plate, their energy of motion is suddenly converted into heat which is given up to the plate. This continuous bombardment of the plate by the stream of electrons attracted to it, results in considerable heat being produced in it especially if the plate current is large (large number of electrons moving to the plate every second) and a high plate voltage is employed (greater velocity of the electrons when they strike the plate). As will be seen from the table above, these are just the conditions which are present in power tubes, especially in the larger ones such as the 245, 210, and 250 type.

The rate at which the heat is developed in the plate, for a non-oscillating tube, is proportional to the product of the plate current and the plate voltage. Since the plate is in a vacuum inside the glass bulb, this heat can be dissipated most by *radiation*, (actually a small part is also dissipated by conduction through the metal plate supports and glass stem). It is a well known law of physics that a black rough body will radiate heat much better than a smooth polished surface, when hot. Therefore the heat radiating properties of the plates of power tubes are increased by coating their surfaces with a rough black carbonized surface layer. This may be produced by spraying them with a solution containing graphite, or by depositing lampblack on them by exposing them to a luminous gas flame during manufacture. Inspection of a 245, 210 or 250 type power tube will reveal this blackened plate. This makes possible the use of a plate of smaller size, for equal heat radiation.

317. Need for the pentode tube: Examination of the characteristics of the various 3-electrode power tubes listed in Fig. 214 shows that in general these tubes do not deliver a very great amount of undistorted power (remember that the figures given in the chart are for the power in *milliwatts*), when we consider that such high plate voltages as specified are applied to the tubes and such large plate currents flow.

For instance, from Fig. 214 we find that a 245 type power tube with 250 volts applied to the plate, has a plate current of .034 amperes flowing and delivers an undistorted power output of 1600 milliwatts (or 1.6 watts). Now the electrical power being supplied to the plate circuit of this tube by the "B" voltage supply device is equal to $W=E \times I=250 \times .034$ or 8.5 watts. The tube only delivers 1.6 watts of useful power or about 1/5 as much as we put into its plate circuit. The rest is converted into useless heat in the plate-to-cathode circuit. There are two reasons for this, and when we know what they are, we will understand just why and how the pentode tube differs from other types of tubes.

Various forms of pentode tubes have been employed in Europe for several years because of the necessity for economical operation of the many battery operated receivers used there. It is essential in equipment of this kind that the plate voltages employed on tubes be as low as possible and that the amplification produced by each tube be as high as possible in order to economize on battery and tube cost. Also, since in most European countries radio set owners are taxed for radio reception on a basis of the number of tubes employed in the receiver, it is essential that each tube be made to produce as much amplification as possible in order to obtain the necessary amplification with a minimum number of tubes. The pentode type of tube fulfills these requirements by providing the same amplification and power output at lower plate voltages (or more amplification and power output at the same plate voltages) than is possible with present forms of 3 and 4-electrode tubes.

Let us now see what undesirable tube characteristics the particular construction of the pentode tube reduces or eliminates. Before proceeding with this study it is important to point out that pentode tubes are five-electrode tubes, but that there are two entirely distinct forms of pentodes or "five-electrode" tubes. One is the *power pentode* and the other is the *screen-grid pentode.* Each has five electrodes, but as we shall see these electrodes are arranged differently inside the tube resulting in characteristics which differ. The power pentode tube is a low-resistance (comparatively) high-output tube designed only for the final stage in an audio amplifier. It is not suitable for use in a radio-frequency amplifier. The other pentode is a high-resistance, low-power output tube designed for radio or audio amplification only; it is of the screen grid type. It is not suitable for use as an output tube.

318. Secondary emission and space charge reviewed: Although secondary emission and space charge were explained in Article 266 and

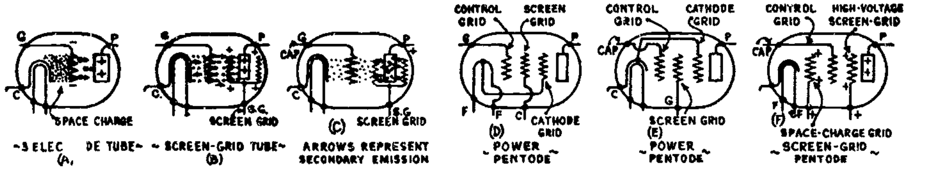


Fig. 232—Development stages of the power pentode and the screen grid pentode tubes.

309, a complete understanding of them is so important in the study of the pentode tube that they will be reviewed briefly again here.

The effectiveness with which a vacuum tube amplifies, depends upon the effectiveness with which the potential changes on the grid affect the plate current or the electron stream flowing between the cathode (or filament), and the plate. This variation in the plate current is caused by a variation in the negative charge existing between the filament and the plate. As this charge is increased negatively—for instance, by adding additional grid bias or by applying the negative half of an alternating signal voltage cycle—the plate current is decreased, the stronger negative charge repelling more electrons seeking a path through the grid to the plate.

The negative charge existing in the space between the filament and the plate of an ordinary vacuum tube consists of two parts, the useful control charge imposed by the grid, and the space charges of the cloud of electrons which are in the space between the cathode and the grid at any instant as shown at (A) of Fig. 232. This negative charge will tend to repel any other electrons which tend to come off from the cathode. The existance of this space charge detracts from the effectiveness of grid potential variations in the same manner that a glass full of water added to, or taken from, that in a large reservoir has a negligible effect on the total, compared with that of the addition or withdrawal of this same amount from a small pan of water. It is obvious that if we could eliminate this negative space charge, the effect of grid potential variations on the electron flow between the cathode and plate would be considerably increased, that is the amplification factor of the tube would be raised. This is exactly what the fourth-electrode, (the screen-grid) accomplishes in the screen-grid tube, by introducing a counteracting positive charge behind the control grid. Some electrons strike this screen grid and current will therefore flow in its circuit. The power wasted in its circuit is small however, because this grid is a coarse mesh and only comparatively few electrons stick to it. The rest are speeded up so much by the accelerating force of its positive charge, that they go rushing through it at speeds as high as twenty thousand or more miles per second, to land on the positive plate behind it as shown at (B). In the space-charge grid connection shown at Fig. 228, the positive charge is introduced *between* the cathode and control grid so it is even more effective in neutralizing the space charge which is normally between the cathode and control grid.

As soon as the space charge is reduced or eliminated, the effectiveness of the plate voltage is also increased of course, since electrons emitted from the filament do not have to overcome the opposition of the space charge when on their way to the plate.

The effect of the space charge could also be reduced by using very high positive plate voltage, but in the 3-electrode tube it would require a rather excessive plate voltage to overcome the effect of space charge. By using the screen grid or space-charge grid, we can achieve the same effect with much lower plate voltages, or using the same plate voltages, we can obtain a great increase in operating efficiency, that is, in amplification factor.

The use of the screen grid or space-charge grid arrangement seems like a very simple way to get rid of the space charge, but unfortunately the effectiveness of the screen grid tube (particularly as a power amplifier), is limited by secondary emissions caused by the bombardment of the electrons against the plate.

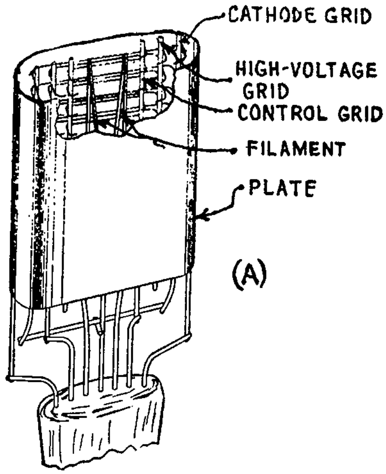
As the electrons, which are moving at velocities of thousands of miles per second, strike the plate, they not only give up their kinetic energy in the form of heat, but also tend to forcibly knock other *secondary* electrons out of the plate. This is called *secondary emission.* It is possible for a single electron to knock quite a few electrons loose from the plate, depending on its velocity. In the ordinary 3-electrode tube these secondary electrons may float around for a fraction of a second and either return to the plate or join the space charge. In the screen-grid tube however, the presence of the highly positive screen grid may attract these secondary electrons and get them moving with sufficient velocity to get away from the field of the plate, and into the positive field of the screen grid as shown at (C), taking a direction exactly opposite to that of the negative electrons leaving the cathode and therefore interfering with their motion (like charges repel) and causing the plate current to decrease. Since one electron may knock out as many as 20 electrons from the plate, if enough secondary electrons are knocked out, the number leaving the plate may be greater than the number arriving from the cathode. In this case, the main electron flow is from plate to screen-grid, that is, the plate current flows backwards. This is shown in the E_p - I_p characteristic curves of a screen grid tube at (A) of Fig. 228. It will be seen that when the plate voltage is less than the screen grid voltage (screen grid voltage for this tube was 75 volts positive), the plate current flows from plate to screen-grid, as shown by the fact that the plate current curves dip down below the zero plate current line, i.e., go in the negative direction. This is the reason for these peculiar bends in the characteristic curves of a screen grid tube. This part of the curve represents a condition of the tube that makes it worthless for the purpose of linear amplification. To prevent this of course, the plate should always be operated at a potential at least equal to that of the screen-grid, preferably higher. This means that even though we gain the advantage of reduction of space charge by using the screen-grid, it speeds up the electrons so much that they cause secondary emission which prevents us from being able to reduce the plate voltage to a value near that of the screen-grid voltage.

Now we are prepared to see just what the additional or fifth electrode in the pentode tube does.

319. The power pentode tube: The introduction of another grid forming the *pentode* or *five-element* tube effectively reduces the secondary emission, making it possible to take practical advantage of the increased amplification due to the screen grid. In the usual form of power pentode, the third grid is connected inside of the tube to the cathode and is commonly referred to as the *cathode grid* or *suppressor grid* since it "suppresses" the secondary emission.

In the direct heater type power pentodes such as the 247 and 233 types, the cathode grid is connected directly to the center of the filament inside the tube as shown at (D), and a standard five prong UY socket is employed with the terminals arranged as shown in Fig. 232. In the separate-heater type power pentode tubes such as the 238 type, the cathode grid is connected directly to the cathode as shown at (E). Therefore no extra external connection is necessary for it. A five prong UY socket is also employed for this type of tube, with the terminal arrangement shown. The control grid terminal is the cap on top of the tube. At the right of Fig. 233 is shown a direct heater type of power pentode with a portion of its plate cut away to show the interior construction and arrangement of the elements. The arrangement of the elements may be seen more clearly from the drawing at (A). This type of tube is designed for use in the output stage of home radio receivers operated from the a-c electric light line.

In pentode tubes the screen grid is sometimes referred to as the *high voltage grid.* This is probably a better name for this element than "screen-grid" because in the power pentode tube the primary purpose of this grid is to accelerate the electrons toward the plate and not to screen



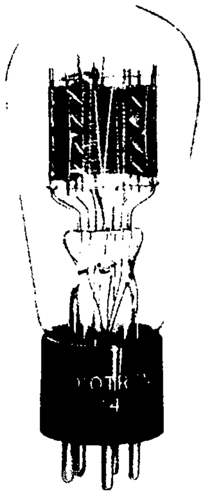


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Fig. 233—**Left:** Skeleton sketch showing the arrangement of the elements in a power pentode tube.
Right: A power pentode tube designed for a-c filament operation. The plate is broken open to show the interior construction.

the input from the output circuit as in the case of the screen-grid tube.

The cathode grid, forms a grounded shield between the plate and the screen grid. As it is at the same potential as the cathode, it has practically no effect on the electrons that have just left the cathode en route to the plate. However, its negative potential, in reference to the plate, is that of the instantaneous plate voltage, with the result that the *secondary* electrons prefer returning back to the plate rather than passing through the cathode grid to get to the screen grid beyond.

An electron leaving the filament then, first comes into the field of the control grid (see (D) of Fig. 232) which will have a certain negative charge. It is drawn through this grid by the positive charge on the plate and screen grid beyond. It next comes into the field of the positive screen grid and is either attracted to it and neutralized, or is speeded up sufficiently so it goes through the screen grid to the cathode grid. It may be retarded by this grid because it is at zero potential. At any rate it is being attracted strongly by the positive charge on the plate just beyond, so it goes through the cathode grid and strikes the plate. If it knocks another electron out, or if it rebounds, it goes back a short distance and is immediately repelled back to the plate by the cathode grid and at the same time attracted back to the plate by the positive charge. In other words, any rebounding electrons or secondary electrons will be attracted back to the plate where they are useful.

The characteristics of the power pentode tubes types 238, 233 and 247 will be found in Fig. 214. The 238 type employs a separate heater construction as in (E) of Fig. 232 and is designed for battery operation in automobile or airplane receivers or in receivers operated from the d-c electric light line. The 233 type is a dry cell operated power pentode with a 2 volt type filament similar to that used in the 230, 231, and 232 type tubes. The 247 is designed for 2.5 volt a-c filament operation in electrically operated receivers.

320. Advantages of power pentode, power sensitivity: In the power pentode tube we approach the condition in which the maximum amount of plate power is controlled by a minimum amount of grid voltage fluctuation. It is a screen-grid tube adapted to power purposes for use in circuits where, with the four element tube, the grid swing would be sufficient to introduce distortion due to secondary emission.

There is a growing tendency to rate power tubes on the basis of *power sensitivity*. This is a very logical method of comparing output tubes, since their prime function is to deliver as much undistorted power to the loud speaker for a given fluctuation of grid potential as possible. At present, there exist two different definitions of this term.

Hanna, Sutherlin and Upp define power sensitivity as the ratio of watts output to the square of the R. M. S. input voltage for a given limiting percentage of distortion.

Still another definition has been proposed by Stuart Ballantine, and H. L. Cobb (proceedings of the I. R. E., March 1930). In view of the fact that sound output from the loud speaker is proportional to the square root of the power, rather than directly proportional to the power, these engineers propose that, "The power sensitivity is defined as the square root of the power output divided by the effective values of the applied sinusoidal grid voltage". By means of the latter rating we can compare directly the equivalent gains of two different types of output tubes of the same power capacity.

One great advantage of the power pentode is its great power sensitivity. For instance, the 245 type power tube which has been used as a power output tube extensively in American made receivers, consumes some 8 watts in its plate circuit, and with a 50 volt signal applied to the grid delivers 1.6 watts to the load or speaker circuit. The 247 power pentode operated at the same plate voltage of 250 volts draws a total plate and screen current of 39.5 milliamperes, so that about 10 watts are used in its plate circuit. However, the power sensitivity of this tube is so high that it will deliver 2.5 watts of undistorted power to the loud speaker when the applied signal voltage is only 16.5 volts. In other words, a single 247 pentode tube when employed in proper circuits will deliver nearly 1.5 times as much power to the loudspeaker with a signal voltage only 1/3 as much. The power pentode is about 3.3 times as sensitive as the 3-electrode power tubes commonly in use. This simply means that using a power pentode is equivalent to using an additional amplifier stage with a voltage gain of 3.3 times. In other words, a good pentode, properly operated, will be almost as effective as two -45 tubes in push-pull, for the same power employed (in power tubes) but possessing so high an amplification constant that it definitely eliminates the first audio stage, and probably, in many instances, will function both as detector and power amplifier, with obvious added economies. The elimination of previous stages automatically eliminates the hum and incidental distortion associated with the discarded tubes.

Another application of the power pentode is in connection with phonograph amplifiers. By using a high ratio transformer to couple the pickup to the power pentode tube, sufficient power output can be obtained by using a single stage of pentode amplification working directly into the loud speaker. Another advantage of the power pentode over the 3-electrode type of power tube is the fact that with a given electrical power taken from the plate voltage supply system, the power pentode will deliver much more power to the loud speaker. This makes it especially valuable in battery operated receivers where economical battery current consumption is desirable. Its complicated structure is a disadvantage of course, as it contains so many metal parts that it is difficult to remove all the air and gas from them and it is rather difficult to make tubes of this type with uniform characteristics by ordinary quantity production methods unless strict inspection is maintained. The circuit connections of pentode tubes will be considered later in connection with battery operated and electrically operated receivers.

321. The screen-grid r-f pentode: If the extra grid of the pentode tube is kept at a positive potential with respect to the cathode, and is placed between the cathode and the control grid as shown at (F) of Fig. 232, it will neutralize partly at least, the space charge between the cathode and control grid. We will then have a screen-grid pentode whose plate current is small, whose inter-element capacity is rather high, whose power output is low and whose mutual conductance is somewhat greater than that of the ordinary form of screen-grid tube and with which greater amplification is therefore possible. Notice that the additional grid in this tube is in an altogether different place than in the power pentode, and that it serves an entirely different purpose. In the power pentode the additional grid prevents secondary emission from the plate. In this tube, which is called the *screen-grid pentode*, its purpose is merely to reduce the space charge, that is, to keep the electrons moving between the cathode and control-grid. In the screen-grid pentode, the extra grid is called the *space-charge grid* as shown at (F) of Fig. 232. It is given a positive charge by connecting it to a positive part of the "B" voltage supply device. It is unfortunate that the grid-plate capacity of the tube increases in almost the same ratio as the possible voltage gain. As a result, objectionable oscillation due to feedback from the plate to the grid circuit is likely to occur when it is used in radio frequency amplifiers, thus making some form of neutralization or oscillation suppression necessary. In one form of screen-grid pentode constructed along the line of the popular 224 type screen-grid tube, excepting that it has the extra space-charge grid, the grid to plate capacitance is almost double that of the 224 type tube. The input capacitance between the control-grid and cathode, and that between the plate and cathode, is also about double that of the 224 tube. It is possibly this fact that will prevent this type of tube from becoming very popular for use in r-f amplifiers. The fact that secondary emission takes place in this tube, causes the entire lower part of its E_p - I_p curve to dip below the zero line indicating a reversal in direction of the plate current, somewhat as shown in the characteristic for the ordinary screen-grid tube in Fig. 228. Like the pentode, this type of tube also suffers from the fact that its structure is rather complex and it is therefore difficult to make uniformly by quantity production methods unless careful inspection is maintained.

322. Grid bias for direct heater tubes: As we shall see later, in practically all applications of the vacuum tubes as amplifiers, for best operation the control grid must be kept normally at a certain steady negative potential with respect to the electron emitter (cathode) when no signal e. m. f. is applied, the value of this steady negative potential depending on the type of tube and the plate voltage applied to it. This is called the grid or "C" bias potential or voltage. Its purpose is to set the operation of the tube at the center of the straight portion of its E_g - I_p characteristic when no signal is applied, so that when the a-c signal e. m. f. is applied to the grid circuit, it merely causes the grid potential to vary above and below this steady applied "C" bias voltage during each cycle, so the grid merely becomes more or less negative due to the signal. The grid is not allowed to swing positive, since then a grid current would flow, which is objectionable. Up to this point, we have considered that the grid was kept at some definite potential by means of a battery called the "C" or grid-bias battery, as shown at (A) of Fig. 234 when the filament is heated by a-c, and at (B) of Fig. 203 when the filament is heated with direct current by an "A" battery. The circuit may be arranged so the C bias voltage is furnished by the plate current of the tube itself, as we shall now see. In order to do this, a resistor R, (called the "C" or grid-bias resistor) is connected in the plate current return circuit as shown at (B) of Fig. 234 for the center-tapped resistor case and at (C) for the center-tapped transformer case. In either case, the operation is as follows, the same notations being used in both diagrams:

The plate current I_p flows from the positive terminal of the "B" voltage supply up through the plate circuit load to the plate, through the tube from plate to filament, down through both sides of the filament circuit and out of the center tap to point A, as shown by the arrows at both (B) and (C). From point A the current flows through the C bias resistor R from D to E, back to the negative terminal and through the B supply device, thus completing the circuit. A certain amount of the total electric potential in the plate current circuit is used up (fall of potential) in forcing this current through R. Therefore the end E of the resistor will be at a lower electric potential than the point D by an amount equal to $I_p \times R$, since in accordance with Ohm's law, current always flows from a point of higher potential to a point of lower potential. Therefore if the grid return circuit (point F) is connected to the minus end of the grid bias resistor as shown, it will be at the same potential as point E and they are both at a lower potential than points D and A by an amount equal to the voltage drop in R. Hence if we know the plate current of a tube and the C bias voltage it requires, we can easily calculate the value of the grid-bias resistor required to produce this. The plate current and grid bias voltage required for any tube operated as an amplifier at any plate voltage may be found in the proper columns in the tube characteristic chart of Fig. 214.

Example: A 224 tube is to be operated as an amplifier with a plate voltage of 180 volts. What value of C bias resistor is required to obtain correct C bias voltage?

Solution: Referring to Fig. 214, we find that for a 224 tube operated as an amplifier with a plate voltage of 180 volts, the plate current is 4 milliamperes (.004 ampere), and the grid-bias voltage should be 3 volts. Therefore the correct value of C bias resistor to use is,

$$R = \frac{E}{I} = \frac{3}{.004} = 750 \text{ ohms. Ans.}$$

Many tubes are designed with rather thick filaments so they may be heated either with direct current or alternating current. The power tubes

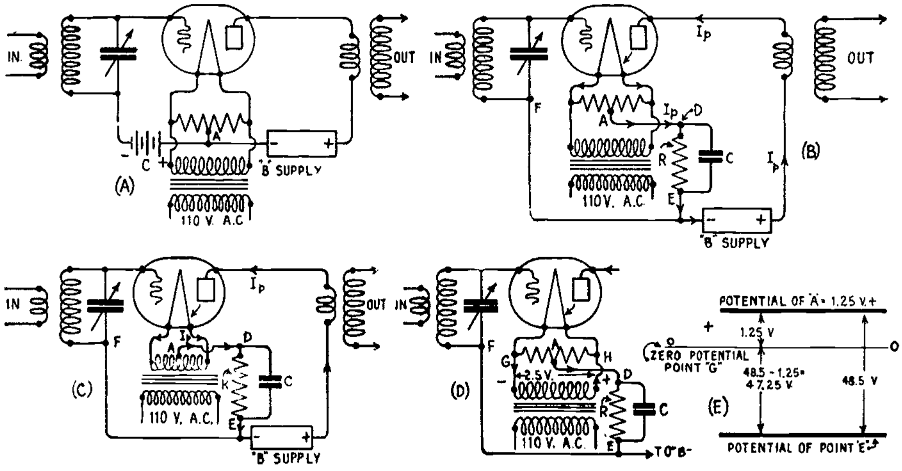


Fig. 234—Methods of obtaining self-grid bias for various types of tubes.

such as the 171-A, 245, 247, etc. are of this type, although the filaments of the latter take so much current that it is usually not economical to furnish the current from batteries. However, if we look up in Fig. 214, the C bias data for the 245 tube for instance, we find that two values of grid bias voltage are specified, one for d-c on the filament and the other for a-c on the filament. The grid bias to be applied when the filament is heated with d-c is 48.5 volts negative and when the filament is heated with a-c it should be 50 volts negative, for a plate voltage of 250 volts. Similarly, the values are different for many other tubes. Let us see the reason for this.

We must remember that all differences of potential in a vacuum tube are referred to the negative end of the cathode as the point of reference. In the case of a direct-heater type filament, this point is the *negative* end of the filament. Now in the case of a battery-operated filament, the negative end is simply the end of the side where the minus terminal of the A battery is connected. If a grid bias voltage of say 48.5 volts is specified as above, it simply means that the grid is kept at a potential 48.5 volts negative with respect to this point. However, if the filament is heated with 60 cycle alternating current instead, as shown in Fig. 234, neither end of the filament can be considered as the negative all the time, for both ends are changing alternately from positive to negative 60 times every second. Therefore we must refer our voltages to whichever end of the filament happens to be negative at the instant considered. When the left side of the filament is negative we have the condition shown at (D). Current flows out of the transformer winding and through the filament of the tube. Current also flows out of the positive terminal of the transformer winding to H, then through the center-tapped resistor to A and to G and back into the negative terminal. For the case of the 2.5 volt type of filament being considered, there is therefore a difference of potential of 2.5 volts between H and G, point H being at the higher potential. Since A is the center-tap, there will be a difference of potential of half this or 1.25 volts between point A and point G, that is, since current flows from A to G, center-tap A is 1.25 volts positive with respect to point G which is the negative end of the filament at this instant, and to which all voltages are to be referred at this instant. Therefore if the C bias resistor R was of the proper value to make point E 48.5 volts *lower* in potential than point D, since point A is 1.25 volt *higher* in potential than point G, point E is really only 48.5—1.25=47.25 volts lower in potential than the negative end G of the filament. This may be understood better from the simple potential level diagram at (E) in which distances above the zero potential deference line O-O represent positive potentials and distances below represent negative potentials. Point A is 1.25 volts above G. Point E is 48.5 volts below A. Therefore point E is 48.5—1.25=47.25 volts below G. These vertical distances might be considered to represent actual potential differences in volts. Now on the next half of the cycle when the right hand side of the filament becomes negative and therefore becomes the reference point for potentials, point A will again be at a higher potential than the negative end of the filament, since current now flows from G to A to N (the reader should draw the diagram for this condition), and we have the same condition.

It is evident from this, that in the case of a-c filament operation the actual voltage drop across the C bias resistor must be greater than the net effective difference of potential required between the grid and negative end of the filament at each instant, by an amount equal to half the filament voltage. In tables of tube characteristics, the actual voltage drop across the C bias resistor is called the grid-bias voltage in either case simply for convenience, although it is the true C bias voltage only in the case of d-c filament operation. This, then, is the reason for the specification of higher grid-bias voltage when a-c is used for heating the filament than when d-c is used. Taking the case of the 245 tube mentioned, we see that the difference between the specified values for a-c and d-c is 50—48.5=1.5. This is close enough to half the value of the filament voltage of the tube (2.5÷2=1.25 volts). Glancing down the columns for the a-c and d-c operation, it will be seen that in each case the grid bias voltage specified when a-c filament operation is used, is equal to the value specified for the d-c filament operation plus half the filament voltage, (see Fig. 214).

Obviously, in radio equipment operated direct from the electric light circuits it is very convenient to obtain the proper grid-bias voltage for the various direct-heater filament tubes by this method, in order to eliminate the use of a battery for furnishing it. Even in battery-operated equipment, this method is very advantageous when the grid bias voltage required is only a small percentage of the plate voltage of the tube, for it eliminates the need for frequent renewals of C batteries. Also, since the grid bias voltage furnished by the resistor R depends on the plate current flowing through it, as the B batteries get old and the voltage drops, the plate current and fall of potential through R drop correspondingly. Therefore, the grid-bias voltage applied also drops automatically so that the proper grid-bias voltage for the particular plate voltage existing is always being applied. For this reason, this system is called the *automatic* or *self-biasing* method of obtaining grid-bias voltage. We shall hereafter refer to it by the latter term.

Referring to (B) of Fig. 234 again it can be seen that the total potential difference in the plate circuit is furnished by the "B" supply device, whether this be a set of dry cell batteries, a "B" eliminator or what not. Part of this is used up in sending the plate current through the load impedance, part in sending the plate current through the plate-cathode impedance, a small part in the filament and half of the center-tapped resistor, (this may be neglected), and part in sending the plate current through the grid bias resistor R, in order to develop the grid bias voltage. If we neglect the plate-load voltage drop and the drop in the filament and center-tapped resistor, the voltage actually effective between the cathode and plate is equal to the voltage of the B supply device minus the grid bias voltage drop in the grid bias resistor. Therefore in receivers employing self bias it should be remembered that the total "B" supply voltage should be higher than the voltage actually desired on the plates, by an amount at least equal to the grid bias voltage appearing across the grid bias resistor. If the impedance of the plate circuit load is high, as in the case of a resistance coupled amplifier, there will also be considerable voltage drop in it, and this should also be considered in the above.

Since the plate current flowing through the grid-bias resistor R is varying when a varying signal voltage is applied to the grid of the tube, the fall of potential in this resistor would also vary correspondingly and therefore the grid bias potential applied to the grid would vary. Let us see just what effect this would have:

Referring to (D) of Fig. 234, let us consider the instant when the a-c signal voltage applied in the grid circuit tends to make the grid more positive (or less negative) than the applied grid bias voltage. This will cause an increase in the plate current. The increased plate current flowing through grid-bias resistor R causes an increased drop of potential in it making point E more negative with respect to the negative end of the filament than before. The effect of this is to increase the negative bias voltage applied to the grid, thus tending to make the grid more negative; or looking at it another way, tending to keep the grid potential from changing as much due to the signal e. m. f. as it would ordinarily, and therefore diminishing the plate current change and volume of sound caused by the signal. This is sometimes called a *degenerative* action because it is just opposite to the signal aiding action of regeneration which we shall study later. On the next half wave, when the signal e. m. f. tends to drive the grid more negative, the plate current decreases. Instantly this results in a lower potential drop through resistor R, and a lower applied negative grid bias voltage, which tends to increase the plate current, thus opposing or weakening the effect of the signal e. m. f., in producing the plate current changes.

The values of C bias resistors recommended for use with various types of tubes, at various plate voltages will be given in Article 324, after we have considered the arrangement to be employed for obtaining self-bias in the case of separate-heater type tubes. The degenerative effect may be decreased greatly by shunting the grid bias resistor R, with a condenser C as shown. This forms in effect a resistance-capacity filter. Let us see how this operates:

Let us assume that a steady plate current of 2 milliamperes flows through resistor R of 2,000 ohms when no signal is applied to the tube. The fall of potential across the resistor is therefore $E = I \times R = .002 \times 2000 = 4$ volts. This charges the plates of condenser C connected across it to a difference of potential of 4 volts. Now the first half of the first alternation of the a-c acts on the grid, drives the grid potential more positive. The plate current increases, and therefore more electrons tend to pass through R every second. Since R offers a resistance of 2,000 ohms to the flow of electrons through it, if condenser C is of large enough capacitance, so that it offers a substantially lower reactance to the flow of electrons into it at this frequency than resistor R does, these additional electrons will accumulate into its negative plate instead of going through the resistor. Therefore the resistor still carries practically the same current as before and so the voltage drop across it is the same and the grid bias voltage has not been affected. It is assumed that condenser C is of large enough capacitance so that these additional electrons crowding into its negative plate during this small interval of time do not increase the potential difference between its plates to any noticeable extent. Now the next part of the signal impulse comes along and drives the grid potential more negative. This tends to reduce the plate current, i.e., reduce the number of electrons drifting through resistor R. The condenser being charged to maximum potential during the previous increasing plate current impulse, will now discharge part of the excess electrons from its negative plate. These go through the resistor and therefore help to keep the voltage drop across it steady. The same thing is repeated over and over on each signal impulse, the condenser storing electrons when the plate current increases and releasing them when the plate current decreases, so that the grid bias voltage obtained from resistor R remains substantially constant. It is assumed that the condenser is of large enough capacitance so that its reactance to the flow of electrons (current) at the frequency encountered in the circuit is much lower than the resistance R which it is shunting. Of course the larger the condenser capacitance is, the better, but the element of condenser cost and space available limit the size of by-pass condensers which can be employed in practice. For practical purposes, in radio-frequency circuits a by-pass condenser is chosen of such a capacitance that its reactance at the frequency of the signal e. m. f. and plate current impulses is less than from one-one hundredth to one-one thousandth that of the resistor it is shunting. In audio-frequency circuits, the condenser reactance is usually kept down to about 0.1 the value of the resistance it is shunting. It has become common practice to use by-pass condensers of 0.2 to 0.5 mfd. for shunting grid bias resistors of r-f amplifier tubes used in broadcast receivers where the frequency may be anywhere from 500,000 to 1,500,000 cycles per second; and to use by-pass condensers from 1 mfd. to 4 mfd. for shunting those used in audio-frequency amplifier circuits where the frequency of the signal e. m. f. and plate current pulsations varies from below 100 cycles to above four or five thousand cycles per second.

The size of condenser to use is determined by the lowest frequency encountered, for since condenser reactance decreases as the frequency is increased, a by-pass condenser good for the lower frequencies will be even better for all frequencies higher than this. The table of condenser reactances in Article 166, may be used for quickly finding the reactance of any size of condenser at almost any frequency. Condensers of the non-inductive type (see Articles 141 and 142) should be employed for this service. By-pass condensers used for this purpose are usually of the paper dielectric or mica dielectric type as shown in Figs. 90 and 91.

Problem: What is the capacitance of a by-pass condenser which will have one-one-thousandth the reactance of the 2000 ohm non-inductive grid-bias resistor it is shunting, at a frequency of 500,000 cycles per second when used in the circuit of an r-f amplifier tube?

Solution: The resistance offered by the resistor is 2,000 ohms regardless of the frequency, provided it is non-inductive. Therefore the reactance of the condenser must be equal to $\frac{2000}{1000} = 2$ ohms. Referring to the table of condenser reactances in Article 166, we find that the capacitance required which has a reactance of 2 ohms at 500,000 cycles may be a 0.25 mfd. condenser. This will have a reactance of 1.28 ohms at this frequency. A 0.2 mfd. condenser will also do, since its reactance would be 1.6 ohms.

Problem: A 227 tube in an audio amplifier in which the lowest frequency is 120 cycles per second, employs a 2,000 ohm grid-bias resistor. What must be the capacitance of the by-pass condenser to be used across it if the condenser reactance is to be not more than about one tenth the reactance of the resistor at this frequency?

Solution: $2000 \div 10 = 200$. Referring to the condenser reactance table in Article 166, we find that at 120 cycles per second, a 6 mfd. condenser has a reactance of 221 ohms. This condenser will therefore be suitable for the purpose. Ans.

The use of a bias resistor in the cathode lead to derive a voltage from the plate current drop, leads to several complications in the case of the power pentode. Since the amplification factor is high, the degenerative effect of audio voltage across this bias resistor is marked in effect. To eliminate this effect which results in decreased power output and loss of fidelity, it is usual to bypass the resistor to B— with a condenser, as we have just seen. The value of capacity necessary with the '47 type pentode is prohibitively large. To reach an optimum for reproduction down to 60 cycles the capacitance would have to be about 10 microfarads since the C bias resistor would have to be about 418 ohms (actually about 400 ohms is used for the grid bias resistor). Of course an electrolytic condenser can be used for by-passing, but there are other better ways of obtaining the grid-bias. Fixed bias by means of a "bleeder" resistor from some point in the "B" supply can usually be obtained by the drop across a resistor of much lower value and can be de-coupled easily from the grid and plate circuits of the pentode as we shall see later when studying receiver circuits in which power pentode tubes are employed. The method of obtaining grid-bias from some point in the B power supply unit is also used extensively for tubes other than pentodes.

323. Grid-bias for separate-heater tubes: Grid-bias for separate-heater type tubes can also be obtained by connecting a grid-bias resistor in the plate return circuit of the tube. It is most conveniently connected as shown at (A) of Fig. 235. The plate current flows from the plate to the cathode, through the grid bias resistor to the negative terminal of the B voltage supply as shown by the arrows.

Since the plate current flows from D to E, point D is at a higher potential than point E, i.e., E is negative with respect to D by an amount equal to the voltage drop $E = I \times R$ in the resistor R. If the grid return wire from F is connected to the lower end E of the grid-bias resistor as shown, both it and the grid will be kept at this negative potential with respect to point D and the cathode. As explained in Article 322, a by-pass condenser C must be connected across the resistor, its value depending on the resistance of R and the lowest frequency of the pulsations of the plate current which is to flow through the resistor. This value depends of course on whether the tube is to be used in a radio frequency circuit or an audio frequency circuit. In the case of a screen-grid tube or variable-mu tube, the same circuit connections may be employed as shown at (B), excepting that since both the plate current and the screen grid current flow back through resistor R, the sum of the two should be used as the current when calculating the value of the grid-bias resistor required, by Ohm's law.

324. Grid-bias for several tubes: In the interests of economy, in radio receivers employing several tubes of the same type, and operated at the same voltages, since similar grid-bias voltages are required they may all be obtained from a single resistance. In the case of direct-heater type tubes, the grid-bias resistor is connected in the center-tap lead of the single

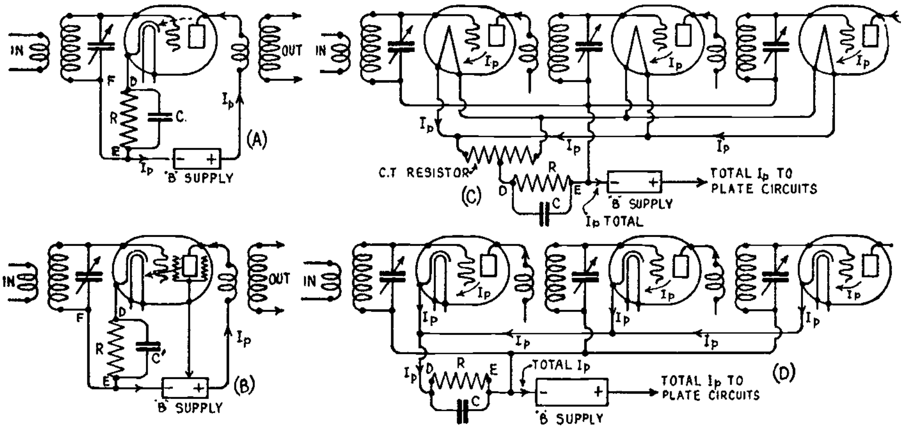


Fig. 235—Obtaining negative grid-bias voltage for separate-heater type tubes.

center-tap resistor (or center-tap on the transformer winding) as shown at (C). Since the combined plate currents of all the tubes flow through this resistor, its value in Ohms should be less than that used for a single tube. Thus, if two tubes are operated from the same grid-bias resistor, since twice as much plate current flows through the resistor as for a single tube, it should be of only half the resistance value for the same bias voltage drop. For three tubes it is 1/3 as large as for 1 tube, etc. This may be understood from the following problem:

Problem: From Fig. 214 it is found that at a plate voltage of 250 volts applied through a plate coupling resistor of 200,000 ohms, the plate current of a 224 screen-grid tube operated as an audio amplifier is .5 milliamperes (.0005 amps.) and the grid bias is 1.0 volt negative. Calculate the grid bias resistor required for (a) a single tube, (b) two tubes operating with one resistor, (c) five tubes operating with one resistor.

Solution: (a) $R = \frac{E}{I} = \frac{1}{.0005} = 2000$ ohms.

(b) with two tubes, double the plate current flows through the resistor.

Therefore: $R = \frac{1}{.001} = 1000$ ohms (half as much as for 1 tube).

(c) for five tubes $R = 2000 \div 5 = 400$ ohms. Ans.

In the case of several separate-heater type tubes obtaining their grid-bias voltage from a single resistor, the connection is as shown at (D), all the cathodes are connected together. The resistor is connected in the combined cathode return lead so that the total plate current of all the tubes flows through it. The value of the resistor is calculated in the same way as for the cases explained above. Of course these connections for the grid-bias resistor are the same for either 3-electrode type tubes or screen-grid tubes, and for either radio-frequency or audio-frequency amplifier circuits. Similarly, when two vacuum tubes are connected in parallel or push-pull, the plate current through the common grid-bias resistor is double that of a single tube, and therefore in order to obtain the same fall of potential for use as grid-bias, only half the value of resistance should be employed as would be used for a single tube.

The following table furnishes the values of R to be used for proper grid-bias for various commonly used tubes when their filaments are operated with a-c. The grid-bias resistor values given are for a single tube, and are calculated from the grid-bias voltage and plate-current values given in Fig. 214. The nearest resistor value which is easily obtainable commercially has been specified in each case, since a few ohms difference in the value of the grid-bias resistor will not affect the operation of the tube.

TABLE OF GRID-BIAS RESISTOR VALUES

Type of Tube		Grid Bias Resistor For A Single Tube (Ohms)				
	90 V. Plate	135 V. Plate	180 V. Plate	250 V. Plate	425 V. Plate	450 V. Plate
226	1600	1400	1800	--------	--------	--------
227	2200	2000	2700	--------	--------	--------
224	--------	--------	375 with	75 V. on	Screen	2000
224	--------	--------	750 with	90 V. on	Screen	--------
171A	1600	1700	2200	--------	--------	--------
245	--------	1400	1500	--------	--------	--------
247	--------	--------	--------	420	--------	--------
210	--------	--------	--------	2200	2200	--------
250	--------	--------	--------	1600	1550	1500

Note: The resistance values given above are for a single tube. If two tubes are to be operated from the same grid bias resistor, only half this resistance value is required, etc.

Later, when studying B power supply devices and modern a-c electric receivers, we will see how grid-bias voltages are obtained in many such receivers by making use of voltage drops occurring in loud speaker field windings, bleeder resistors, etc. The latter methods are used in many radio receivers on account of their convenience, low cost, and several advantageous operating features, which will be explained.

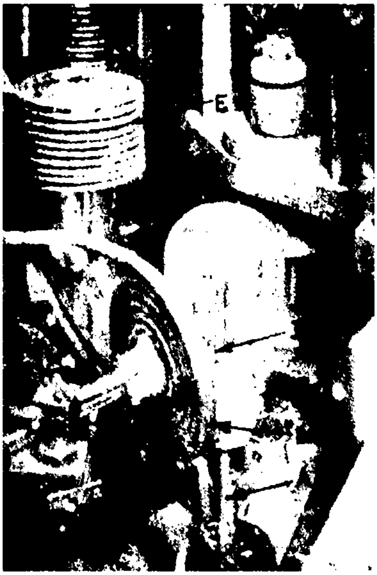
325. Vacuum tube construction: Vacuum tubes are made in many forms, with various sizes, shapes and arrangements of electrodes in order to produce certain desirable characteristics to make the tube best suited for a particular use. The filaments may be designed to be operated from dry cells, storage batteries or raw alternating current. The tubes can be constructed to handle from a few milliwatts to several thousand watts of power. The filaments may be either of the thoriated tungsten type or coated with the oxides of barium or strontium to increase the electron emission for a given temperature. They may be made in the form of round wires, or flat ribbons; arranged in the form of a straight wire, an inverted V, a double V, etc. The plates are usually plain box-shaped, or cylindrical, with the grids corresponding. The relative spacing of grid, filament, and plate, as well as the fineness of the mesh in the grid, also varies in the different tubes. Some tubes have been designed with a multiplicity of filaments, grids and plates. In Europe, some tubes have been designed with multiple elements so as to contain within the glass bulb all the necessary parts for one or two amplifier stages. These have not attained great popularity in the United States.

Illustrations of several types of vacuum tubes are shown in Figs. 193, 196, 215, 220, 226, 227, 229 and 233. The student should study these carefully at this point. The construction of the filament has already been considered in Articles 299 and 301. We have seen that the oxide coated type is the most popular at the present time. The usual recommended limits of filament voltage variation are plus or minus five per cent of rated voltage. This means that the maximum permissible voltage is equal to 1.05 times the rated voltage and the minimum permissible voltage is 0.95 times the rated voltage. For a 227 tube rated at 2.5 volts these values are found to be 2.63 and 2.38 respectively. This overall range of ten per cent takes care of slight line voltage variations which may occur in receivers operated from the electric light lines, but is, of course, not sufficient to take care of any wide variations in line voltage, for in some localities (small towns especially), the line voltage may vary as much as twenty-five per cent.

The grids are usually made of fine molybdenum ("molly"), or nickel wire, wound in the form of either a round or flattened spiral, around two nickel supports, and welded, or otherwise fastened to them, at each turn. The inner screen-grid in the '24 type of screen-grid tube consists of a nickel wire. The outer screen grid is of nickel mesh as shown in Fig. 227. The chief advantages of mesh as an outer element material for radio tubes are that it permits free radiation of heat from the intermediate elements, whose operation at low temperatures is desirable, and that during the evacuation process it permits more rapid inductive heating of the elements which it surrounds. The former advantage is of great importance in tubes where a considerable amount of heat is given out by the filament. The advantages of nickel as a mesh material are many: it is pliable, and the mesh can be readily formed into any shape desired; it is easily cleaned by baking in a hydrogen atmosphere, and is relatively immune to tarnishing on standing or handling; it can be readily spot-welded to other nickel parts; it has a relatively high melting point; and it can be secured in a pure state and at a reasonable cost. The use of nickel mesh is restricted to the outer element of the tube for several reasons. The two grids within the plate of a screen-grid type tube are of comparatively small diameter, must be accurate in diameter, and if made of mesh would have to be of very open weave. Under these conditions, a more satisfactory grid can be manufactured using a spirally-wound wire than using woven mesh. In order to obtain satisfactory operation, the plate of the tube would have to be of very fine woven material if mesh were used; because of the difficulty and cost of weaving such fine mesh, solid nickel strip is still used for the plate by many manufacturers.

The greatest obstacle encountered in the production of good vacuum tubes is gas. Utmost precautions must be taken to be sure that all the gas is removed from the tube before sealing. For this reason the pumping is carried out as far as possible within the economic time limit, followed by the flashing of a chemical or "getter" to clean up the remaining gases. The metal parts are frequently baked in a hydrogen atmosphere, to remove the oxygen from the pores of the metal. Even so, with nickel for the support wires, plate and grid, there is considerable imbedded gas which is certain to be liberated when the tube is in use, resulting in gassy tubes. For this reason, molybdenum or "molly" plates are frequently used, also molly wire is used for supports and grids. However, this metal is far more expensive than nickel, and introduces a serious increase in cost. This is a very important consideration in a field such as the vacuum tube industry, which is highly competitive. For this reason, the nickel parts continue in general use. The plates of power tubes, rectifier tubes, and other large tubes are covered with a carbonized surface layer. This makes them rough and black and aids in increasing the radiation of heat from them. The filament is supported at the bottom and top. In some tubes, additional bracing to prevent mechanical vibration of the elements is secured by a piece of mica holding the grid, filament and plate supports rigidly at the top. This reduces microphonic noises caused by variation of distance between the elements due to mechanical vibration. The slight variation of element spacing due to vibration would cause the plate current to vary likewise, resulting in a sound of the same vibration frequency from the loud speaker.

326. Manufacture of vacuum tubes: Fig. 196 shows the assembly stages of a 201-A type vacuum tube. Fig. 227 shows a few of the assembly stages of a 224 type screen-grid tube. The metal parts are first assembled on the metal supports and fastened mostly by spot-welding. The entire assembly is mounted on a glass flare through which the connecting wires are sealed, and from which a hollow tube extends at the bottom. The flare is then sealed to the outer glass bulb as shown at the right of Fig. 196, making an upright assembly.



Courtesy Electronics Magazine

Fig. 235A—"Bombarding" the metal parts of a vacuum tube during evacuation. The air being pumped out of bulb C through glass stem A. B is the "bombarder" coil which flashes the "getter" at D. E is the "bombarder" coil which heats up all the metal parts to release the air trapped in the pores of the metal and glass.

The long glass tube is attached to the special high vacuum pumps which exhaust the air out. Several tubes are placed on a manifold for exhaust. They are heated by gas flames while the exhaust pumps are in operation. This quickly drives out all air and gas bubbles which may be entrapped in the pores of the walls of the bulb and all of the metal and glass parts inside of it. For a similar reason, the filament is usually kept heated by an electric current during this time. The elements are now heated to a red heat to drive out any remaining gas, by means of an external radio-frequency induction coil called a "bombarder" which drops over the glass bulb as shown at E of Fig 235A. The rapidly alternating powerful magnetic field of the coil induces powerful eddy currents in the metal parts inside, which heat them to a red heat and thereby helps to free the occluded gases which are immediately drawn off by the pumps. Of course the field has no effect on the glass bulb which is an insulator. After the tube has been evacuated as much as possible by the pumping process, it is sealed off, and the high frequency bombarder coil which is lowered over the tube heats the elements excessively to a red heat by induction. This forces out the remaining gas molecules since they expand due to the heat, and at the same time the "getter" material vaporizes and enters into vigorous chemical combination with the freed gases. Upon removal of the high-frequency coil, the vaporized "getter" condenses on the comparatively cool inner walls of the tube where it forms the familiar silver or reddish film so noticeable in vacuum tubes.

Several materials are suitable for use as getters. Among the more common are: magnesium, (same as ordinary flashlight powder), barium, aluminum, Misch-metal (a mixture composed of several rare metals of the cerium-group), calcium and cerium. Magnesium and barium are perhaps the two most widely used getters. A tiny metal cup containing the getter is usually mounted in an inverted position, usually below and to the side of the plate, so the getter is not thrown against the metal elements in the tube when it vaporizes. All of the operations of sealing the flare to the bulb, evacuating, bombarding, flashing and sealing-off are performed automatically by modern machinery. A number of tubes are mounted on a large circular turntable, which rotates slowly. Each tube comes around in succession to the devices which automatically perform the various operations described above. It is due to automatic machinery of this type that the cost of manufacture of vacuum tubes has been decreased so markedly during the past few years.

After the tube has been sealed off, it is cemented to the Bakelite base and the lead-in wires are solderd to the tube prongs. These are made of hollow brass tubing, plated to prevent further corrosion. The tube is then tested and aged by operating it at definite filament voltages for certain lengths of time until the filament emission becomes stable and constant. A rough test for gas content is made by bringing a high-frequency spark coil up near to the glass bulb. If the tube contains an excess of gas, it will be ionized by the rapidly alternating field of the coil and the characteristic blue glow due to this ionization will be produced.

The actual measurement in finished vacuum tubes consists in measuring the "inverse" current that flows in the grid circuit under some standard condition of operation of the radio tube. By "inverse" current is meant a current which flows in the grid circuit when the grid is negative with respect to the filament, that is, a current which flows in the sense of grid to filament in the exterior circuit. It can be demonstrated that this current originates from the ionization of the gas tube, and is therefore largely proportional to the gas content of the tube.

In the common types of radio tubes, the magnitude of the grid current is from a few hundredths of a microampere to several microamperes, depending on the excellence of the vacuum in the tube and the test conditions chosen. Currents of this size represent about the lower limit of sensitivity of the very best portable electrical measuring instruments that can conveniently be used in factories and factory laboratories.

Every possible effort is made to not only produce as perfect a vacuum as possible in modern vacuum tubes, but by means of the heating of the metal parts and the flashing of the "getter", to eliminate even the small bubbles of gas and water vapor absorbed in the microscopic pores of the metal and glass parts. The exhausting apparatus consists of mercury vapor pumps in series with ordinary rotary or reciprocating pumps. Gas pressure is usually measured by the height of the column of mercury it will support. A *micron* of pressure is equal to that exerted by 1/1000 of a millimeter of mercury. The average new vacuum tube has a vacuum of 2 or 3 microns, a micron being one-millionth of the usual atmospheric pressure of 15 pounds per sq. in. An incandescent lamp has a vacuum of 150 microns. Special long-life tubes are being made with a vacuum of less than 1 micron.

A "soft" or low-vacuum tube cannot withstand the high voltages necessary for amplification, although it may be used at low voltages as a detector. The life of a tube is largely dependent upon the degree of vacuum existing in it, varying from 100 hours for a poor vacuum to several thousand hours for a good vacuum.

The structure of vacuum tubes calls for the use of various metals, and other materials. An idea of the many materials entering into the actual construction and manufacturing processes connected with the manufacture of various types of vacuum tubes, may be obtained from the following list which is published here by the courtesy of the R. C. A. Radiotron Co.

GLASS BULBS AND PARTS

Silver oxide
Lead acetate
Glycerine
Silica
Sodium carbonate
Calcium oxide
Sodium nitrate
Lead oxide
Borax
Zinc oxide
Cobalt oxide
Potassium carbonate
Calcium aluminum floride
Arsenic trioxide

BASES

Isolantite
Bakelite
Porcelain
Wood fiber
Zinc
Copper
Nickel
Tin
Marble flour
Ethyl alcohol
Nigrosine
Zinc Chloride
Malachite green
Ammonium chloride
Petroleum Jelly

SUPPORTS

Glass
Mica
Lava
Magnesia
Nickel
Molybdenum
Monel
Alumina

LEADS

Iron
Nickel
Copper
Zinc
Borax

GETTERS

Magnesium
Calcium
Strontium
Barium
Caesium
Phosphorus
Carbon
Mercury
Mischmetal

ELECTRON EMITTERS (filaments and cathodes)

Tungsten
Thorium nitrate
Carbon
Nickel
Platinum
Iridium
Cobalt
Iron
Titanium
Silicon
Barium carbonate
Strontium carbonate
Calcium carbonate
Barium nitrate
Strontium nitrate
Silica
Alumina
Magnesia

PLATES

Nickel
Monel
Molybdenum
Iron

GRIDS

Nickel
Monel
Copper
Molybdenum
Chromium

GASES USED IN MANUFACTURE

Hydrogen
Helium
Neon
Argon
Nitrogen
Oxygen
Natural Gas

Copper and iron find their way into the manufacture of tubes in the form of stem leads. A special heavy iron wire is wrapped with copper and drawn down through dies until their combined diameter is the proper size desired. Thus a small iron wire with a thin shell of copper is formed, known as "copper-clad." Copper-clad possesses practically the same expansion and contraction as glass and can be fused into glass without fear of cracks due to unequal expansion, hence the tube will not lose its vacuum because of cracks which might otherwise be formed.

327. Effect of gas in a vacuum tube: The foregoing explanations of the actions taking place in the vacuum tube were based on the supposition that a very perfect vacuum existed in the tube. Under these conditions, the tube operates entirely by the normal unimpeded electron stream between the filament and plate. If the space in the tube contains more than the slightest trace of gas, and the plate voltage is high, the operation is somewhat more complicated, and a larger plate current will usually flow for a given plate voltage, provided ionization takes place.

The actual rate of emission from the filament is not affected, but the liberated electrons on their way to the plate collide with the atoms of the gas, causing "ionization by collision". On account of this action, larger plate currents will usually flow with a given plate voltage in tubes having a poor vacuum. Air of course is a gas. Present day vacuum tubes are made with a high degree of vacuum so that no ionization takes place.

Ionization in a tube might at first seem desirable, since its effect is to increase the plate current. Actually, however, it is undesirable since it interferes with the normal operation of the tube. Also, since the ions which are driven violently against the negatively charged filament are much more massive than electrons, the bombardment actually seems to tear away the surface of the filament, disintegrating it and reducing its useful life. Ionization in a tube is usually accompanied by a visible blue glow discharge, although a blue glow in a tube may be produced by other actions which are not harmful. The tube usually becomes very erratic in behavior when in this condition. It is not sensitive in a receiver, since the plate current becomes so large due to the ionization that it is practically unaffected by variation of the grid voltage. Some of the old gas-filled detector tubes could be made to ionize strongly at plate voltages as low as 100 volts. Tubes containing some gas are called *soft* or *gassy* tubes. They were very popular one time for use as detectors. Tubes having a very high degree of vacuum are called "hard" tubes. They make the best amplifiers.

Practically all tubes used in modern radio receivers are high-vacuum or "hard" tubes. Tube manufacturers employ elaborate machinery and manufacturing operations in a special effort to remove every last trace of air from the inside of the tube during the course of manufacture. The scientific "de-gassifying" processes applied to remove even the slight amount of air entrapped in the pores of the metal elements and inside surface of the glass tube are well known examples of this. This is partly due to the effort to produce tubes having longer filament life, and to the practical problem of producing tubes for operation at high plate voltages. These high plate voltages (such as exist in the 245, 210 and 250 type tubes) cause ionization effects which would be absent in tubes designed for lower plate voltages, for a given amount of air or gas present. Commercial forms of "gassy" tubes are apt to be rather non-uniform on account of the practical difficulties involved in manufacturing tubes of this type on a large scale by quantity production methods, and turning out a high percentage of perfect tubes which are all exact duplicates of each other, each having the same number of molecules of gas.

REVIEW QUESTIONS

1. Why are many different types of vacuum tubes manufactured? Would it not be better to have a single standard type of tube?
2. What is the purpose of the filament in (a) the direct-heater type of tube; (b) the indirect-heater type of tube?
3. Describe the two types of filaments used in the former types of tubes, and explain the advantages of each. Which one is used most?
4. What causes a decrease of electron emission in the thoriated tungsten filament and how can such a filament be reactivated? Is this possible with an oxide-coated filament?
5. What materials are used for (a) oxide-coated filaments; (b) oxide-coated cathodes?
6. How should a tube be tested for "emission"?
7. Explain two causes of the hum produced if an ordinary thin filament such as is used in the 201-A type of tube, is heated with alternating current.
8. What special construction features do the filaments of direct-heater type tubes suitable for a-c filament heating have?
9. How is hum-free operation obtained in the separate-heater type of tube? Draw a sketch showing the construction and relative location of the elements of a 3-electrode tube of this type. Mark on it, the complete filament and plate circuits.
10. What is the purpose of the center-tapped resistor, or center tapped filament transformer winding, used when a-c filament

operation is employed? State which method is best,—with your reasons. Where should the C-T resistor be placed in the set?

11. State several advantages of separate-heater type tubes over the 226 type tubes, for a-c filament operation. Why may direct-heater type tubes be employed in the last audio stage of a receiver, without resulting in objectionable hum?
12. What supplies the low a-c filament voltages required for a-c tubes?
13. What happens to a tube when the oxide-coating on the cathode has all been used up? What must be done when a tube reaches this condition?
14. Draw a simple circuit diagram showing a filament heating transformer supplying a-c current to the filaments of five separate-heater type tubes if (a) the filaments are connected in parallel, (b) if the filaments are connected in series. What are the advantages of each arrangement?
15. Why must the filament circuit connecting wires in a-c operated receivers be run close together or twisted?
16. The filaments of four type 235 tubes, two type 227 and two type 247 tubes in a radio receiver are all connected in parallel. Assuming that each filament is rated at 2.5 volts and 1.75 amperes, calculate the total current and voltage which the low-voltage filament winding of the transformer must supply to the tubes. What is the total wattage supplied to all the filaments? If the efficiency of the transformer is 80 per cent, how many watts are taken by its primary from the 110 volt a-c line?
17. Draw a sketch showing the capacitances which exist between the various elements in a 3-electrode vacuum tube, marking each one with its proper name.
18. Explain (with sketches) how feedback can take place from the plate circuit to the grid circuit of an r-f amplifier stage, due to large grid-to-plate capacitance in the tube. Why is oscillation in an r-f amplifier objectionable?
19. Explain (with sketches) the construction of the 4-electrode screen-grid tube and show how this construction greatly reduces the grid-plate capacitance of the tube.
20. What is the approximate capacitance between the plate and grid in a 227 type tube, and to what value has it been reduced in the 224 screen-grid type?
21. Explain (with sketches) (a) the cause of space-charge in a tube; (b) why it is objectionable; (c) how the arrangement of the elements in a space-charge grid tube greatly reduce it. Why is the space-charge grid form of tube not used for radio-frequency amplification?
22. What is a variable-mu tube? Explain the special feature of its construction (with sketches) which is responsible for its par-

ticular characteristics. Also explain what happens as the potential of the grid is made more and more negative. In what part of a radio receiver is this type of tube used especially. Why?

23. What is the difference between the purpose of an ordinary amplifier tube and the purpose of a "power tube"? What is meant by the "power sensitivity" of a power tube?
24. Explain (with sketches) the construction and arrangements of the elements (a) in the power pentode tube, (b) in the screen-grid pentode tube. What causes secondary emission in a tube; what harmful effects does it have on the operation of the tube; and how is it prevented in the pentode?
25. What are the advantages of the power pentode over the ordinary 3-electrode forms of power tubes? What important disadvantage does the screen-grid pentode have, that reduces its desirability as an r-f amplifier tube?
26. Draw simple sketches showing the relative location of the electrodes in the following types of tubes: (a) 3-electrode; (b) screen-grid; (c) variable-mu; (d) space-charge grid tube; (e) power pentode; (f) screen-grid pentode. Assume separate-heater construction in each case and mark the names of the elements on each sketch. Now starting with the 3-electrode tube, point out briefly the difference in the construction between each type and the particular special characteristics which this results in.
27. Draw a practical circuit for obtaining proper grid bias for two 227 type tubes operated as r-f amplifiers in a broadcast receiver, with a plate voltage of 180 volts. From the grid-bias voltage and plate current values given in the table of Fig. 214, calculate the value of the grid-bias resistor required to obtain correct grid bias voltage. What size of by-pass condenser would you employ across the resistor?
28. Repeat question 27, using three 224 type tubes operated with a plate voltage of 180 volts and a screen voltage of 75 volts. Explain in detail, how the grid-bias voltage is obtained in each case.
29. What value of resistor would be used in each case if only a single tube were used?
30. What are the grid and plate in a vacuum tube usually made of? Why?
31. Explain briefly the process of manufacture of a vacuum tube, including in your discussion the reason for the use of the "bombarder", and the "getter".
32. Why is it so necessary to eliminate every possible trace of air from a tube, even to the extent of liberating the tiny air bubbles which are entrapped in the pores of the metal parts and glass bulb?

CHAPTER 20

VACUUM TUBE DETECTOR AND AMPLIFIER ACTION

THE VACUUM TUBE DETECTOR — GRID BIAS DETECTOR — GRID LEAK AND CONDENSER DETECTION — SQUARE LAW AND LINEAR DETECTORS — POWER DETECTION — GRID LEAK AND CONDENSER POWER DETECTION — GRID BIAS POWER DETECTION — TWO-ELECTRODE LINEAR POWER DETECTOR — COMPARISONS OF DETECTOR ARRANGEMENTS — VACUUM TUBE AMPLIFIER ACTION — MAXIMUM VOLTAGE AMPLIFICATION — CONDITIONS FOR UNDISTORTED AMPLIFICATION — DISTORTION DUE TO INCORRECT GRID BIAS — DISTORTION DUE TO OVERLOADING — DISTORTION DUE TO CURVED CHARACTERISTIC — RESULTS OF TUBE DISTORTION — TESTING FOR DISTORTION — REVIEW QUESTIONS.

328. The vacuum tube detector: In Chapter 16, the manner in which electromagnetic radiations from radio transmitting stations are intercepted by the receiving antenna and the way in which the principle of electrical resonance (tuning) may be employed to allow only the signals of that station which it is desired to receive, to pass through the receiver was explained. The necessity for some form of detector arrangement which not only changes the alternating high-frequency signal voltages into pulsating direct current, but also makes the earphones or loudspeaker responsive only to the successive maximum values or envelope of the rectified r-f current was also explained. We found that this could be accomplished by means of the simple crystal rectifier or detector with a small condenser connected across the speaker, but that crystal detectors are no longer used to any extent in radio receivers because of several objectionable features which they have. The reader should review Articles 252 and 254 briefly at this point. The function of the so-called "detector" in radio receivers is really that of *demodulation.* We learned that in the transmitting station, the audio-frequency voice-currents are made to modulate the strength of the successive cycles of the high-frequency carrier current as shown at D of Fig. 171 and in Fig. 172-A. The function of the detector in the receiving circuit is just the reverse of this. It must "de-modulate" or separate the radio-frequency current cycles from the audio or voice frequency variations as shown in Fig. 186. The term "de-modulation" is really more descriptive of the real action of this device than "detector" is. We shall often refer to it as such in our work. It should always be remembered that the detector does much more than merely rectify the a-c signal impulses to d-c plate current. It must also remove the r-f variations in the plate current. In this, it is assisted by the plate circuit capacitance, as we shall see. The vacuum tube can be made to act as a detector or demodulator by connecting it in either of two ways. One is by keeping the grid excessively negative by a grid-bias voltage, so the tube operates at the lower bend of its characteristic curve. This is known by the various names of *C-bias* detection, *grid-bias* detection and *plate-current* rectification. The other is by means of a grid condenser and resistor connected in the grid circuit. This is called *grid leak and condenser* detection, or *grid circuit* rectification. The former method is used most in our present day powerful receivers and will be explained first.

329. Grid bias detector: During our study of the characteristic curves of vacuum tubes, we found that two bends occur in the usual E_g - I_p curve, one at the bottom and one at the top as shown at (D) in Fig. 236. The lower bend E, occurs at some negative grid potential value and the upper bend F, occurs at some positive grid potential value. If the proper value of negative grid bias voltage is applied to the tube by means of a C battery in the case of a battery-operated tube as shown at (A), or by a grid-bias resistor in the case of a separate-heater type a-c tube as shown at (B) for a 3-electrode tube and at (C) for a screen-grid tube, the tube may be made to operate at the bend of the curve. This is the condition under which grid-bias detection can be accomplished. A detailed explanation of the action which takes place follows:

Let us suppose that a negative grid bias potential has been applied to the grid circuit, so that in the absence of a radio signal voltage, the grid assumes a steady voltage which is the same as the potential of the grid-return lead. The *grid-return lead* is the wire which completes the circuit from the lower end of the tuned circuit back to the negative terminal of the C-bias voltage source, see (B). This actual grid voltage is the *operating grid potential,* and gives the point E on the E_g - I_p characteristic of (D) of Fig. 236 at which the detector tube operates. Under this condition a steady plate current I_p flows, whose value is represented by the height of point E above the zero plate current axis.

When a radio-frequency signal voltage such as is developed across the tuning coil and condenser LC at (A) is applied to the detector grid, this voltage is superimposed upon the steady operating grid potential, making the actual grid potential alternately more and less than the operating grid potential. This is illustrated at (D) where the curve representing the signal voltage applied to the grid is drawn vertically below, about the normal operating grid potential as an axis. This voltage curve starting at 1, increases to 2 in the negative direction, then back to zero at 3, then to 4 in the positive direction, and so on for a number of cycles. The "plate current" curve shows the corresponding changes produced in the plate current, decreasing from 1 to 2, increasing from 2 to 4, etc. For any point on the signal voltage curve, there is a corresponding point marked with a similar number in the plate current curve. Take any point on the signal voltage curve, such as point 2. Draw a line up from 2 to the characteristic curve as shown by the dotted line in the figure. From the point of intersection, draw a horizontal dotted line to the right. This determines corresponding point 2 on the plate current curve. By repeating this construction for a number of points, the plate current curve is determined, the horizontal scale of this curve being the same as that for the grid voltage curve.

Let us examine the plate current curve to see what has happened. First, we see that for each cycle of the a-c signal voltage the plate current decreases a small amount, as from 1 to 2 to 3, but also increases a larger amount from 3 to 4 and back. That is, due to the bend in the E_g - I_p curve, the plate current changes produced by equal half cycles of the signal voltage in opposite directions, are not equal. Therefore, the plate current variations are not symmetrical. It is evident that the sharper the bend of the E_g - I_p curve is, and the nearer the operating grid potential is set to the value corresponding to the exact bend, the more perfect will be the cut-off of the plate current changes caused by the negative half cycles of the signal voltage, that is, the more perfect the rectification. It will also be noticed that the plate current variations as represented by the portion of the plate current curve above the dotted line is practically a duplicate as regards wave-form, of the signal voltage variations. Furthermore the changes in grid voltage due to the signal have been *amplified* by the tube. This is one important advantage of the vacuum tube detector over the crystal detector since the former not only performs the process of demodulation, but also amplifies the signal voltage changes, whereas the latter acts merely as a rectifier and produces no

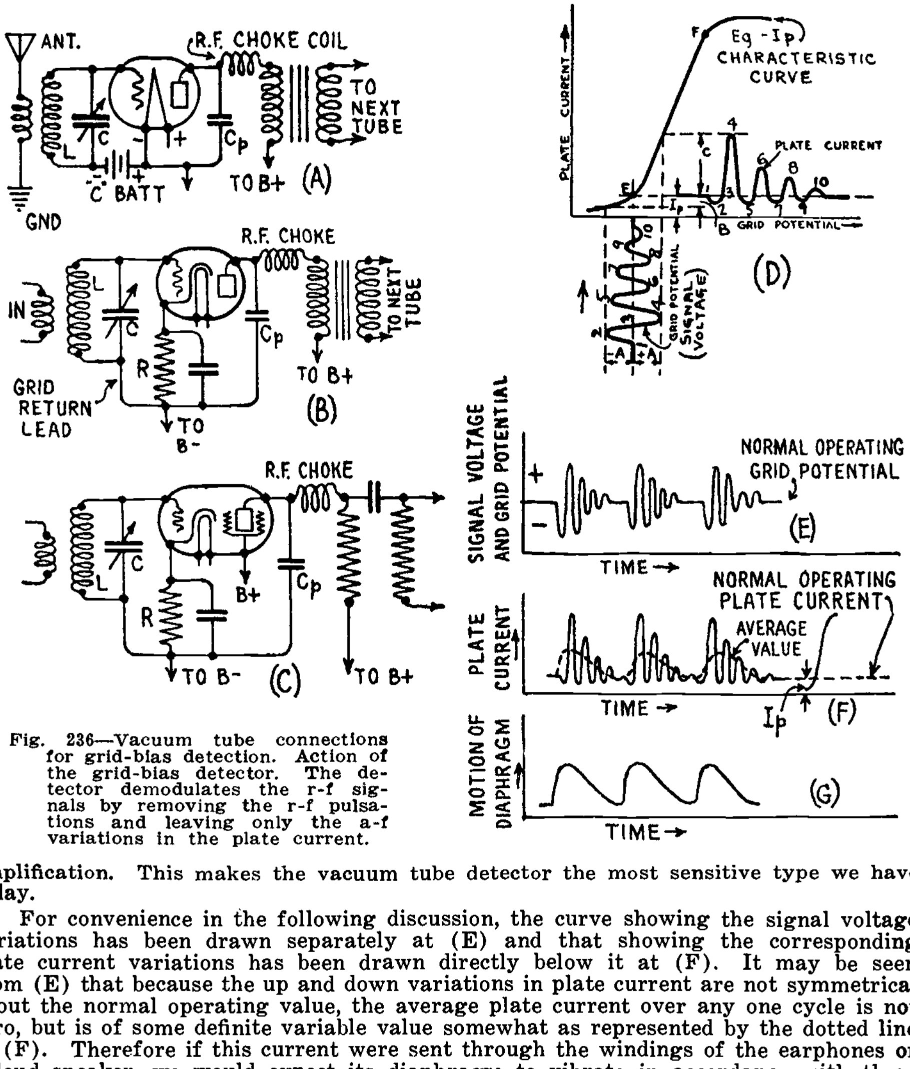


Fig. 236—Vacuum tube connections for grid-bias detection. Action of the grid-bias detector. The detector demodulates the r-f signals by removing the r-f pulsations and leaving only the a-f variations in the plate current.

amplification. This makes the vacuum tube detector the most sensitive type we have today.

For convenience in the following discussion, the curve showing the signal voltage variations has been drawn separately at (E) and that showing the corresponding plate current variations has been drawn directly below it at (F). It may be seen from (E) that because the up and down variations in plate current are not symmetrical about the normal operating value, the average plate current over any one cycle is not zero, but is of some definite variable value somewhat as represented by the dotted line at (F). Therefore if this current were sent through the windings of the earphones or a loud speaker, we would expect its diaphragm to vibrate in accordance with these average values on the dotted line. If, however, the plate circuit is shunted by a condenser C_p of suitable value as shown at (A), (B), and (C), it will act as a filter to smooth out the high-frequency variations in the plate current to a considerable extent, making the mean plate current value much higher and eliminating the radio-frequency variations in the plate current. This is desirable when the detector is followed by an audio-frequency amplifier and especially so, when the audio amplifier is of the "resistance coupled" type as we shall see later.

The action of this plate circuit capacitance is very important in the operation of the detector. It can be seen that each time the grid potential swings still more *negative*, very little plate current flows, but on each *positive* half cycle of the applied signal voltage, a small increase in plate current takes place during the very small fraction of a second that the signal voltage has swung in the positive direction. By storing up current in the plate circuit condenser during these rapid pulses of plate current, and releasing it during the depressions, the variations are smoothed out by its filter action and the current actually flowing through to whatever device is connected in the plate circuit of the detector tube more nearly represents the gradual increase and decrease of the carrier wave which has been caused by the program transmitted. The plate circuit capacitance is really necessary as a high-frequency current storehouse to store electrons during the peaks of the plate current pulses and deliver them to the plate circuit during the depressions.

Care must be taken to see that condenser C_p which acts as a little storage reservoir, is of large enough capacitance to effectively store the tiny currents but not so large that it does not charge and discharge rapidly enough to keep in step with the r-f variations. If the condenser is of too large a capacitance it will charge and discharge too sluggishly and will affect the audio-frequency variations of the plate current and reduce the high audio notes. In order to assist the action of this condenser, a radio-frequency choke coil (of about 85 millihenries when a .0001 mf. condenser is used) is usually connected in the plate circuit as shown at (A), (B), and (C), the inductive action of this choke tending to oppose the high frequency changes in plate current. A choke and condenser used for this purpose are shown at the right of Fig. 124. They really form a low-pass filter as explained there. In most practical detector circuits, enough capacitance exists between the plate and cathode of the tube and between the plate and grid circuit of whatever device is connected in the plate circuit, to enable this action to take place even if no additional r-f choke coil and condenser are connected in the detector plate circuit, but the action is usually improved by the use of these extra parts. In many modern receivers, two condensers are connected across the r-f plate choke to form a more efficient low pass "pi" type filter as shown at (C) of Fig. 123.

It is evident then that the plate current actually flowing through whatever device is connected in the plate circuit of the detector is a pulsating direct current which varies in value in accordance with the *audio frequency* variations of the signal voltage impressed on the grid, as shown at (G). The plate filter blocks out all radio-frequency variations in the plate current. If this current were sent through the winding of a pair of earphones or loud-speaker, the diaphragm would move in accordance with the wave-form of (G) if the signal having the wave-form of (E) were impressed on the tube.

Hence, by operating the tube at the lower bend, the effect of every cycle of the signal voltage is to produce a certain *increase* and a much smaller *decrease* in the plate current, as shown by the plate current curve at (D). It is evident that the operation of the tube about the point F on the upper bend of the curve by putting a positive voltage or bias on the grid, would be similar to that on the lower bend, with the exception that at every cycle the incoming signal would produce a large decrease and small increase of plate current. However, the operation around the lower bend is preferable in practice and is used most, since the steady plate current I_p flowing in the plate circuit at all times is much smaller than in the case of the upper bend, so the current drawn from the "B" batteries (or other "B" power supply unit) is not so great, therefore saturation of the core due to this plate current flowing through the primary winding of the audio transformer which may follow is not so liable to happen. Another reason for not using the upper bend of the curve is that when the grid is made positive, considerable current may flow in the grid circuit. This is objectionable as we shall see in Art. 340. Also, with separate-heater type tubes, it is much easier to obtain a negative grid bias by means of the ordinary grid-bias resistor connection shown.

In the grid bias detection just described, it is evident that if there were no capacitance or inductance, in the plate circuit, the plate current would be a direct current varying in strength at radio frequency, that is, the same frequency as the applied signal voltage. If we consider detection to mean "demodulation" of the signal, tnen is it evident that the tube itself really serves to *amplify* the signal only, the process of *detection* or *demodulation* taking place in the *plate circuit* by the action of the external plate circuit capacitance and inductance as explained. Therefore it is often called "plate rectification". While a detector tube does amplify the r-f signal somewhat, this r-f amplification may be rather small under conditions where the radio-frequency resistance of the plate circuit load is insufficient (see Art. 337).

Since the grid bias detector action depends upon placing the operating point of the tube at the bend of the E_g - I_p characteristic curve, it is necessary to make whatever adjustments are necessary to satisfy this condition. There are three ways in which the operating point may be moved up and down the plate current-grid voltage curve until the most pronounced bend, and most satisfactory detection condition are found. These are; first, by changing the grid bias; second by changing the plate voltage; and third, by changing the filament temperature. Since the latter is usually kept constant during the operation of a tube, the problem resolves itself into employing the proper grid bias voltage for whatever plate voltage is to be employed. Different types of tubes have different requirements in this respect. The exact values of grid bias to employ will be considered later, when discussing power detection.

330. Grid leak and condenser detection: In the grid leak and condenser method of detection, the demodulation of the signal takes place in the grid circuit of the tube. It is therefore called *grid circuit* rectification. The most common form of this circuit uses a *grid leak* consisting of a non-inductive high resistor of several million ohms, and a grid condenser usually of the mica dielectric type, connected in the grid circuit either as at (A) or (B) in Fig. 237. At (C) the equivalent connection for a separate-heater type of tube is shown. This circuit was for many years practically the only one in use—and it is still not altogether out of date. Some broadcast receivers still use it and most short-wave sets use it, but in the broadcast field it is being gradually replaced by the plate circuit detector.

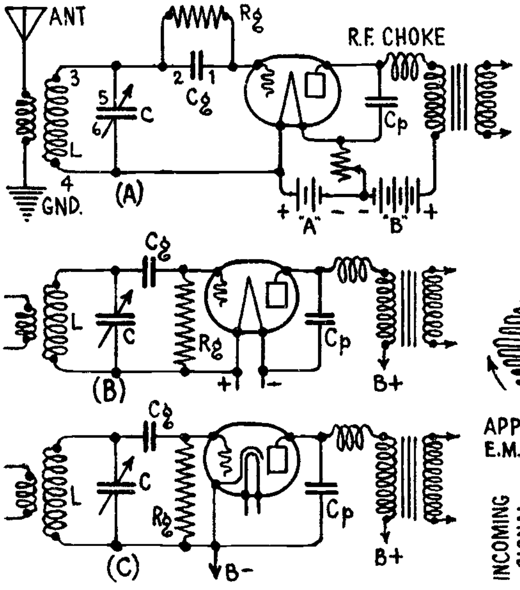
There are several ways of explaining the action of this type of detector, all of them being rather complicated. In one, the action is considered on the basis of the grid current which flows. In the other one, the potentials on the grid are mainly considered. We shall explain it by the latter method. Let us first forget about the grid leak resistor R_g and see what happens in the circuit due to the flow of electrons in the various parts.

With this circuit, when no signal is being received, a steady plate current I_p flows from the plate to the cathode and back through the circuit, depending on the voltage of the plate and the temperature of the filament. If the grid return is to the positive side of the filament, the normal grid potential is at E, (usually slighty positive).

When a signal is received by the antenna, an alternating e.m.f. is set up across the coil and the plates of the tuning condenser C.

Let us refer to (A) of Fig. 237. During one half of each cycle, the signal e.m.f. causes electrons to flow out of plates 5 of the tuning condenser, around to 3 and 4 of the tuning coil and into plates 6 and the filament. Plate 2 of the grid condenser is positive because it has lost some of its electrons since during this half cycle the signal e.m.f. has made terminals 2, 5 and 3 positive. A part of the stream of electrons being emitted from the filament or cathode strike the grid. These electrons immediately rush from the grid to condenser plate 1. The insulation (dielectric) of the grid condenser prevents the electrons that go into plate 1 from crossing over to plate 2.

During the next half cycle, the signal e.m.f. in L is reversed, electrons therefore rush from 6 to 4, to 3, and into 5 and 2, but the electrons that have already collected on the grid, and condenser plate 1 during the first half of the cycle cannot go anywhere, that is, they are trapped on the insulated part of the circuit comprising the grid and the one plate of the grid condenser. The stream of negative electrons coming over from the filament on their way to the plate repels them, since they are also nega-



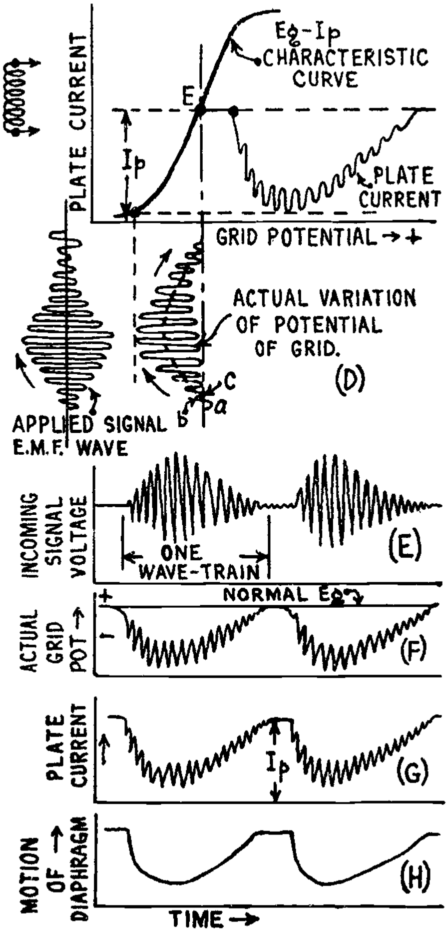


Fig. 237—Various possible circuit connections for a grid-leak type detector. Right: action of the grid leak type detector, showing how the r-f variations are removed and only the a-f variations remain. The grid potential becomes more and more negative for each pulsation in a wave-train of applied signal voltage. This causes a decrease in the plate current as shown at (G).

tive, and pushes them back. There is left then, a slight excess of negative electrons or negative charge on the grid and plate 1 at the end of the first cycle. During the next cycle of the signal voltage the same thing is repeated and there is left a slightly greater excess of electrons on plate 1 and the grid. As the number of electrons accumulating on the grid and plate 1 increases during each cycle, the mean potential of the grid becomes more and more negative, and the plate current is therefore becoming smaller and smaller. This would go on for a number of cycles of the signal voltage until so many electrons have collected on plate 1 that their charge would react on the grid and prevent any more electrons entering the grid from the filament. The tube then becomes blocked and no further action can take place on the grid until some means is provided for the excess of electrons to escape from plate 1 of the grid condenser. We do not want the tube to block in this way, but want the negative charge on the grid to be cumulative only during the number of r-f cycles which constitute a positive (or a negative) half of the *audio cycle*, and then we want the grid to be free to build up a new potential corresponding to the next half of the audio cycle, and so on. Then we will have accumulated grid voltages varying according to the audio-frequency, and the plate current will vary similarly. Moreover, the amplification factor of the tube will be employed and we will obtain both demodulation and amplification.

This is accomplished by connecting a very high resistance (in the neighborhood of a million ohms) either across the grid condenser as at (A), or between the grid terminal of the tube and the filament as at (B), or the cathode as at (C). The action is exactly the same for either of the connections. Since the resistance is high, the electrons flow through it at a rather slow rate because the resistance opposes their motion. This high resistance is called the *grid leak* because it provides a path for the trapped electrons to "leak" through it from the grid to the filament or cathode. The leak should have just enough resistance in combination with the grid condenser capacitance used, to allow the excess of electrons to leak off before the next signal impulse comes in. The entire action just described takes place very rapidly during the time it takes for one *wave train* of the signal to come in. A wave train comprises all the r-f variations in signal voltage taking place during the time one cycle of the audio or voice current modulation takes place. This is illustrated at (E). For instance, for a station broadcasting with a carrier frequency of say, 1,000,000 cycles per second (300 meter wavelength), there would be 1,000,000 divided by 2,000, or 500 r-f cycles for each single cycle (lasting 1/2000 of a second) of an audio note of 2,000 cycles being transmitted. That is, in a single wave train represented in (D) and (E), there would actually be 500 r-f oscillations occurring during the short period of 1/2000 of a second. It is really impossible to picture such rapid action in our minds.

Now let us see what has happened to the plate current during this time. We have seen that for each cycle of the signal e.m.f. coming in, the grid grows more and more negative due to the accumulation of the trapped electrons on it. The more negative the grid becomes, the more it reduces the plate current. Throughout a series of r-f signal voltage cycles then, the average plate current grows less and less as shown by the plate current curve at (D). Also, the grid potential, instead of varying exactly in accordance with the applied signal voltage variations as it does when a grid condenser is not used (see (D) of Fig. 236), now goes up to *a* in the positive direction, then down to *b*, then up to *c*, and so on. During each cycle, the *average* grid potential decreases. The result is that the plate current, instead of varying up and down symmetrically, grow less and less with each cycle of a wave train and follows along a dipping current curve as shown at (D) and (G), having little ripples in it for each r-f cycle of the incoming signal. It is evident that since the plate current has these little r-f ripples or variations in it as shown at (G), the use of the low-pass filter system consisting of the condenser C_p alone, or this condenser with the r-f choke coil in series with the plate as shown at (A), will smooth out these ripples in the same way as described in the discussion of the grid bias detector. The plate current will then vary as shown at (H) for the signal voltage wave shown at (E), the r-f ripples having been removed by the plate circuit condenser C_p. The diaphragm of the earphones or loud speaker through which this current flows will also move back and forth in accordance with this, and the wave form of the sound it produces will be the same.

For the action just described to take place, it is necessary that the grid be positive at least during a part of each cycle as signals come in, in order to attract some of the electrons emitted from the filament. The grid may however be connected to the negative end of the filament (or to the cathode in a separate heater type tube). It will then have the same potential as the filament or cathode, and its voltage will become momentarily positive during part of each wave-train as signals come in.

It is evident that in the grid leak and condenser method of detection, the demodulation process takes place in the grid circuit. Consequently this is usually called *grid circuit rectification*. In this system, the radio-frequency signal voltage applied to the input is really changed to audio-frequency variations in grid potential, and the audio-frequency variations are amplified in the plate circuit. Because of this amplification, this type of detector is more sensitive than the grid bias type. The grid condenser and grid leak resistance must be so proportioned that the electrons causing the grid charge cannot leak off through the leak path to any appreciable extent in the extremely short time between any two cycles of the incoming r-f signal voltage; but so the electrons do leak off during the time over which one *wave train* is being received. A "wave train" may include from several hundred to a thousand or more cycles of the r-f signal voltage. The grid leak connection shown at (B) and (C) is especially advantageous in present-day single control receivers as we shall see later. High-grade grid leaks having permanent and accurate values of resistance should always be used. A grid leak whose resistance varies, will cause crackling and frying noises while receiving a program. The resistance element is usually enclosed in a glass tube with metal end-caps for connection and is designed to snap into metal clips furnished on the grid condensers. A typical grid condenser and grid leak resistor are shown in Fig. 238. The value of grid leak resistor used must have a low enough resistance to allow the accumulated negative charge on the grid to leak off during the interval between the wave trains. Its resistance must be high enough to prevent the charge from leaking

Fig. 238—Grid condenser with clips into which the grid leak resistor at the right may be snapped.

off the grid too rapidly, in which case there would be only a small change of plate current produced and the signal strength as heard in the phones would be reduced. For weak signals, such as are received during long-distance reception, a tube is much more sensitive if higher resistance grid leaks are used. In either case, if a grid leak having too high a resistance is used it will result in excessive accumulation of negative charge on the grid, blocking the action of the tube, or making the signals sound mushy. This is usually accompanied by a characteristic "cluck-cluck-cluck" sound in the phones or loud-speakers as the charge leaks off at intervals through the insulation between the tube elements, tube prongs, etc. The values of grid leaks and condensers to use will be discussed in Article 333.

331. Square law and linear detectors: Due to the fact that the amount of amplification which could be applied to the incoming r-f signal voltages by the r-f amplifiers in use several years ago was very small, the typical radio set of that time employed a grid leak-grid condenser type of detector that was intended to operate with a radio-frequency input voltage of 0.1 volt or less. These detectors operated with low plate voltages of from 45 to 90 volts. Operation was entirely along the *curved* portion of the plate current-grid voltage characteristic. Such detectors give non-uniform response since in most cases the voltage appearing across the plate circuit load is proportional to the *square* of the input signal voltage. Therefore, doubling the signal voltage input produces 2 x 2 or 4 times the output, etc. Such detectors are called *square law* detectors because their output follows the "square" law. This would seem to be a big advantage, and from the standpoint of sensitivity in loud signals it is, but from the angle of tone quality it is a disadvantage.

When a detector follows a square law, it produces some second harmonic distortion which is proportional to M/4, where M is the percentage modulation of the r-f signal. The distortion consists of production of the second harmonics (double frequencies) of the notes actually being transmitted, and also all the possible sum and difference frequencies. Thus if the transmitting station is simultaneously transmitting notes of 2,000 and 2,500 cycles, the output of the square law detector in addition to containing these desired frequencies, will also contain the double frequency components of 4000 and 5000 cycles, and the sum and difference components of 4,500 and 500 cycles. When the signal is modulated 100 per cent, this distortion reaches a maximum of 25 per cent. Under this extreme condition these distortion components would be 25 per-cent as large as the desired components, so that weak-signal detection of signals that have a high degree of modulation will not give satisfactory results from this point of view. The present tendency in broadcasting is to increase the modulation to 100 per cent, at least on the loud *fortissimo* passages of music being broadcast, so as to utilize as completely as possible, the output of the transmitter. Most of the larger stations are now using 100 per cent modulation. Grid leak detectors operating at low plate voltages, being square law detectors, will produce too much distortion of the 100 per cent modulated signals received from these stations.

This is one of the reasons why linear detection is being used more and more. A detector is *linear* when the audio frequency output voltage appearing across its plate circuit load is directly proportional to the r-f signal voltage input. Thus a signal input three times as great produces an output voltage three times as large etc. Such detectors are absolutely essential for distortionless detection. The ordinary power detector of either the grid leak or grid bias type has approximately such a characteristic and so gives substantially undistorted rectification.

332. Power detection: A *power detector* is one that will not overload when very large r-f input signal voltages are applied to its grid circuit, and which will handle considerable electrical *power* in its output. Power detectors are usually operated with rather high voltages. Either a grid bias type or a grid leak and condenser type of detector may fulfill the conditions of power detection if they are operated properly.

Receivers built during the early days of radio employed two or three stages of tuned radio-frequency amplification using the three electrode tubes of the 201-A, 226, or 227 type which were the only ones available at that time. It was impossible to secure much amplification per stage with these tubes, because of the difficulty of preventing oscillation due to feedback in the tubes themselves, and other forms of feedback coupling. Therefore, the signal was not very strong when it reached the detector, and it was necessary to use at least 2 stages of audio-frequency amplification after the detector in order to make the signal strong enough to operate a loud speaker satisfactorily. Now that it is possible to build high-gain r-f amplifiers without oscillation troubles, thanks to the screen-grid tube, in modern receivers the signal voltage is first amplified greatly before it reaches the detector. It is not uncommon to use 5 and 6 high-gain amplifier stages before the detector, both to obtain high gain and the necessary number of tuned circuits for satisfactory selectivity. Therefore the detector must handle quite large signal voltages without distortion, and in most cases feeds directly into a single power output audio stage and then to the loud speaker. It is in receivers of this kind that *power detectors* must be used, for the signal voltages are entirely too large to be handled by the old forms of detectors. In some cases, the loud speaker may even be operated directly from the output of the detector without employing any audio amplification. Linear and power detectors are very closely related in practice, since they usually go together, although no detector has a perfectly straight-line characteristic. In the usual meaning of the term, "power detector" is used in connection with detection when the r-f signal voltage applied to the detector input is at least 1 volt or more.

333. Grid leak and condenser power detection: According to the information obtained by Mr. F. E. Terman from several thousand tests on power detectors (the results of which were published in the Dec. 1930, I. R. E. Proceedings), power detectors of the grid leak and condenser type can be made to produce satisfactory detection under all conditions, provided the proper values of plate voltage, and grid leak and condenser are employed. The proper values for suitable weak signal detection are different from those for strong signal detection. Some of this data is reviewed here.

"When a radio-frequency signal of at least several volts amplitude is applied to a suitably adjusted grid-leak detector, the action taking place in the grid circuit is different from the action for voltages less than 1 volt. The rectified grid current charges the grid condenser negatively and causes the average grid potential to have a negative value. This average value is always such that the positive crests of the signal make the grid go positive a small amount. Each time the grid goes positive, grid current flows, and makes up for the current that leaks off through the grid leak during each cycle.

At times when the signal amplitude is decreasing in size, it is necessary that the grid leak allow the grid condenser charge to leak off at a rate that will cause the average grid potential to reduce at least as fast as the signal amplitude is changing. This requirement calls for values of grid condenser capacity and leak resistance smaller than usually used.

If high-quality output is to be obtained from the grid-leak power detector, it is necessary to have the proper grid leak and condenser combination. Suitable values for any tube are, a grid leak of about ¼ megohm and a 0.0001-mfd. grid condenser. With these proportions the average grid potential will be able to change as fast as the signal amplitude, up to modulation frequencies of 5000 cycles.

The overloading point of the grid-leak power detector is reached when plate rectification causes increase of plate current, while grid rectification causes decrease of plate current. Plate rectification thus neutralizes the grid action and causes distortion.

As the maximum amplitude of a fully modulated wave is twice the carrier amplitude, a particular tube will handle half as big a carrier wave acting as a power detector as it can amplify, using the same plate voltage in both cases. Thus, a 201A-type tube with 90 volts on the plate usually uses a 4½-volt C bias. The peak amplitude of carrier wave that can be handled at a plate voltage is one-half of this, or about 2¼ peak volts.

The maximum audio-frequency power output obtainable from the grid-leak power detector is slightly over one-fourth of the undistorted power the tube can give as an amplifier at the same plate voltage and a suitable grid bias. Thus, the 210-type tube at 247½ plate volts will put out 340 undistorted milliwatts as an amplifier, and will put out about 100 undistorted audio milliwatts as a power detector.

The approximate audio-frequency output of a grid-leak power detector can be obtained by a simple computation. It is apparent that the average grid voltage of the power detector follows the modulation of the signal. This variation in average grid potential applies an audio-frequency voltage to the grid of the detector tube, and it is this audio-frequency grid voltage when amplified by the tube acting as an amplifier that constitutes the audio-frequency output of the detector.

In the ideal detector, the audio-frequency voltage applied to the grid would be equal to the modulation voltage in the signal. If the degree of modulation is m, and the carrier amplitude is E_s, the ideal amount of modulation voltage is mE_s. The actual power detector is only about 75 to 85 per cent perfect, and will apply to the grid an audio-frequency voltage about 75 to 85 per cent of mE_s. The percentage tends to rise slightly as the signal amplitude becomes large, but under ordinary conditions it is surprisingly nearly constant at this approximate range for all tubes.

In order to deliver power, the detector tube must operate with a high plate voltage. At the same time, the bias of the grid leak power detector is approximately zero except when the signal is coming in, and so the allowable plate current sets a limit to the plate potential. Tubes such as the 201A, 112A, and 227 can operate as power detectors with 90 to 135 volts on the plate, and under such conditions will handle an r-f voltage of at least 2 volts on the detector grid without distortion. When a 227 or 224

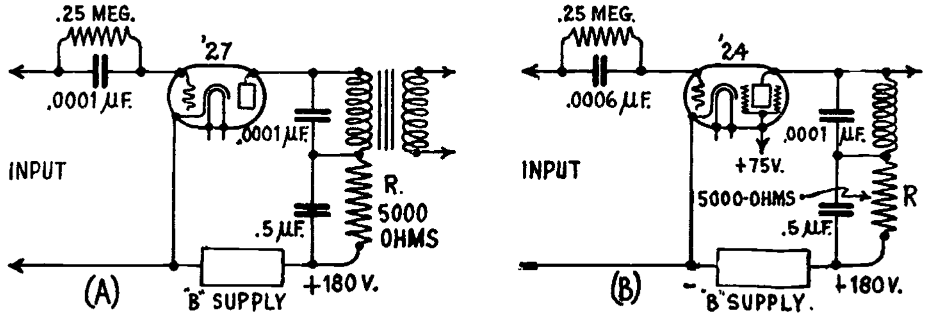


Fig. 239—Connections for '27 and '24 type tubes as grid leak-condenser type power detectors.

type grid-leak condenser detector is to operate with small signal voltages (under 1 volt) applied to the grid, the grid condenser should be of .00025 mf. capacitance and the grid leak should be of 1 megohm, with a plate voltage of 180 volts in each case, with the grid return to cathode. This is for broadcast band reception. When used in this manner with small input voltages, it will be necessary to have one stage of audio-frequency amplification between the detector and the input to the power tube. This is because the detector output with weak signals is not sufficient to properly load up the power tube. By changing the proportion of the grid-leak and grid-condenser size it is possible to operate the power tube directly from the output of a suitable detector tube for strong signal voltages. Values of .0001 mfd. for the grid condenser and 250,000 ohms for the grid leak resistor with the grid return leak returned to a negative grid bias of about 1 volt should be used with these tubes. It will be noted that these proportions are different than those for weak signals.

A means of avoiding the effect of high plate current when high plate voltages are employed in this method, is shown in Fig. 239 for both '27 and '24 type tubes. With no signal, since the grid has no bias voltage, the plate current would be rather high. Therefore, the plate voltage is dropped through the resistor R so that the plate current is at a safe value. The incoming signal provides a negative bias, lowering the plate current. This cuts down the drop through R, and allows the full plate voltage to be effective. The '27 and '24 type tubes should be operated with the values shown, with the grid return directly to the grounded cathode. The efficiency of rectification in either case is about 85%. The grid circuit puts a load resistance of about 150,000 ohms (with a 0.25 meg. leak) on the tuned circuit ahead of it. This is higher than with the old types of weak-signal grid leak detector.

334. Grid bias power detection: In the grid bias type of power detectors commonly used, rather high plate voltages and negative grid bias voltages are employed. The amount of grid-bias voltage usually applied in power detectors of this type is roughly about 10% of the plate voltage value.

The '24 type screen-grid tube may be used as a power detector in this way by applying a plate voltage of 180 volts or more. If the load resistance is half megohm or more, it is safe to apply as much as 250 volts from the B power supply device. As the plate impedance of the tube operated this way is high, the only way to place a sufficiently high load impedance in its circuit is to use a resistance of half megohm or greater, as shown at (A) of Fig. 240.

When the load resistance and the plate voltage have been fixed, it is only a question of fixing the grid bias and the screen voltage. Both depend on the applied plate voltage and on the resistance in the plate circuit as well as on each other. If a potentiometer of fairly high resistance, say 30,000 ohms, is connected from the screen-return to the "grounded" grid-return, and the cathode is connected to the slider, it is always

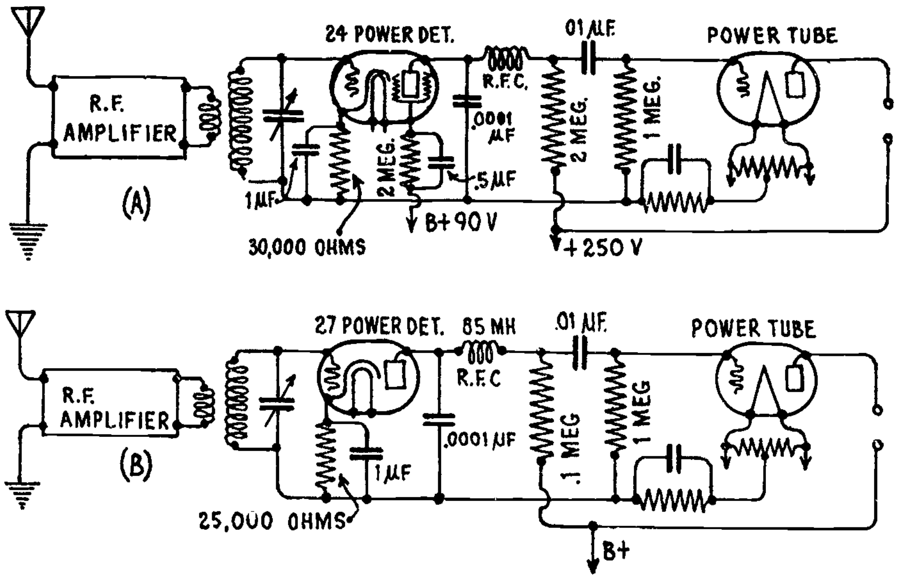


Fig 240: (A) Grid bias power detector with '24 type a-c screen-grid tube.
(B) Grid bias power detector with '27 type a-c 3-electrode tube.

possible to find the best combination for either best detection or best amplification. If this method is adopted, the combined potentiometer and screen terminal should be connected to B + 75 volts. If the potentiometer method is not used, it is best to give the screen a voltage of about 45 volts and then adjust the grid bias until the detecting efficiency is the best.

As far as detecting efficiency is concerned, the same may be obtained with a large number of combinations, even when the voltages are very low, say 45 volts on the plate with correspondingly lower voltages on the other elements. But for power detection, it is necessary to make them high as suggested above. A by-pass condenser of about 2 microfarads should be connected across that portion of the potentiometer which is in the grid circuit and one of about 1 mfd. across the other portion. If a by-pass condenser is connected across the load resistance, it should be very small because a small condenser is very effective across a resistance of half megohm.

If a fixed grid bias resistor and fixed screen voltage are employed as shown at (A) a grid bias resistor of 20,000 to 30,000 ohms may be employed. The screen-grid voltage may be obtained as shown, being actually about 45 volts positive. The '27 tube may be used as a power detector with quite satisfactory results if a special transformer is used to couple this tube to the power tube. The a-c plate resistance is rather high, so it is necessary to use a special coupling unit.

If desired, the '27 type power detector may be resistance coupled to the power tube as shown at (B) with less gain. The usual grid bias resistor for a '27 tube operated this way is 20,000 or 30,000 ohms at a plate voltage of 180 volts. Some set manufacturers use as low as 12,000 ohms. The resistor should be by-passed with a condenser having a capacitance of at least 1 mf. as shown.

The '27 type tube may be operated as a very sensitive and efficient grid bias type power detector by connecting it as shown at (A) of Fig. 241. With this arrangement, the '27 type tube is almost as efficient as the '24 type screen-grid detector and is able to handle quite a large signal-voltage input to its grid circuit without overloading. For instance, at an input signal voltage of 9 volts R.M.S., the output signal voltage across the 80 henry choke L is 40 volts R.M.S. at the values of plate voltage and grid bias shown, for a 30% modulated signal. The value of grid bias resistor shown, places the normal grid voltage at 10.9 volts negative. If a plate circuit "resistance load" is to be employed instead of the inductance L, the values should be as follows; plate voltage applied by B power supply=250 volts; grid bias resistor 20,000 ohms; plate circuit resistor 200,000 ohms.

335. Multiplex linear power detector: A form of linear power detector in which a two element or "diode" connection of a '27 type tube is employed is shown at (B) of Fig. 241.

The "diode" detector consists of a 227 tube with its grid and plate connected together to form in effect a single plate. As its function is merely that of a linear detector and it does not amplify since there is no grid, it is supplemented by the '27 type tube marked "det-amp.". In the "diode" rectifier, the marked curvature, at low values of applied signal voltage, causes distortion unless the input level is maintained high enough to avoid excursions into the curved range. In other words, we must maintain operation on the straight-line portion of the characteristic.

The peculiar input circuit, common to all diode detectors and shown in this circuit, is made necessary by the high damping (or low input resistance) of the tube when operated in this fashion. The high damping factor, limiting the gain in the previous r-f stage, the low output efficiency (not to be confused with rectifying efficiency) and other factors all contribute to the need for a high-gain a-f amplifier, as evidenced by the fact that three audio stages usually follow the "diode" detector.

Diodes have the advantage of a long-range of distortionless straight-line operation, as compared with a comparatively small curved portion of the characteristic. This advantage has led to their use in several commercial receivers.

335A. Comparisons of detector arrangements: A comparison of "power" and "weak-signal" detection shows that the former is superior in that it introduces less distortion, is a more efficient rectifier, gives less disturbance with strong static impulses, and results in an increase in the

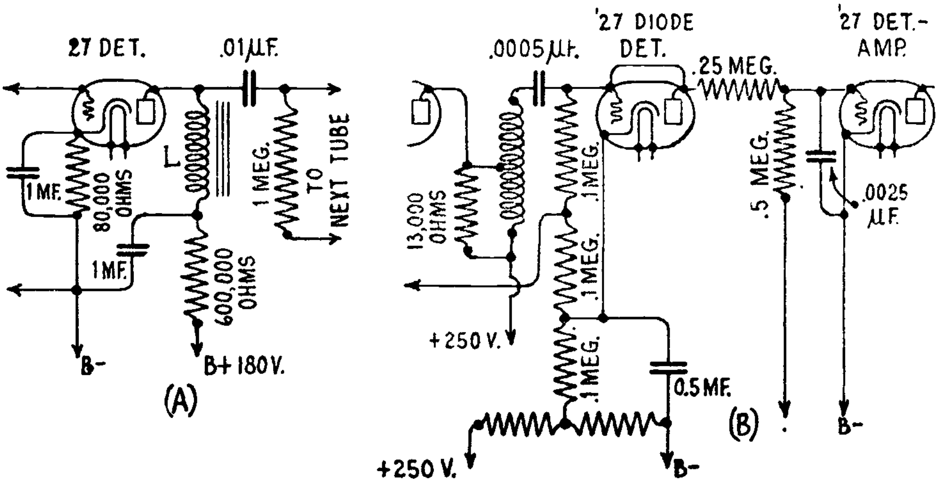
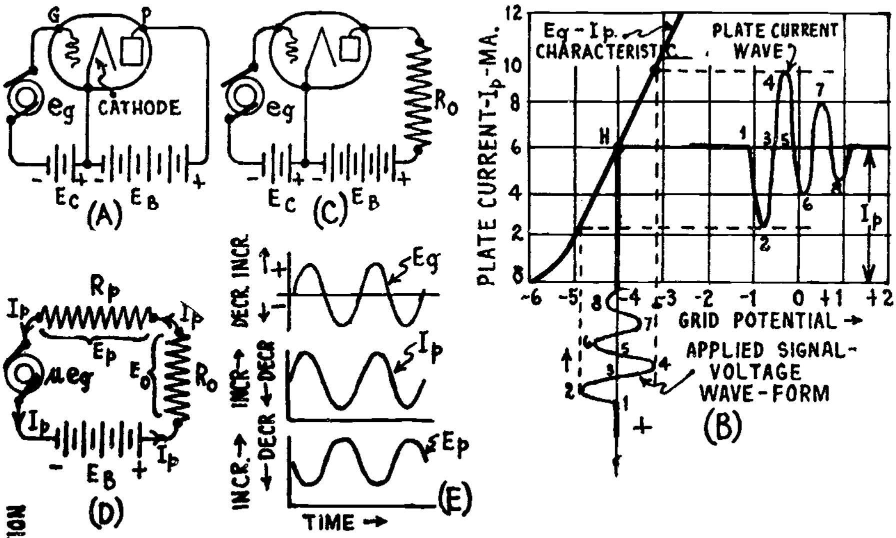


Fig. 241—(A) Connections for '27 type tube as a sensitive linear detector capable of handling large signal voltages.
(B) Connections of "Multiplex" diode linear power detector.

effective selectivity. The linear power detector is obviously here to stay, and the future will see it used more and more. It has even been suggested that some day the input to the loud speaker will be obtained by rectifying a very large radio-frequency signal of perhaps 100 volts, using a vacuum tube, or perhaps a copper-oxide element, without the use of any audio-frequency amplification at all.

Power detection requires more radio-frequency amplification than does the weak-signal detector, and not many years ago this was a real disadvantage. The screen-grid tube has altered the situation however, by making it comparatively simple to obtain high radio-frequency amplification per stage without trouble from regeneration. Inasmuch as it is still necessary to use the same number of tuned circuits in screen-grid sets as before, in order to obtain the necessary selectivity, the additional radio-frequency amplification is so easy to obtain that it is a great advantage.

336. Vacuum tube amplifier action: Vacuum tubes used in modern radio receivers serve three purposes, they amplify, they detect or demodulate and they rectify. We have studied detector action, and will now consider the action of the tube as an amplifier. As explained in Articles 283 and 284, a vacuum tube having a grid may be used as an amplifier when connected in suitably arranged circuits, because any voltage variations impressed in the grid or input circuit are reproduced on a much larger or amplified scale across any impedance connected in the plate



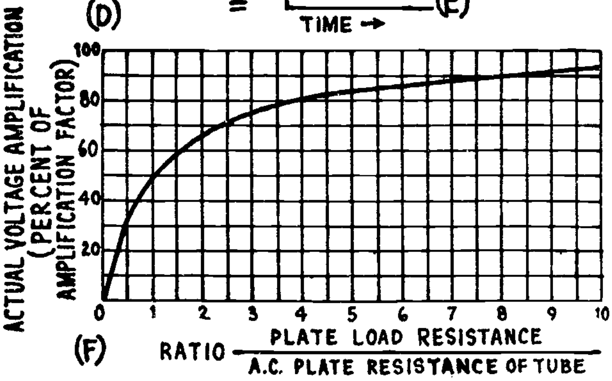


Fig. 242—Study of the vacuum tube as an amplifier. Varying signal voltages applied to the grid circuit cause corresponding variations in the plate current, which cause larger or "amplified" voltages to appear across the plate load impedance Ro. The actual voltage amplification, expressed as a per cent of the mu of the tube, which can be obtained with various values of load impedance may be found from (F).

circuit. The fundamental action of the tube as an amplifier was discussed in the previous articles referred to, but it will be studied more in detail now. We will now see just how a tube amplifies voltage variations applied to its grid circuit,—and how much.

In order to understand the action of the tube as an amplifier, let us refer to (A) of Fig. 242. Here a vacuum tube is connected with its proper plate and grid potentials as shown. The filament voltage may be neglected since it serves no purpose other than to supply heating current to the filament. In our discussions of vacuum tubes as amplifiers, we will show ordinary three-electrode tubes for simplicity in the diagrams, but it should always be kept in mind that the same actions take place in 4-electrode screen-grid tubes and 5-electrode pentode tubes unless otherwise specified. Let e_g be the alternating signal voltage applied to the grid circuit, represented here simply by an a-c generator. It is evident from our previous discussions of vacuum tube action, that the application of this signal voltage to the grid will cause the grid potential to vary about the mean grid potential which is due to the steady grid bias voltage applied to the tube, and this in turn will cause variations in the plate current.

To understand just what takes place let us refer to (B) which represents the E_g - I_p characteristic curve of the tube for some particular fixed value of plate voltage. It shows the plate current in milliamperes for any value of grid potential. Let us assume that the steady grid bias voltage supplied by the grid bias source E_c is 4 volts negative. This sets the operating point of the tube at H on the characteristic curve, and a steady plate current of 6 milliamperes flows. Now let us suppose that an a-c signal voltage as represented by the signal wave-form shown at the lower part of (B) is applied to the tube. The effect of the individual cycles of this signal voltage will be to add and subtract from the steady grid bias voltage, and so vary the potential of the grid. For instance, when the signal voltage varies negatively from point 1 to 2, it causes the grid potential to change from -4 to almost -5 volts. This causes the plate current to decrease from point 1 to point 2 on the plate current curve. When the signal voltage increases positively from points 2 to 3 to 4, the plate current increases from corresponding points 2 to 3 to 4 as shown. It is evident that the result of the application of the a-c signal voltage is to cause the plate current to rise and fall above and below its steady normal no-signal value of I_p. When the grid potential decreases (is made more negative) the plate current decreases; when it increases (is made less negative) the plate current increases. Therefore the plate current variations are in phase with the grid potential variations. If a load resistance is connected in the plate circuit as shown at (C), when the plate current increases due to an increased grid potential, the voltage drop $I_p R_o$ across the resistor R_o increases, and for this reason the voltage E_p actually applied to the plate decreases. That is, the true plate voltage *decreases* when the grid potential *increases*, and it *increases* when the grid potential *decreases*. Hence, the plate voltage and grid potential variations are 180°. out of phase. The phase relations of these three factors are shown at (E) of Fig. 242. They should be remembered as they are very important in some considerations of amplifiers. It will be noticed that the plate current changes produced by this signal voltage are quite large. Since the applied plate voltage is steady in value, it is evident that the effect of variations of the grid potential is really to vary the internal resistance of the plate-cathode path in the tube. This variation of the internal plate resistance causes the plate current to vary. All the applied plate circuit voltage appears as a voltage drop between the plate and cathode.

In order to make these large plate current variations useful, it is necessary to connect some form of resistance or impedance, called the *plate circuit load*, in series with the plate current, so that the varying plate current flowing through this impedance will produce varying falls of potential through it, the varying falls of potential being communicated to another circuit in either of several ways (by transformer coupling, resistance coupling, or impedance coupling as we shall see later). At (C) an impedance R_o of some sort, (shown here simply by a resistance symbol and considered as a resistance for simplicity in the following discussion), has been connected in the plate circuit. The changing plate current must flow through this plate load impedance as well as through the internal plate impedance R_p of the tube. This changing current flowing through these impedances causes a voltage drop to appear across each; E_p appears across the plate-cathode and a voltage drop E_o appears across the load R_o. The voltage drop across each part is of course proportional to the impedance of that part. In order to simplify the visualization of the action, engineers prefer to consider the tube circuit drawn in simple form as at (D) of Fig. 203. Here the grid circuit with its applied signal voltage, is replaced by a small a-c generator put right in the plate circuit. The voltage of this schematic generator is equal to the voltages of the applied a-c signal multiplied by the amplification factor (mu) of the tube, i.e., μe_g. This is so, because any change in voltage of the grid has the same effect on the plate current as a voltage "mu" times as large acting directly in the plate circuit (see Articles 283 and 284). The internal impedance of this generator is equal to the internal plate impedance of the tube. This equivalent tube circuit is shown in simplified form at (D) of Fig. 242.

We have already considered the effect on the tube action of the varying voltage drop through the plate circuit load. We found in Article 292 that it was the cause of the "dynamic" characteristic of the tube being different than the static characteristic. We are now interested in finding the conditions for maximum *voltage amplification.*

337. Maximum voltage amplification: In a vacuum tube amplifier it is of course desirable to obtain as much amplification as possible. Therefore, it is important to know just what circuit conditions are necessary in order to obtain maximum amplification, and just how much this amplification will be.

Referring to (D) of Fig. 242, let I_p be the plate current flowing at some particular instant and R_p and R_o be the plate and load resistance respectively. Let e_g be the grid potential at the instant considered. The e. m. f. of the plate battery E_b is then all used up in sending the plate current through these two resistances and is equal to the potential drop $I_p R_o$ through the load resistance, plus the potential drop $I_p R_p$ between the plate and cathode of the tube. This latter drop is E_p. Thus:

$$E_b = E_p + I_p R_o$$

from which

$$E_p = E_b - I_p R_o$$

which expresses the difference of potential between the plate and cathode of the tube. (Whether these two voltage drops can be added together by simple arithmetic or not depends on the nature of the load. In fact the very properties of the combined circuit depend on the kind of impedance for which R_o stands. For instance, it may stand merely for a simple non-inductive resistance, or for a more or less complicated tuned circuit, etc. We are considering merely the simple case with resistance load.)

Suppose now, that the grid potential e_g is varied so as to increase the current I_p in the plate circuit; then the resistance drop $I_p R_o$ in the plate load will increase correspondingly. It then follows from the above equation, and from a consideration of the simple series circuit, that with the battery voltage E_b remaining constant, the *actual effective plate potential* E_p will *decrease.* Conversely, when I_p is *decreased* by decreasing the grid potential, the effective plate potential E_p will *increase.* The greater the load resistance, (or more generally the greater the load impedance Z), the greater the variation of effective plate potential E_p resulting from a given change of plate current I_p, brought about by a given variation of grid potential e_g. This is plainly shown in the "dynamic characteristic" curves at (A) of Fig. 210 where it may be seen that the slope or slant of the dynamic characteristic curve *decreases* as the resistance (or impedance) of the external plate load is *increased.* As an extreme case, for infinite load impedance, the curve would be parallel to the grid voltage axis, showing that the variations of grid potential would produce no variation of the plate current, but would produce *maximum* variations of plate potential. Since the voltage across the plate load at each instant is equal to the fixed B battery voltage minus the plate potential existing at that instant, it is evident that the voltage variations across the plate load are *amplified variations* of the grid or (input) *potential variations.*

If the load is a non-inductive resistance R_o, the total plate circuit resistance is R_o+R_p. Therefore, the *change* in plate current (amps.) produced by the signal voltage μe_g (referred to the plate circuit) is determined by

$$I_p \text{ (change)} = \frac{\mu e_g}{R_o+R_p}$$

This varying current flowing through the load resistance R_o produces a change of voltage across it of

$$\text{(Load voltage change)} \quad e_o = I_p R_o = \frac{\mu e_g R_o}{R_o + R_p}$$

but the ratio of this output voltage appearing across the load, divided by the input signal voltage e_g, is the voltage amplification G, produced by the tube. Hence:

$$G = \frac{e_o}{e_g} = \mu \frac{R_o}{R_o + R_p}$$

If the second part of this equation is very large (i.e., approaches unity) the value of G will be very nearly equal to the amplification constant of the tube. When R_o is infinitely great, the voltage amplification becomes actually equal to the amplification factor of the tube. This is the *maximum* amplification that can be obtained from the tube. But this is only theoretical, since an infinitely great resistance constitutes an open circuit, and under such conditions there would be no voltage applied to the plate and the tube would not function. To be strictly correct then, we should state that the voltage amplification approaches more closely to the theoretical maximum value, namely, the value of the amplification factor, as the value of the load resistance is raised, until such a point is reached that the mean plate potential becomes too low to allow the tube to function properly. It is of course impossible to build primary windings of coupling transformers, or coupling impedances to have infinite impedance in practice, so the full "mu" of the tube is never realized. Practically, however, it is possible to obtain quite a large fraction of the "mu" of the tube. For instance, if the resistance of the load is made three times the plate resistance of the tube, then since the load resistance is ¾ of the total resistance and the plate resistance of the tube is ¼ of the total resistance, the voltage amplification will be ¾, or 75% of the "mu" of the tube. In this case, if the plate resistance is 15,000 ohms, the voltage appearing across a coupling resistance of 45,000 ohms will be equal to the signal voltage times 75 per cent of the "mu" of the tube. If the load resistance equals the a-c plate resistance of the tube, half the amplification factor of the tube is obtained. The larger the plate circuit load is made, the greater is its ratio to the total resistance, and therefore the greater will be the voltage amplification. At (F) of Fig. 242, the actual voltage amplification as a percentage of the amplification factor, is plotted on the vertical scale; and the scale on the horizontal axis is plotted with the ratio of the plate load resistance to the a-c plate resistance of the tube. This curve is applicable to any tube. From it, the voltage amplification as a percentage of the mu of the tube may be found if the ratio of the load resistance and the a-c plate resistance of the tube are known. This is reproduced here by courtesy of "Wireless World Magazine."

When considering a tube which has a very high plate resistance, it is evident that any ordinary amount of resistance put in series in its plate circuit makes little difference to the *variations* in the plate current. For example, a '27 type tube with a plate resistance of 9,000 ohms would have about the same variations in plate current if a load of 1,000 ohms were added to the plate circuit. But if another 9,000 ohms, or even more were added, the variations in the plate current would decrease. In other words, the mutual conductance of the circuit, i.e., the relation between the variations in the plate current and the variations in the input signal voltage, decreases.

The plate resistance of a '35 type screen-grid tube, for instance, is about 350,000 ohms. Its mutual conductance is about 1100 micromhos. Now if a load resistance of 50,000 ohms is connected in series with the plate circuit of the tube, the plate current variations will only decrease by about ten per cent, and the mutual conductance will decrease the same amount.

We can say, then, that with a high-resistance tube, the mutual conductance of the circuit is about the same as for the tube with no-load resistance, that the variations in the plate current in the entire circuit is equal to the alternating grid voltage multiplied by the mutual conductance, and that the voltage amplification from such a tube is equal to the product of the mutual conductance and the load resistance. Thus: variations in current (with or without load) $= E_g \times G_m = \frac{\mu e_g}{R_o + R_p}$.

Voltage amplification $= G_m \times R_o$.

It is interesting to note that the maximum amplification that can be secured from a three-element tube working into a resistance is the mu of the tube, but that the maximum amplification obtainable from a screen-grid tube depends not so much upon its amplification factor but upon the mutual conductance. This is because the load resistance that can be built up for the tube to work into is limited—we cannot get resistances beyond perhaps 200,000 ohms in an r-f circuit at broadcast radio-frequencies, or much less than this figure at higher frequencies.

Example: (a) A 227 type tube ($R_p = 9{,}000$ ohms, and "mu" $= 9$) is being worked into a plate load of 27,000 ohms. What is the actual voltage amplification; (b) If a 10 volt signal were applied to the grid, how much would the plate current vary? (c) What would be the variation in voltage drop across the load resistor?

Solution: (a) actual voltage amplification, $G = \mu \frac{R_o}{R_o + R_p} = 9 \times \frac{27{,}000}{27{,}000 + 9{,}000} = 6.7$

(b) plate current variations $= \frac{\mu e_g}{R_p + R_o} = \frac{9 \times 10}{27{,}000 + 9{,}000} = .0025$ amps, or 2.5 ma.

(c) load voltage variations $= .0025 \times 27{,}000 = 67.5$ volts. Ans.

It is evident from the foregoing, that in order to obtain a large percentage of the voltage amplification possible from an amplifier tube, the impedance of the plate load into which it works, must be as large as possible. This should be remembered. If instead of a resistance R_o, an inductive load is connected in the plate circuit of the tube, the varying output voltage across it will depend not only on the magnitude of the signal voltage variations applied to the grid, but also on their frequency, because the impedance of an inductance increases as the frequency increases, since $X_L = 2\pi fL$. If the resistance of the load is high compared with its reactance, the discrimination toward certain frequencies is lessened, and the amplification approaches that obtained with a resistance load.

338. Conditions for undistorted amplification: In our consideration of the action of the vacuum tube as an amplifier at (B) of Fig. 242, no mention was made of distortion which may be produced in the wave-form of the plate current due to various factors which may affect the operation of the tube. In the case shown, the form of the plate current variations is an exact enlarged duplicate of the signal voltage variations applied to the grid i.e., this is no *distortion.* This is so, because the proper grid bias voltage (for the particular plate voltage employed) was purposely selected so that the normal operating point H of the tube would fall at the middle of the comparatively straight part of the E_g - I_p characteristic. An amplifier tube should always be operated this way. The negative grid bias voltages specified for the various tubes at the various plate voltages given, in Fig. 214, are those which place the operating point at this middle point on the curve, and should always be employed when using tubes as amplifiers.

Thus if we desire to operate say a '24 type tube as an amplifier using a plate voltage of 180 volts, referring to Fig. 214, we find that a grid bias voltage of 1.5 volts (negative) must be applied to the grid. This makes the tube operate at approximately the center of the straight part of its characteristic curve when no signal is applied to the grid.

The conditions for undistorted amplification are (a) the grid bias and magnitude of the a-c input signal voltage must be such that the tube operates only over the straight part of its E_g - I_p characteristic; (b) the load resistance must be large with respect to the internal plate resistance of the tube R_p. We shall now see what happens if these operating conditions are not observed.

339. Distortion due to incorrect grid bias: In the case shown at (B) of Fig. 242, the grid bias voltage was correct, so the tube operated over the straight portion of the characteristic curve and distortionless amplification was produced.

Suppose the negative grid bias voltage applied to the tube is too great, as in (A) of Fig. 243, so that when a signal voltage is applied to the grid as shown, the negative half cycles of the signal voltage cause the grid potential to swing so far negative that the tube is operated on the lower curved part of its characteristic where the plate current changes are *not* proportional to the grid potential changes. As can be seen from the diagram, the curve showing the resulting plate current variations, is no longer similar in shape to that of the grid (signal) voltage, and its average value is no longer equal to the plate current I_p flowing during the zero signal condition, as is true when the bias is such that the input signal voltage carries the grid operating point only over the straight part of the curve. The parts of these curves representing the decreases in plate current, are partly shut off; and distortion results because the plate current changes caused by the equal positive and negative halves of the signal voltage cycles are not equal (or are not amplified alike). The average plate current is now greater than that during the no signal condition, as shown.

If a milliammeter were connected in the plate circuit of a tube operating this way, as shown at (B), it would show an *increase* in the plate current when signals were applied to the grid, or when a particularly loud signal came through; an indication of distortion due to too much grid bias voltage. This method of indicating distortion is a very simple and effective one and is used especially for detecting distortion in the tubes in audio amplifiers. This will be considered in Article 344.

If the negative grid bias applied to the tube is great enough, and the input signals are strong enough, the grid may be forced so far negative on strong signals that the plate current may be reduced to zero altogether on the negative half cycles. This will produce even worse distortion since the tube would now be operating under the conditions shown at (D) of Fig. 236, i.e., the tube is operating as a grid bias detector instead of as a distortionless amplifier. Rectification of this sort taking place in r-f amplifier stages due to the loud signals from local stations may produce cross-modulation. This will be studied later.

If the grid bias voltage is too small, the tube may operate near the upper bend of the curve around E, and distortion again occurs as shown at (C) of Fig. 243 due to the fact that when the positive half cycles of the signal occur, the tube is operating on the curved part of the characteristic where the changes in plate current are not proportional to the

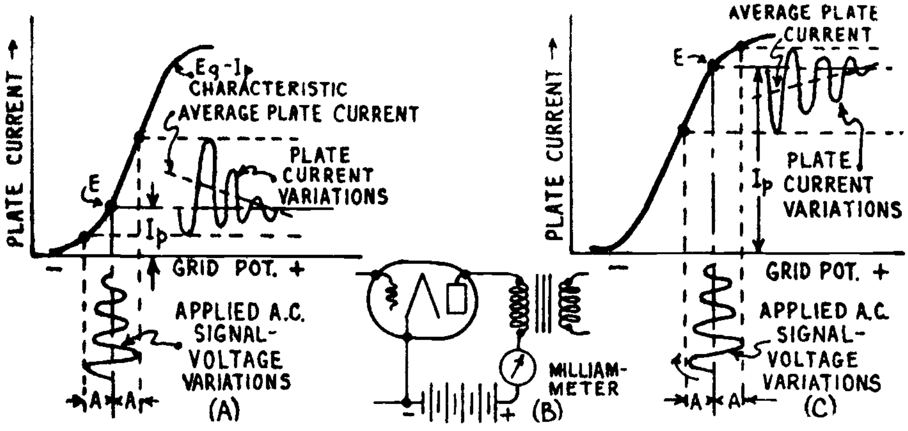


Fig. 243—(A) Distortion of wave-form of plate current, resulting from excessive negative grid bias.
(B) Connection of plate circuit for indicating tube distortion.
(C) Distortion of wave-form of plate current, resulting from insufficient negative grid bias.

changes in grid potential. The result is that the average plate current (shown by the dotted line) is now less than the normal no-signal plate current I_p. If a milliammeter is connected in the plate circuit, the needle will kick *down* every time a loud note comes through. This indicates distortion due to operation at the upper bend of the characteristic curve.

340. Distortion due to positive grid: It is possible for an amplifier tube to be operating with such a grid bias voltage, that the positive half cycles of the a-c signal voltage applied, are not great enough to drive the grid potential to the extreme positive potential illustrated at (C) of Fig. 243, where the tube operates at the upper bend of the characteristic. It may just drive the grid slightly positive each time as shown at (A) of Fig. 244. We shall now see that even this condition will cause distortion. The E_g-I_p characteristic curve is no longer straight after positive potentials are applied to the grid, it begins to curve downward, and at high enough positive grid potentials, it becomes practically horizontal as shown. Distortion will occur as soon as the positive half cycles of the input signal voltage make the grid positive. The reason for this is as follows:

As soon as the grid becomes positive with respect to the cathode, it acts exactly like a plate and attracts some of the negative electrons being emitted by the cathode. These electrons flowing to the grid and down through the grid circuit to the cathode, constitute a current in the grid circuit. This grid circuit current must flow through the resistance of the electrical apparatus connected in the grid circuit (secondary of preceeding coupling transformer, etc.). There is then, an I R drop in the grid circuit due to this, so that at each instant, the potential of the grid is not equal to the applied signal voltages but is equal to this value minus the voltage drop in the input circuit due to the grid current—just as the effective plate voltage applied to a tube is not the voltage of the B battery, but is this voltage minus the voltage drop in the output load resistance. The greater is the input signal voltage, the more the grid goes positive on each positive half cycle, the greater is the voltage drop in the grid circuit resistance, and the smaller is the proportion of the signal voltage that is actually effective on the grid. The voltage drop due to grid current really prevents the actual grid potential from swinging as far positive as it otherwise would on the positive half cycles of signal. The result of this is that the increases of plate current due to the positive half cycles of the signal are not as great as they otherwise would be, the plate current variations are not exact enlarged duplicates of these signal voltage variations, and therefore distortion has taken place. This may be seen from (A) in Fig. 244. If the grid did not go positive and cause a grid current to flow, the actual potential variations would be along points 1-7-3-8-5-9 etc. of the signal voltage wave, and the plate current variations would follow along points 1-7-3-8-5-9 of the plate current wave. Actually however, since there is a voltage drop in the grid circuit each time the grid becomes positive, the grid potential does not swing as far positive as points 7-8-9, etc. would indicate, but only swings out to points 2-4-6 as shown by the dotted line. Likewise the plate current changes only swing to points 2-4-6 on the plate current curve. Evidently, distortion takes place.

For the reasons shown above, the grid of a tube operated as an amplifier should never be allowed to go positive in ordinary circuits, or distortion will result. The selectivity of an r. f. amplifier circuit is materially reduced if the grid goes positive, since the voltage drop produced in the secondary of the tuning coil due to the grid current, materially reduces the

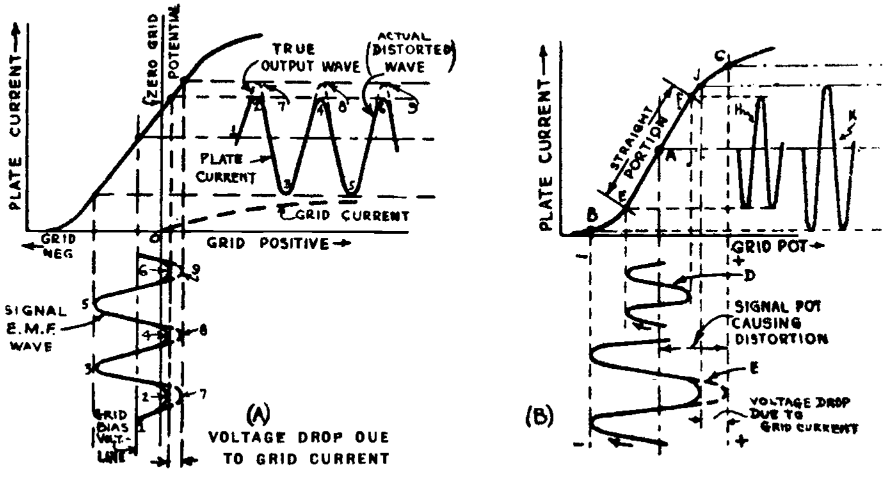


Fig. 244—(A) Distortion of the wave-form of plate current due to signal voltage driving the grid positive.
(B) Distortion of the wave-form of the plate current due to too large a signal voltage applied to the grid circuit.

signal potential (of the desired station) actually applied to the grid. Since this decreases the signal response of the desired station, a decrease in selectivity results. Therefore it should be carefully remembered that any amplifying tube should be so operated that the grid will at all times be kept negative under the usual signal conditions. This is another reason for using the proper value of negative "C" bias. The "C" bias values given in Fig. 214 are the proper ones recommended by the tube manufacturers. Notice that the "C" bias recommended increases as the plate voltage is increased. This will be readily understood by referring to the graphs at the right of Fig. 197. The characteristic curves for the higher plate voltages fall above and to the left of those for the lower voltages. Therefore the normal operating point of the grid must be shifted to the left by using higher "C" bias voltages, when high plate voltages are employed.

341. Distortion due to overloading: Even though the grid bias voltage applied to the grid of an amplifier tube is such that the tube operates at the certain point A of the straight portion of its characteristic curve as shown at (B) of Fig. 244, distortion may result if the signal voltage is so large that it drives the operating point of the grid down to the lower bend of the E_g - I_p characteristic curve or makes the grid positive during the positive half cycles of the signal. This is the condition where the tube is overloaded, i.e., too large a signal voltage is being applied to its grid circuit. This condition is shown at (B).

If a relatively small signal voltage D is applied, since it causes the grid potential to vary only over the straight portion of the characteristic curve between points E and F (and the grid is always negative), no distortion takes place, as shown by the fact that the curve H showing the plate current variations produced, is an exact enlarged duplicate of the signal-voltage curve D. If a very large signal voltage E is applied, distortion may occur due to two causes. First, the grid potential is driven over the upper bend of the E_g - I_p characteristic, and second, since the grid is driven positive during each positive half cycle of the signal e. m. f., a grid current flows, causing a voltage drop in the grid circuit so that instead of the grid potential moving up to point C on the curve each time, it actually only moves to point J. The resulting distorted plate current variations are shown by curve K.

In a case like this, since the average plate current is increased during the negative half cycles, and is decreased during the positive half cycles, the pointer of a milliammeter connected in the plate circuit would kick up and down violently every time a loud passage was received, indicating distortion due to overloading of the tube.

342. Distortion due to curved characteristic: In the tubes which are used to deliver *power* to a load, such as a loud speaker, etc., distortion may also occur due to an excessively curved E_g - I_p characteristic at the lower part, caused by using a plate load having too low a resistance. This will be considered later when studying power tube circuits.

343. Results of tube distortion: The result of the various forms of distortion which may result by operating the tube in any manner which will cause the tube to operate over the curved part of its characteristic, is to make the wave-form of the plate current variations, and magnified output voltage variations across the plate load, different from that of the applied signal voltage. This means that the sound waves produced by the loud speaker due to these currents, will not be a duplicate in every respect of those impressed on the microphone in the broadcasting station. Hence the necessity for avoiding all forms of distortion. The output current or voltage variations produced as a result of severe distortion may be very complex and very much different from those of the input signal voltage.

When a tube distorts, it adds to the output circuit, certain frequencies which are not present in the input. The currents of all of these frequencies added together at any instant equals the actual total plate current at that instant. The combination of all the wave-forms of these harmonics produces the resulting wave-form of the actual plate current.

The *maximum permissable grid swing* is the range of voltage on the grid which will not cause distortion either because of the grid going positive or because of the operating point traversing the lower bend. By "grid swing" is usually meant the *total* swing of grid voltage due to both the positive and negative halves of the a-c input voltage cycles. Thus, if the grid swing is 5 volts it means that the potential of the grid varies 2.5 volts above and 2.5 volts below some fixed value, a total swing of 5 volts. In this case, 2.5 volts is what we ordinarily refer to as the "peak" voltage of the a-c. Unfortunately, in many cases the term "grid swing" is also referred to as the maximum or peak value of the a-c signal voltage in one direction from zero (see (A) of Fig. 69). Obviously, the grid swing by this definition is half of that in the former case. It would be best to refer to the *total* grid swing by the former definition, and refer to that of the latter definition by the term "peak voltage". In order that no distortion be produced in a vacuum tube operating as an amplifier, the grid bias voltage is made *at least* as large as the "peak" value of the applied signal voltage in one direction, so that even when the positive half of each cycle is being received, the grid does not go positive. The grid bias voltage should preferably be a little greater than this value, in case extra strong signal impulses should be received during the rendering of a musical selection, etc. The grid swing must of course be referred to the dynamic characteristic curve of the tube.

344. Testing for distortion: One of the simplest methods of testing for distortion occuring in amplifier tubes, in order to determine the cause, and remedy it if possible, is by connecting a d-c milliammeter of suitable range depending on the plate current of the tube to be tested (see Fig. 214) in the plate circuit of the tube, as shown at (B) of Fig. 243. Of course the moving coil and pointer have too much inertia to be able to follow the individual variations of each cycle of the plate current, but they will follow the *average* values of the current. As explained in the previous articles, when a signal starts to come in or when a particularly loud musical passage or speech sound is being received, the cause of the distortion will be indicated by which way the pointer of the milliammeter deflects or "kicks". These may be summarized as follows:

(1) meter pointer kicks *downward*—too small a negative grid bias.

(2) meter pointer kicks *upward*—too great a negative grid bias.

(3) meter pointer fluctuates up and down—too large a signal voltage swing being applied to the grid of the tube.

A fluctuation of meter reading of over 10 per cent from its normal steady value should be taken as an indication of distortion which is bad enough to be noticeable to the average human ear.

The remedy for case (1) is either to increase the negative grid bias voltage on the tube, or increase the plate voltage, or if these adjustments are not possible in the particular amplifier being considered, to reduce the input signal voltage applied to the tube. The remedy for case (2) is to decrease the grid bias voltage or the plate voltage, or else decrease the incoming signal voltage applied. The remedy for case (3) is obviously either to increase the grid bias and plate voltages until a longer straight portion of characteristic is available; reduce the signal voltage; or use a different type of tube having a longer straight portion of characteristic i.e., one able to handle larger signal voltages. There is also another remedy for case (3), that of connecting two amplifier tubes in push-pull so that only half the total signal voltage is applied to each tube in turn. This circuit will be considered in connection with audio amplifiers in Art. 447.

REVIEW QUESTIONS

1. Why is detection or "demodulation" necessary in a radio receiver?
2. Explain briefly, the action of the grid-bias type of detector. Draw a sketch showing an alternating signal voltage wave applied to the grid circuit of a grid-bias detector and by projecting up to the E_g - I_p curve of the tube, construct the resulting plate current curve.
3. Why is it preferable to operate the tube at the lower bend of the curve in grid bias detection?
4. Show by means of circuit sketches, how the necessary negative grid bias voltage may be obtained for operating the following types of tube as grid-bias detectors: (a) 3-electrode direct-heater type; (b) 3-electrode separate-heater type; (c) screen grid direct-heater type; (d) screen grid separate-heater type.
5. Explain briefly, the action of the grid leak and condenser type of detector. Draw the same kind of a sketch for this type, as described in question 2.
6. What is the purpose of: (a) the grid condenser; (b) the grid leak resistor, in this type of detector?
7. What is meant by "square law" detection. Why is it objectionable under present broadcasting conditions?
8. What is linear detection? What type of detector is practically a linear detector?
9. What is meant by power detection? How does a power detector differ from the ordinary forms of detectors used several years ago. What recent change in radio receiver design has led to the extensive use of power detection?
10. Draw circuit sketches showing the following types of tubes ar-

ranged for grid leak and condenser power detection, and also separate sketches showing the arrangement for grid bias power detection: (a) 227; (b) 224; (c) 232.

11. Why may a grid leak and condenser detector be made more sensitive than a grid-bias detector?
12. What would happen if a high-gain r-f amplifier were employed ahead of a low-voltage type of detector such as was commonly used several years ago, if the r-f amplifier applied a signal voltage of about 5 volts to the detector?
13. Explain (with diagrams) the action of the vacuum tube as an amplifier. Why is it necessary to connect an impedance in the plate circuit to secure useful amplification from a tube?
14. What must be the value of the load connected in the plate circuit of an amplifier tube in order to obtain an amplification equal to the amplification factor of the tube?
15. It is desired to obtain 90 per cent of the possible amplification from a '24 type tube operated at a plate voltage of 180 volts. Its "mu" is 400 and its a-c plate resistance is 400,000 ohms. What load resistance is required?
16. A 10 volt signal is applied to the grid circuit of the above tube. What voltage variations appear across the load resistance?
17. Explain how detection or "demodulation" may occur in an improperly adjusted radio-frequency amplifier.
18. How must an amplifier tube be operated in order to secure distortionless amplification insofar as the tube itself is concerned?
19. What will be the effect on the wave form and the average value of the plate current of an amplifier tube if (a) it is operated with too great a negative grid bias voltage; (b) too small a grid bias voltage; (c) too great a signal? Illustrate each answer by means of a sketch, assuming a sine-wave voltage applied to the grid circuit, for simplicity.
20. Explain how a milliammeter connected in the plate circuit of an amplifier tube may be used to indicate when distortion is present in the tube and just what is causing the distortion. Illustrate your answers with sketches. If the milliammeter pointer deflects to a steady position when the signal is being received, what does this indicate?
21. A pure sine-wave sound of 1,000 cycles is played before the microphone in the broadcast studio. This is transmitted by the station, and is received and amplified at a receiving station. The r-f amplifiers in the receiver are being operated at an excessively negative grid bias. Will the sound heard in the loud speaker be different than that at the microphone? Give reasons for your answer, and show with sketches, just what the waveform of the received signal current will be after it has been amplified. Compare this with that of the original sound.

CHAPTER 21.

RADIO FREQUENCY AMPLIFICATION

NEED FOR AMPLIFICATION — REQUIREMENTS OF THE RECEIVER — STRENGTH OF THE RECEIVED SIGNAL (MICROVOLTS PER METER) — DESIRABLE FIELD STRENGTHS — TYPES OF R-F RECEIVING SYSTEMS — TUNED RADIO-FREQUENCY AMPLIFICATION — MULTIPLE TUNED R-F — RESISTANCE COUPLED R-F AMPLIFIER — PLATE IMPEDANCE COUPLING — GRID IMPEDANCE COUPLING — PARALLEL PLATE FEED — SELECTIVITY OF MULTIPLE STAGES — DESIRABLE TUNING CURVE SHAPE — HOPKINS BAND REJECTOR SYSTEM — THE BAND SELECTOR — BAND SELECTOR SYSTEMS — CROSS-MODULATION AND PRESELECTOR — VARIABLE TUNING CONDENSERS — SHAPES OF CONDENSER PLATES — S.L.C., S.L.W., S.L.F. CENTRALINE CONDENSERS — REDUCTION OF TUNING CONTROLS — EFFECT OF ANTENNA ON SINGLE CONTROL RECEIVERS — CONDENSER GANGING — EQUALIZING THE CIRCUITS — PURPOSE OF THE VOLUME CONTROL AND ARRANGEMENTS — AUTOMATIC VOLUME CONTROL — COUPLING IN THE "B"-SUPPLY — AUTOMATIC TUNING AND REMOTE CONTROL — THE SUPERHETERODYNE RECEIVER — REVIEW QUESTIONS.

345. Need for amplification: Now that we have studied the operation of the tuned circuit and the construction, characteristics, and operation of vacuum tube detectors and amplifiers, we are prepared to consider the various types of amplifiers employed in radio receivers for strengthening the weak signal voltages set up in the antenna circuit by the passing electromagnetic radiations.

At (C) of Fig. 180 a simple receiving circuit employing a crystal detector was shown. In this receiver a tuned circuit was employed to separate the signals of the desired station from those of all other stations, by so adjusting the tuned circuit that it was in resonance at the frequency of the carrier current of the desired station. Under this condition, the tuned circuit offered minimum impedance to the flow of currents of this particular frequency, and a much higher impedance to currents of all other frequencies (from all other stations). In this way the currents from all other stations were suppressed and the current from the wanted station was allowed to build up quite strong voltages across the tuned circuit, these being applied to the detector and causing operation of the earphones. In this circuit there is no voltage amplification other than any slight gain due to the tuned circuit, so that the loudness of the signal heard in the phones is entirely dependent on the strength of the signal received in the antenna circuit, the design of the primary-secondary coupling and that of the tuned circuit.

In (A) of Fig. 236 and (A) of Fig. 237, a vacuum tube was used as a detector or demodulator in place of the crystal detector. Since the vacuum tube not only performs the function of demodulation, but also amplifies the input signal voltages somewhat, the signals heard in the phones are somewhat stronger than when the crystal detector is employed. A set of this type gives fairly satisfactory earphone operation from powerful broadcasting stations located short distances away. Since the amount of energy decreases very rapidly as the distance from the transmitting station is increased, it is evident that a simple one-tube set of this type cannot be used for long-distance reception because the very weak voltages induced in the antenna circuit are not strong enough (even when amplified by the detector tube), to operate the earphones. Increased sensitivity can be obtained by the use of regeneration, but there is a very definite practical limit to this.

The use of earphones has become unpopular, as people desire to hear radio programs in comfort with loud speakers which produce enough volume of sound to be heard clearly in rooms of large size. Loud speakers require a stronger operating current than ordinary earphones do, since they do more work in setting a larger amount of air in motion. A large volume of sound from a loud speaker represents the expenditure of a great deal more energy than is ever picked up by the antenna, and therefore the energy delivered to the speaker must be supplied by some local source in the receiving equipment, and the rate of expenditure of this local energy must be controlled in such a way that it varies as nearly as possible in exact accordance with the varying amplitude of the high-frequency voltage generated in the antenna circuit by the passing fields. This extra energy may be added most conveniently by means of vacuum tubes operated as amplifiers. Of course the extra energy in this case really comes from the B-power supply device used with the tubes. In order to accomplish this, the varying signal voltage is applied to the input or grid circuit of the vacuum tube. The amplified signal-voltage variations appear across whatever load is connected in the plate circuit of the tube, (see Art. 336 and Fig. 242).

The next question to be settled is just where to introduce the amplification. It is evident that we have two choices in this matter. Assuming the use of a vacuum tube as the detector or demodulator, we could amplify the weak radio-frequency signal voltage variations before they are fed to the detector (*radio-frequency amplification*). The tendency in receiver design has been to amplify the radio-frequency signal voltages before they are applied to the detector and also amplify the audio output after leaving the detector. This arrangement is still used, but as a result of the development of satisfactory high gain screen-grid amplifier tubes, power detectors, and pentode power tubes, the tendency has been to increase the radio-frequency amplification used ahead of the detector, and use less audio amplification after the detector, on account of the many advantages of the former. It is not unlikely that receivers of the future will not employ any audio amplification at all, all of the amplification being applied to the signal voltage variations before they are fed to the detector. This will necessitate the development of suitable detector tubes or other demodulation devices (not necessarily of the vacuum tube type), which are also capable of efficiently applying a large amount of undistorted power directly to the loud speaker. In order to understand why amplification ahead of the detector is so advantageous, we must see just what the radio receiver is called upon to accomplish.

346. Requirements of the receiver: (1) The modern receiving set must separate the signals of any station it is desired to hear, from those of all other stations. The *selectivity* of a receiver is a measure of this ability to discriminate between the wanted and unwanted signals. Of course we would like to have a receiver which will respond only to one given station at a time, and not at all to any other, no matter how powerful the undesired signal is, or how close in frequency it is to the desired signal. This perfect selectivity is very difficult, if not impossible to attain in practice, but we now have receivers which are as selective as we really need them under present broadcasting conditions.

(2) The receiving equipment must also amplify the incoming signal voltage of the desired station until sufficient energy is available to operate the loud speaker as loudly as desired. The *sensitivity* of a receiver is a measure of the overall amplification from the antenna-ground terminals of the receiver to the loud speaker. Needless to say, it is desirable to have the sensitivity as high as possible, for then it requires but a small input signal voltage to deliver considerable output power to the speaker. It is also true however, that a sensitive receiver without adequate selectivity is useless, for the more sensitive it is, the more stations it tends to bring in at once with loud speaker volume and therefore the greater is the need for eliminating the signals of these unwanted stations.

There is another very definite limitation to the amount of sensitivity required. The combination of all noises coming into a radio receiver is usually taken to be the *noise level.* These noises are caused by true static, electrical interference, by re-radiating receivers, or by any apparatus or device which produces electrical impulses which may be picked up by the receiver. The limit of radio reception is governed by the distance and power of the transmitter and also by the stray electrical disturbances which drown out the signals as soon as the intensity of the latter falls to a certain degree. A point is reached where the signal from the station has less strength than these stray impulses forming the *noise level.* It is then impossible to receive the station without this interference, because the receiver will amplify the noise voltages equally as well as it amplifies the true signal voltages, since they are of the same electrical nature.

(3) A receiver must also reproduce in the form of sound waves, the exact wave-form of the sound set up in the broadcasting studio. The *fidelity* of a receiver is a measure of how well it reproduces the actual sound wave originating in the broadcasting studio. If a note of a certain loudness and frequency is sung into the microphone, then this note when reproduced by the loud speaker of the receiving equipment should be exactly the same both as regards wave-form, frequency and intensity. This should be true for any sound within the range that may be broadcast. In other words, a receiver that delivers a perfectly undistorted signal is one which has a uniform or flat frequency response curve from the antenna to the loud speaker output. This considers the loud speaker as part of the receiving equipment—which it most certainly is. Of course, this assumes that the equipment in the broadcasting station does not cause any distortion. In modern high-class stations, this is so nearly true that we may assume that their output is perfectly undistorted. Most transmitters now being constructed have an audio frequency range of 30 to 10,000 cycles with very small deviation from uniform frequency amplification over this range. While receivers which are perfect as regards the above three considerations, are practically impossible to attain in practice, many present day receivers are so sensitive, selective and produce such excellent frequency response (the average ear would not detect the small distortion present) that very satisfactory performance is obtained.

347. Strength of the received signal (microvolts per meter): We have already studied the factors which affect the energy radiated from the antenna of the transmitting station. We found that since this energy spreads out over a large area in all directions, the amount available at any receiving antenna to set up voltage in it is extremely small even when the transmitting station is only a few miles distant. In order to compare the strengths of the signals received from various stations and the sensitivity of various types of receivers, it has become a practice to call the *voltage* that is induced in the receiving antenna, the *field strength* of the transmitter at that particular point on the earth's surface. The voltage set up in the average antenna is usually a few thousandths of a volt (millivolt). Since the voltage induced in a higher antenna will be greater than that set up in a lower one, it has become standard practice to rate field strength as so many *microvolts per meter*, or so many *millivolts per meter*. Micro-volts is commonly used, because the e. m. f. induced in an antenna is so small, that the use of the volt as a unit would necessitate the use of decimals in most cases. Thus, an antenna having an effective height of one meter, (1 meter is slightly over 3 feet) and having 10 microvolts induced in it is located in a field strength of 10 microvolts per meter. An antenna 5 meters high and having a voltage of 10 microvolts induced in it, is situated in a field of strength of 10 divided by 5, or 2 microvolts per meter, etc. The *effective height* of an antenna bears little relation to the actual height in meters of the antenna. It depends on many things—how well the antenna is insulated, the kind of soil over which it is erected, etc. The effective height of an antenna is somewhat less than its actual physical height above the ground and in most receiving measurements it is assumed as an average of 4 meters (13 feet). Of course the greater the field strength existing at the location of the receiving antenna, the more the volume one can get out of a receiver. Likewise, with a greater field strength, less amplification is required to produce a given output from the receiver.

348. Desirable field strengths: According to Dr. Alfred N. Goldsmith, (proceedings of the I. R. E. Oct., 1926) the type of reception to be expected with various field strengths at the receiving antenna is as follows:

Signal Field Strength (millivolts per meter)	Grade of Reception
0.1	poor reception
1.0	fair reception
10.0	very good reception
100.0	excellent reception
1,000.0	extremely strong reception

Antenna Power (watts)	Reception Range (miles)
5	1
50	3
500	10
5,000	30
50,000	100

From the point of view of signal strength, it is of course desirable that the transmitter stations employ considerable power so as to send out intense fields which are much stronger than those set up by static disturbances, electrical appliances and other devices. The ignal voltages will then be stronger than those set up by these sources of electrical interferences and the latter may easily be suppressed.

349. Types of r-f receiving systems: In order to obtain the amount of amplification necessary for satisfactory loud speaker volume, it is usually necessary to employ more than one amplifier tube. Modern amplifiers employ a number of stages of amplification, the signal being fed

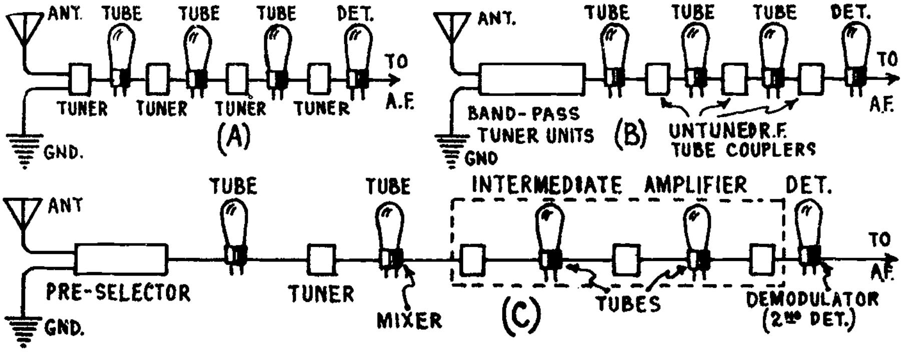


Fig. 245—(A)—T-R-F receiver system. (B) Band selector system. (C) Superheterodyne system.

to the grid circuit of the first tube. The output voltages appearing across the load in the plate circuit of this tube are fed to the grid circuit of the next tube, etc. It is not at all uncommon to use 5 or more high-gain stages of amplification ahead of the detector. The problem of tuning can of course be solved by using as many resonant circuits as are necessary to reduce the strength of the signal-voltage variations of the unwanted stations down to a value where they do not cause interference with those of the station being received. The degree of selectivity required for this purpose depends both on the signal strength of the stations it is desired to receive and that of the unwanted stations whose fields affect the receiving antenna simultaneously.

There are several arrangements possible with the amplifying tubes and tuned circuits in the r-f amplifier. As shown at (A) of Fig. 245, we may select and amplify in successive steps by following each tuned circuit by an amplifier tube. This is the common method used in tuned radio-frequency ("t-r-f") amplifiers. The overall response of the several tuned circuits to frequencies off resonance is diminished, in a logarithmic function. That is, if a single stage delivers 5 times as much voltage at the frequency of resonance as it does at some other frequency, the total discrimination in favor of a desired signal is 5×5 or 25 in a 2 stage amplifier, or 5^N if there are N stages.

In another type of receiver, the selectivity and amplification are accomplished separately as shown at (B). Either the selection is accomplished first by means of a series of tuned circuits usually in the form of a "band-pass" tuner, and the output voltage is then amplified by a vacuum tube amplifier which amplifies signals of all frequencies the same amount; or else, the amplification is accomplished first and then selection by tuned circuits follows. The former method is best of course because it is relatively easier to suppress the unwanted signals as soon as they are received than it is to suppress them after they have been amplified by the amplifier along with the wanted signals. The selector in the former system is commonly known as the "band-pass tuner" or "band selector" because it selects or passes a band of frequencies 10 kc wide.

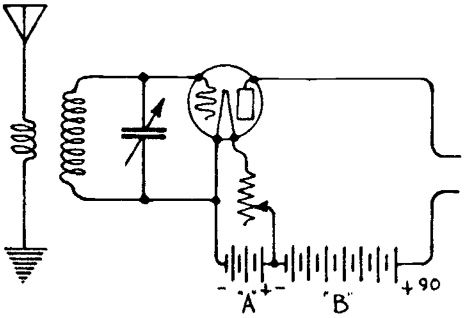
In the superheterodyne system of reception which has become exceedingly popular, the incoming signal is first selected partially in the pre-selector or r-f amplifier, then the frequency of the signal is changed to a lower frequency (which can be more efficiently amplified), and is then amplified at this intermediate frequency by the "intermediate-frequency" amplifier. It is then demodulated by the so-called "second detector", as shown at (C). A certain amount of selectivity is also obtained in the frequency-changing process. We will study the tuned radio-frequency, and "band selector" systems first, reserving the superheterodyne receiver for later detailed study in Chapter 22.

In spite of all the changes which have taken place in radio receiver design, there has been very little change in the fundamental principles involved in amplifier design, although certain new principles have been added and the constants of most circuits have been revised to suit the newer types of vacuum tubes. Of course the mechanical construction of the parts have been continually changed in order to reduce the cost of raw materials necessary, greatly simplify and cheapen the manufacturing processes, and reduce the overall dimensions of the entire receiver.

350. Tuned radio-frequency amplification: A single stage of *tuned radio-frequency* (hereafter abbreviated t-r-f) amplification shown at the left of Fig. 246 is connected ahead of a grid leak-condenser detector to form the circuit shown at the right. The circuit is that for a simple battery-operated receiver, but of course the same general arrangement could be employed for a-c operated tubes (with proper filament and plate voltage supply) or for a screen-grid type of r-f amplifier. We are concerned mainly with the simple t-r-f type of circuit at this time; later we will study several variations of it with different types of tubes, etc. The r-f transformer T has been added to the detector. As we have already considered the detailed theory of the tuned circuit and r-f transformer in Articles 245 to 250, we will not repeat this. Also, the action of the vacuum tube as an amplifier and detector was studied in detail in Chapter 20 (from Art. 336,—on), so this will not be repeated again. (The reader is advised to review this material at this time if necessary, in order to better understand the work which is to follow.)

To add a stage of t-r-f amplification to the detector, it is only necessary to couple the antenna circuit to the grid circuit of the amplifier tube by some device, such as an r-f transformer, and to couple the output or plate circuit of the r-f amplifier tube to the input or grid circuit of the detector tube. If the transformers are used for coupling, this means connecting the primary of the first transformer into the antenna circuit, and the secondary in the grid circuit of the amplifier tube. The secondary of each transformer is tuned by means of the variable tuning condenser as shown, to form a series resonant circuit. We will now proceed with the explanation of the operation of this simple t-r-f circuit of Fig. 246:

Very weak r-f voltages are induced in the antenna by the passing radiations sent out by the broadcasting stations. The induced voltages cause currents of corresponding frequencies to flow up and down the antenna circuit between the antenna and ground (since the antenna circuit is really a condenser circuit, see Fig. 177 & 179). The antenna circuit contains a number of these signal currents received simultaneously from various stations, and all having different frequencies. These currents, flowing through the primary coil of the first transformer, produce magnetic fields which link and unlink with the secondary coil and induce potentials of corresponding frequencies in it. This coil and its associated tuning condenser form a resonant circuit, the resonant frequency of which is determined by the inductance of the coil and the capacity setting of the condenser. The impedance or opposition to the flow of current of this frequency is very small, while the opposition to the flow of currents of all other frequencies is high. Therefore, the induced potential across its secondary which is of this resonant frequency, is able to send an appreciable amount of current at this frequency through the tuned circuit. This current causes corresponding voltage variations between the ends of the secondary or between the grid and filament of the amplifying tube. The varying plate current of the tube flows through the primary of the coupling transformer T. This current is a *pulsating direct current* (because the plate current of a vacuum tube can only flow from plate to filament or cathode), having pulsations occurring at the frequency of the signal being received and varying in strength according to the modulation. The flow of this pulsating current through the primary of transformer T produces a magnetic field which induces an alternating voltage in the secondary, of the same frequency as the potential across the grid of the first tube, but of a greater amplitude. The steady flow of the "B" battery current through the primary to the plate has no inducing effect in the transformer, but as soon as it becomes interrupted or varied due to the signal, the magnetic field varies accordingly, and an r-f voltage is induced in the secondary. (This is in accordance with the well known laws of



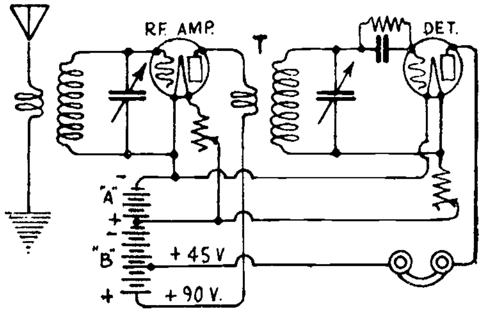


Fig 246—**Left:** Single stage of t-r-f amplification.
Right: Single stage of t-r-f and detector with common filament and plate voltage supplies.

electromagnetic induction.) This voltage acts between the grid leak and condenser terminal, and the filament of the detector tube, producing a pulsating direct current varying at the audio or modulation frequency in the plate circuit and the phones, where the amplified signal is reproduced in the form of sound waves.

The real use of the coupling transformer "T", then, is to obtain an alternating voltage of radio-frequency across the grid circuit of a tube, from the pulsating plate current of the preceding tube. Obviously the higher this input voltage to the grid circuit of the second can be made, for a given value of pulsating current in the plate of the first tube, the more efficient the coupling and the louder will be the signals. Usually the transformer is made to give a step-up in voltage by having a greater number of secondary turns than primary turns, although there are other factors which affect this. Also it is evident that the larger is the impedance of the primary winding of this transformer, the greater will be the amplification obtained from the r-f amplifier tube, since this primary forms the plate circuit load for the tube (see Article 337). The use of the tuned circuits results in additional gain due to the stronger voltage variations set up across the tuned circuit by the current flowing through it at resonance.

The filaments of the two tubes are connected in parallel across the common A-battery with variable rheostats for adjusting the filament cur-

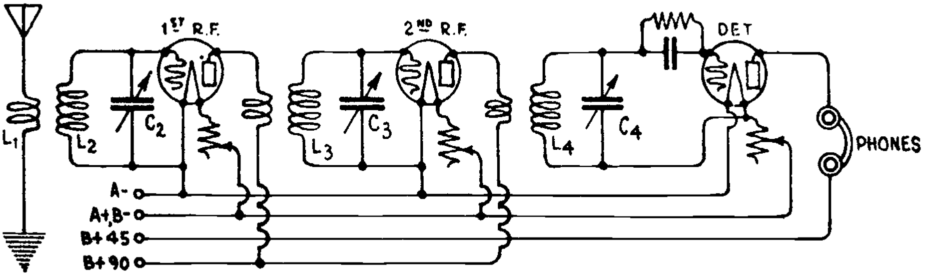


Fig. 247—2 stages of tuned radio-frequency amplification and detector.

rent. The plate circuits are also connected in parallel across the common "B" battery, 45 volts being applied to the plate of the detector and 90 volts to that of the r-f amplifier tube.

351. Multiple tuned r-f: Since a single r-f amplifier stage would hardly provide sufficient selectivity or amplification for satisfactory reception, more similar stages may be added to it. An additional stage connected to it is shown in Fig. 247. Theoretically, any number of amplifier stages (an amplifier stage consists of the amplifier tube together with its coupling device), could be added, but in practice, the number is determined by the total amplification desired, the amplification produced by each tube and coupling device, and in many cases the selectivity desired, since this determines the number of tuned circuits to be employed. The simple five tube t-r-f receiver, popular for several years, employed two stages of r-f amplification, detector, and two stages of audio amplification.

352. Resistance-coupled r-f amplifier: The successive amplifier tubes in radio frequency amplifier stages can be coupled by resistances as shown in Fig. 248. Here the variation of the plate current in the plate resistor R_1 produces across it a varying voltage drop which actuates the grid of the next amplifying tube. It is necessary to introduce blocking condensers "C" to prevent the high plate voltage of each tube from being impressed directly on the grid of the following tube. The grid circuit is returned through the grid resistor R_2 to the negative side of the filament or to the negative terminal of a C-battery for proper grid-bias voltage.

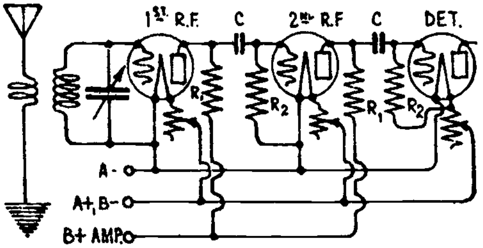


Fig. 248—2 stage resistance-coupled r-f amplifier and detector.

The relationship between voltage and current is independent of frequency for a pure resistance, and therefore in the case of resistance amplification with a three-electrode tube the voltage amplification obtained would be the same for all frequencies if there were really no capacity or inductance anywhere in the plate circuit. But although the series resistance R_1 may be made sufficiently free from inductance and capacity to ensure practically constant impedance over the range of frequencies likely to be encountered in practice, a comparatively large amount of capacity does exist between the plate and cathode of the tube itself; the plate and cathode constitute the two plates of a "small" condenser as shown in Fig. 224 and Fig. 249.

Now, although no direct current will flow through a circuit having a condenser in series, alternating current can, and therefore a fraction of the pulsating plate current of the tube will flow in and out of the plates formed by this capacitance (the plate and the cathode) instead of all passing through the coupling resistance R_1. Since the amplified voltage developed across R_1 is proportional to the variations in current through it, it follows that this by-passing of some of the current through the plate to cathode (or filament) capacitance will result in the pulsating voltage across R_1 being less than

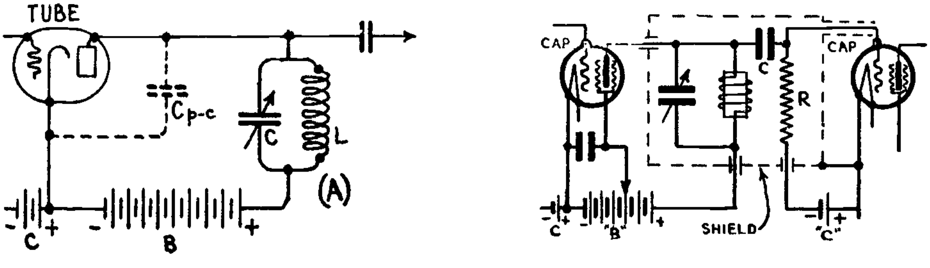


Fig. 249—Left: How the plate-cathode capacitance of the amplifier tube acts as a shunt capacitance across the plate load.
Right: Tuned plate impedance coupling for r-f amplifier.

if no capacitance were present, and the efficiency of the arrangement as an amplifier is impaired for radio-frequency signals. The grid-cathode capacitance also shunts grid resistor R_2.

The loss of amplification due to the inter-electrode capacitance of the tubes does not become serious until the amplifier is used to amplify radio frequencies, since the reactance of this capacitance is rather high at the low frequencies, and hence it does not act so much as a shunt. For this reason, this type of amplifier is generally unsatisfactory for use as an r-f- amplifier for short wave or broadcast band reception because of the high frequency and the large shunting effect of the plate-cathode capacitance. Resistance-coupled amplifiers give good results on long-wave reception at around 300,000 cycles (1,000 meters) or less. At these comparatively low frequencies the tube capacitances do not have such a great effect. However, all of the amplification in a resistance coupled amplifier is derived from the tubes themselves, no voltage step-up being obtained from the coupling device. This makes it necessary to employ a larger number of tubes for a given amount of amplification than when transformer coupling is used. Under modern broadcasting conditions, more than one tuned circuit would have to be used in an amplifier of this type in order to obtain the required selectivity. The resistance-coupled amplifier is especially useful where it is desired to amplify signals over a very wide range of frequencies without changing any of the apparatus in the circuits. For instance, an amplifier of this type can be designed to amplify signals from about 1,000 meters to 20,000 meters without changing the parts in any way.

As we shall see later when discussing audio amplifiers, resistance coupling lends itself to audio-frequency amplification, because by proper design of the amplifier the degree of amplification obtained can be made practically uniform over the whole of the range of audible frequencies, a desirable condition for high-quality reproduction from a receiver. It is for this reason that audio amplifiers in television receivers are almost entirely of the resistance-coupled type since they must amplify a very wide range of audio frequencies. The resistance-coupled a-f amplifier will be studied in detail in Articles 432 and 433.

Note: Another objection to the resistance-coupled amplifier is that in order to actually obtain a large proportion of the amplification factor of the amplifier tube, the plate coupling resistor R_1 must be of large value, (see (F) of Fig. 242). For instance, if the coupling resistor equals the a-c plate resistance of the tube, only half the mu of the tube is obtained. If this resistor is made of high resistance, the voltage drop ($I_p \times R_1$) due to the plate current flowing through it will be large, with the result that the voltage actually effective at the plate will be materially reduced. Of course, one remedy for this is to employ a B voltage supply device which will apply higher voltage to the circuit, but the cost of such devices increases very greatly as their voltage rating increases. As a compromise between these conflicting conditions, resistance amplifiers are usually designed with a plate load resistance R_1 of at least 3 to 5 times the a-c plate resistance of the tube, together with a B voltage supply at least equal to the maximum permissible *actual* plate voltage given in the manufacturer's rating of the tube.

353. Plate-impedance r-f coupling: Since the object is to connect as high an impedance as possible in the plate circuit of an amplifier tube in order to realize a large proportion of the tube's amplification factor, it has been thought at times that a coil having a rather low resistance and large inductance could be used in place of the resistance in the amplifier described above. This arrangement would be called *plate impedance coupling.*

A coil having a large inductance has a high impedance at high frequencies, and if it is constructed so its ohmic resistance is fairly low, the voltage drop across it due to the *steady plate current* flowing through it would not be very great, and normal B voltages could be used. Since it has a high impedance, any variations in the plate current flowing through it, due to an incoming signal, would produce large inductive voltage variations across it, and these would be communicated to the grid of the next r-f tube. Here, as in the case of the resistance coupled amplifier, the plate-cathode and grid-cathode capacitances (see (A) of Fig. 249) become the factors limiting the possible amplification, due to partial by-passing of the *varying* plate current which would otherwise all flow through the plate impedance and produce useful voltage variations across it. In addition, the distributed-capacity existing between the individual turns of the coil also acts as a by-pass. The amplification will be reduced at all frequencies except the one at which the coil and the total coupled stray capacitance across it are resonant. At this particular frequency, a parallel resonance circuit forms, and since such a circuit presents a very high impedance to flow of currents of the resonance frequency through it, the tube is working into a high impedance at this one frequency and high amplification is produced.

This suggests the use of an arrangement whereby a parallel variably-tuned circuit may actually be connected in the plate circuit and tuned to whatever frequency it is desired to receive. This is practical and will now be described. An impedance may be used when this type of amplifier is used for audio-frequency amplification as we shall see.

354. Tuned-plate impedance r-f coupling: The arrangement for a typical amplifier stage with tuned-plate impedance coupling is shown at (A) of Fig. 249.

Here the inductance coil L is tuned to parallel resonance, at the particular frequency of the signal it is desired to receive, by means of the variable tuning condenser C. The tuned circuit offers a high impedance to the flow of current of the frequency of resonance through it, and so acts as a high impedance load in the plate circuit of the tube at this frequency. Under this condition good amplification may be secured. When it is desired to receive the signals of another station broadcasting on a different frequency, the variable tuning condenser is adjusted to bring the circuit to resonance at this frequency and so on. Thus, maximum amplification is produced for the frequency to which the tuned circuit is resonant. Of course the tube amplifies all other signals as well, to a degree depending upon the impedance which this parallel circuit offers at this frequency. It is therefore necessary that this circuit tune sharply in order to obtain good selectivity, so that its impedance to the frequencies of all unwanted signals will be much lower than that to the frequency of the wanted station and therefore the amplification of the tube at these other frequencies will be low.

Actually, the condenser C is not the only capacitance across the tuning inductance L. Another small condenser C_{pc}, (shown dotted), due to the capacitance between the plate and cathode of the tube is actually shunted across the coil. It will be remembered that this is the condenser which caused the shunting action across the load in both the resistance and impedance-coupling circuit schemes. Since this capacitance is now really in parallel with the tuning condenser D, it means that the exact capacity setting of C necessary to tune Coil L to resonance at a given frequency, is really slightly less than the formulas for resonance indicate, by an amount equal to this plate-cathode capacitance.

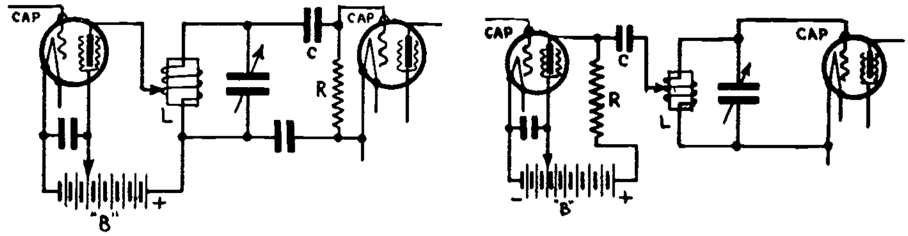


Fig. 250—**Left:** Plate-autoformer coupling in an r-f amplifier.
Right: Grid-autoformer coupling with parallel-feed plate supply.

Since fairly low resistance radio-frequency inductance coils are easily constructed, and since the effective impedance of a parallel tuned circuit may be made very high at resonance, by using a large inductance of low ohmic resistance value (effective values as high as 100,000 ohms or so are rather easy to attain), fairly good amplification may be obtained by this arrangement. However, the selectivity is rather poor due to the fact that the plate resistance of the tube is really shunted across the tuned plate circuit (if we consider the circuit from the point of view of the latter), thus lowering the effective impedance. Tuned plate coupling is especially advantageous when screen grid tubes are employed as the r-f amplifiers, because since screen grid tubes have rather high a-c plate resistances (400,000 ohms for a '24 type screen-grid tube as compared to only 9,000 ohms for a '27 type tube) it is necessary to use a plate circuit load of high effective impedance if much amplification is to be obtained. The use of a parallel tuned circuit is one of the most convenient ways of obtaining this high impedance. A typical tuned-plate circuit r-f amplifier stage with screen-grid tubes is shown at the right of Fig. 249. From the end of the impedance leading to the plate of the tube, a lead runs to a blocking condenser C, the other side of which is connected to the grid of the following tube. The variations in voltage across the impedance cause electron flows which are communicated around through the B battery circuit and grid leak resistor R to the other plate of the blocking condenser and the grid. The blocking condenser serves the purpose of preventing the high direct positive plate voltage of the first tube from being impressed directly on the grid of the following tube, as it would if the top of the tuned circuit were connected directly to the grid of the second tube. This condenser may be of about .001 mfd. capacitance for an r-f amplifier.

A serious disadvantage of this method of coupling is that there is a strong tendency to oscillate, due to feedback through the grid-plate capacity of the vacuum tube when the plate circuit is tuned to resonance (unless screen-grid tubes with their very small grid-plate capacity are employed). This tendency is especially strong in multi-stage amplifiers. It can be reduced by various stabilizing methods, but these reduce the obtainable amplification. However, this type of coupling can be used to good advantage with screen-grid tubes. Also, all of the amplification is produced by the tube itself, no step-up in voltage being produced in the coupling circuit between successive tubes as is the case with properly designed coupling transformers, where there may be a step-up in voltage from the primary to the secondary. Another disadvantage is that as the movable condenser plates are at +B potential (since they connect to the positive terminal of the B voltage supply) the rotor plates and condenser frame must be insulated carefully from the grounded metal shielding usually employed in this type of amplifier. This can be taken care of, but it complicates the set construction somewhat.

355. Auto-transformer coupling: In the straight tuned-plate impedance coupling shown in Fig. 249 the tuning is rather broad, even when good tuning coils having low ohmic resistance are employed. If, however, the coil and condenser are connected as shown at the left of Fig. 250, the selectivity will be greater: The tuning coil really acts as an auto-transformer now:

The plate current of the tube flows up from the lower end and out of the tap to the plate. This part of the winding is therefore the primary of the transformer. The varying plate current flowing through this, induces a higher voltage in the secondary which consists of the entire coil. The primary and secondary voltages will be 180 degrees out of phase, in accordance with the theory of ordinary transformer action. The inductive coupling between the primary and secondary parts of the winding (for the same number of primary turns) is greater in this type of coil than in one having a separate primary and secondary, hence a greater plate circuit impedance is built up with a relatively small number of turns, resulting in greater overall amplification. The selectivity of this arrangement is good, but the fact that the tuning condenser plates are at the high B+ potential is a disadvantage. This is known as *plate auto-transformer coupling*. In the grid *auto-transformer* coupled circuit shown at the right, this disadvantage is removed by connecting the auto-transformer L with its tuned secondary in the grid circuit and coupling it to the plate circuit by a high resistance R and a coupling condenser C of about .001 mfd. or so. The position of the tap on the tuning coil determines what proportion of the entire coil acts as the primary, and therefore this affects the voltage step-up in the coil. However, the fewer the number of turns included between the bottom and the tap, as the primary, the smaller is the impedance being placed in the plate circuit of the tube and therefore the less is the amplification derived from the tube. Consequently, if the tap were moved down step by step, the selectivity would increase as the number of turns actually included in the plate circuit were reduced. A point is reached however, where further lowering of the tap produces considerable overall decrease in amplification.

356. Parallel-feed plate supply: In the circuits shown in Figs. 246, 247, 249 and the left of Fig. 250, the direct plate current of the tube flows directly through the tuning coil. In the circuit at the right of Fig. 250, this current flows through the resistor R. So far as any steady direct plate current flow through R is concerned, it has no effect on the coil. However, when any variation in the plate current occurs due to a signal, the variation in voltage drop through the resistor is communicated to the coil circuit by means of the blocking condenser C. This connection is known as *parallel-feed* plate supply, because the direct plate current does not flow through the coupling unit, but rather through a separate parallel circuit employed for that purpose.

A choke coil having low distributed capacity is usually employed in place of resistor R in practice, so that the voltage drop due to the passage of the steady plate current is not excessive. Parallel-feed plate supply can also be used in transformer-coupled audio amplifiers, as we shall see later, in order to eliminate the effects of core saturation which might be caused by the steady direct plate current flowing through the primary of the transformer. At (A) of Fig. 251 the use of an r-f choke coil (an inductance of about 85 millihenries) for parallel-feed in an auto-transformer coupled r-f stage is shown; and the arrangement in a transformer-coupled audio amplifier stage is shown at (C). A larger size of coupling condenser and choke coil is needed in the case of audio amplifiers, as shown, on account of the lower frequency. The coupling condenser is usually of .25 mfd., and the choke of 30 henries inductance. For a radio-frequency amplifier, a choke of 85 millihenries is usually employed with a coupling condenser of from .001 to about .005 mfd.

357. Selectivity of multiple stages: The selectivity (measure of the ability of a receiver to suppress the signal impulses of all unwanted stations) of a radio frequency amplifier depends on the number of tuned stages, and the selectivity of each stage. The first factor is illustrated at the left of Fig. 252.

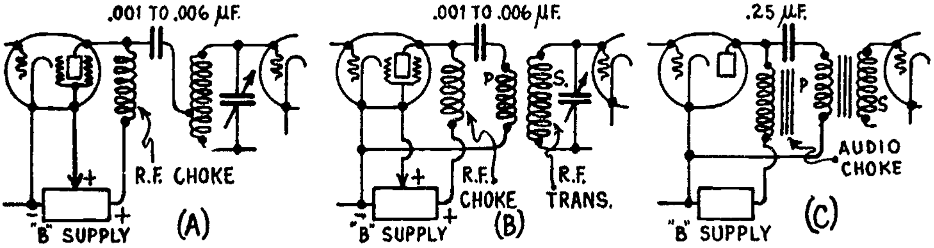


Fig. 251—Parallel-feed plate supply systems. (A) and (B) for an r-f amplifier; (C) for an audio amplifier.

Let curve A represent the response curve of a single tuned r-f stage, that is, the height of the curve at any point represents the "per cent of the amplification at resonance" which is obtained at the frequency corresponding to that point. The receiver is supposed to be tuned to resonance at 600 kc. Then, a signal having a frequency 5 kc off resonance (above or below the frequency of resonance), is amplified about 90 per cent as much as one of the resonance frequency,—which is taken as 100 per cent. A signal having a frequency 10 kc off resonance is amplified only 81 per cent as much as the signal to which the circuit is tuned, etc. Now if another stage with characteristics exactly identical to the first is added to it, the selective action shown by curve B is obtained. This can be understood from the fact that if for a signal of a certain frequency off resonance the first tuned circuit reduced the strength to 90 per cent, then the second tuned circuit would reduce the strength to 90 per cent of what came through the first stage, i.e., 90 per cent × 90 per cent, or 81 per cent. A third tuned stage would reduce it to 81 per cent × 90 per cent, or 73 per cent. A fourth tuned stage would make it 73 per cent × 90 per cent, or 66 per cent, etc. Reference to the curves at a point 5 kc off resonance, shows the selective action referred to above. Under these conditions of selectivity, a signal voltage whose frequency is 5 kc off resonance, is only amplified 66 per cent as much as that of a signal of the frequency to which the circuits are tuned.

The illustration at the right of Fig. 252 shows in a pictorial way how the signal strength is increased and the width of the frequency band passed through is decreased, as the number of tuned r-f stages are increased. Starting at the antenna circuit at the left, the undesired signals are reduced somewhat by the first tuned circuit, then all signals are amplified by the vacuum tube to a greater strength (as shown by the higher curves), then the next tuned circuit further reduces the strength of the undesired signals, etc. It is obvious that the tuning of each stage must be designed to be broader than that desired from the amplifier as a whole, due to the successive reducing action of the various tuned circuits. It should be remembered that the selectivity is gained entirely by means of the tuned circuits, none whatever is obtained from the vacuum tube, because a vacuum tube will amplify without discrimination, voltages of any frequency applied to its grid circuit. It is evident, then that in ordinary tuned r-f amplifiers, sharp tuning may be obtained by employing a number of tuned stages and amplification is obtained by using a number of amplifier tubes. Under present broadcasting conditions with powerful stations,

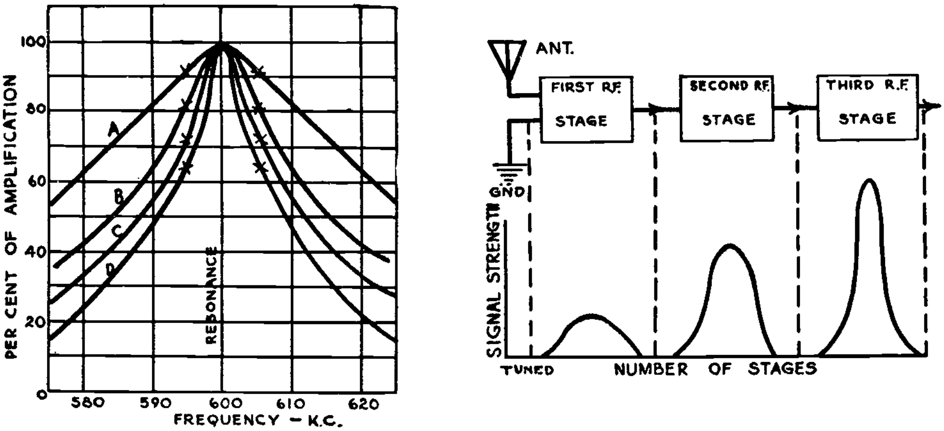


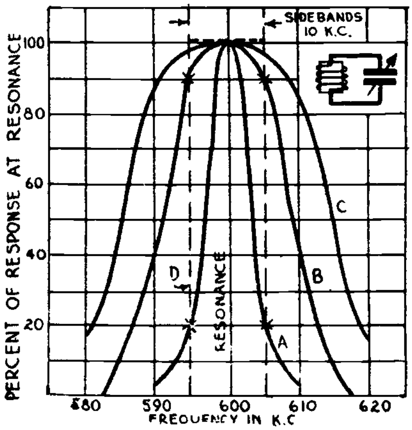
Fig. 252—Left: Why several tuned circuits in cascade increase the selectivity by successively reducing the strength of the unwanted signals.
Right: Pictorial representation of how several tuned stages amplify, and sharpen the tuning.

a single tuned circuit is unable to sufficiently weaken the signals of undesired local stations to make them inaudible. In practice, a number of such stages must be used to obtain the necessary selectivity to be able to completely eliminate the signals of all other stations when listening to any one station.

358. Desirable shape of tuning curve: It would seem from this discussion that it is very desirable to obtain an overall tuning curve which is very narrow and steep, somewhat as shown by curve A at the left of Fig. 253. A tuning characteristic like this would mean that only the signal currents of the station transmitting with a carrier frequency equal to that to which the tuning circuits were tuned, would be allowed to pass through the amplifier freely, the signals of stations of all other frequencies would be very greatly reduced in strength by the high impedance offered to their flow by the series tuned circuits. Actually, a tuning curve as sharp and peaked as this is undesirable from the standpoint of good audio-frequency reproduction as we shall see.

In order to obtain a sharp tuning characteristic like that of curve A, the tuned circuits must have low a-c resistance. The a-c resistance of a good isolated tuned circuit can be made as low as 10 or 12 ohms at a frequency of 1,500 kc. (200 meters wavelength). However, its resistance when placed in an actual receiver depends largely upon what circuit and objects are brought near its magnetic field. The associated circuits may consist of coupled primaries, and the input circuits of vacuum tubes which are connected directly across the tuned circuits. The mechanical things include metal end-plates of condensers, shielding, etc. From the standpoint of signal strength and selectivity alone, all these factors should be controlled so that a low resistance results in the tuned circuits. However, the resistance can be made so low, and the tuned circuits made to tune so sharp, that an undesirable effect is produced. This is known as *cutting sidebands.* Curve A of Fig. 253 has purposely been drawn very sharp to illustrate this condition. The frequency of resonance is assumed as 600 kc.

Consider that a musical selection is being played in a station transmitting at 600 k. c. (500 meters), and that the signals of this station are



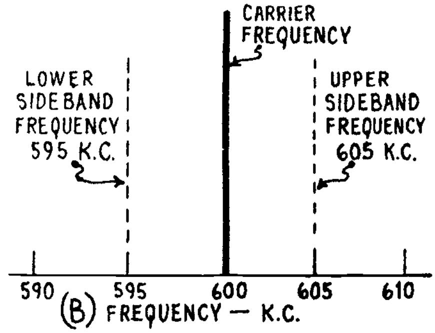


Fig. 253—Left: Effect of resistance on the sharpness of tuning of tuned circuits.
Right: Illustrating sideband frequencies 5 k.c. above, and below, a carrier frequency of 600 k.c.

being picked up at the receiving station and are impressed on the tuned circuit whose characteristic is represented by curve A at the left of Fig. 253. Although many of the larger broadcasting stations are equipped to transmit all audio frequencies up to 10,000 cycles, the fact that most radio receiving equipment in general use at the present time is not able to reproduce sounds above 5,000 or 6,000 cycles, and also the fact that many stations located in the same vicinity are assigned to transmit with carrier frequencies only 10 kc different from each other, has resulted in their transmitting only those sounds between about 40 and about 5,000 or 6,000 cycles. We will consider for our discussion that the upper limit is 5,000 cycles.

Therefore at the broadcasting station considered, the 600,000-cycle carrier current wave is modulated by the audio-frequency currents ranging from 40 to 5,000 cycles. Consider first that only a 5,000-cycle note is being played by the orchestra. This 5,000-cycle audio current then combines with the 600,000-cycle carrier current producing two additional currents, one having a frequency equal to the "sum" of these two (605,000 cycles), and one having a frequency equal to the "difference" of these two (595,000 cyles), see (B) of Fig. 253, and Arts. 383 & 384. Therefore, to receive this note, the r-f amplifier must pass these two currents through it with equal strength. You will notice that they differ in frequency by 10,000 cycles, or 10 kilocycles. Now if a 3,000-cycle note is played, the carrier wave will contain a 603,000-cycle note and a 597,000-cycle note and the amplifier will have to amplify these equally. It can be seen that if the entire range of musical frequencies is being covered at once by the orchestra there will be present a carrier wave covering a *band* of frequencies from 605,000 cycles to 595,000 cycles, and in order to secure faithful reproduction at the receiver, *every one* of these frequencies must be *passed through the r-f amplifier and amplified equally.* If any frequency is suppressed in the amplifier, then that note will not be reproduced in the loudspeaker, and the music will not be a true reproduction of that played in the broadcast studio. This condition would occur if the frequency response of any one tuned circuit or of the entire r-f amplifier were as shown by curve A. All the frequencies to 5 kilocycles above the carrier and the 5 kilocycles below the carrier (10 kc. altogether) constitute what are known as the "*sidebands.*"

It is evident that in this case the response for the 595 and 605 kc. sidebands (5,000 cycle audio note) is only 20 per cent as large as the response of sidebands near the resonance frequency. Therefore this high 5,000-cycle note would be heard very weakly, if at all, in the loudspeaker. Other notes lower than this would be suppressed in varying degrees as shown. This frequency response is evidently too sharp for good audio quality reproduction.

Tuning characteristics represented by curve B would be more nearly ideal, since the response at 595 kc. is 90 per cent of the response at resonance. Curve C is obviously a further improvement in this respect. However, curves B and C indicate broad tuning with poor selectivity and consequent danger of station interference. It can be seen that with this type of tuned circuit some compromise must be effected. Some compensation for the loss of the high frequency notes due to cutting of side bands by over-selective tuning circuits can be secured in the audio amplifier and reproduced by designing this to have a rising characteristic at the high frequencies. This means selecting the audio and reproducer units to match the operating characteristics of the r-f amplifying system.

Obviously the ideal response curve would be that shown by the dotted lines at D. This tuning curve has straight vertical sides, a flat top, and is 10 kc. wide. Since the peak of the wave is no greater at the carrier frequency than at 5 kc. above or below the carrier, equal transmission is obtained on all frequencies within the 10 kc side-band range.

Frequency response, or tuning curves, approaching this can be obtained in several ways by means of band-pass filters, coupled circuits, or the special Vreeland and Hopkins circuits which will be described. The actual existance of the sideband frequencies mentioned above has been questioned by many authorities since from the physical point of view, the modulation which takes place in the broadcasting station is *amplitude modulation* of the carrier current. However, whether we fully accept the idea of the existance of the sidebands or not, the fact remains that it helps considerably in explaining some phases of tuning circuits. At any rate, the fact that circuits which tune too sharply will suppress the high-frequency audio notes issuing from the loud speaker, can be demonstrated experimentally, so the facts remains that the tuning circuits should not be made too selective if good tone quality is to be preserved. We will now proceed to a study of several circuit arrangements which are employed to obtain a tuning curve which approaches the steep-sided flat-topped curve of D.

It is interesting to note that strictly speaking, the ordinary simple tuned circuit is really a band-pass filter passing a rather limited band of frequencies. The broader is the tuning of such a circuit, due to resistance, etc., the wider is the band passed, as will be seen from curves B and C at the left of Fig. 253. The objection to this form of circuit is of course that if it is made to tune broadly enough to pass a band of 10 kc. without reduction in strength, it will also pass many more frequencies above and below this (see curve C) because the sides of its tuning curve are not straight. What we desire is a tuning circuit able to transmit without reduction a band of frequencies about 10 kc. wide, and to sharply cut off all frequencies above and below the band, as shown by curve D.

359. Hopkins band rejector system: In the Hopkins band rejector circuit arrangement, a band-pass effect (see Article 187) is obtained and all frequencies above and below the band are suppressed or rejected. This circuit is particularly adapted for use with screen-grid amplifier tubes because it places a high impedance load in the plate circuit of the amplifier tubes. A description of this circuit, developed by Mr. Charles L. Hopkins, follows:

"The Hopkins circuit is actually an impedance-coupled amplifier in which the impedance of the output circuit of one tube is common to that of the input circuit of the succeeding tube. Of course, one object of the amplifier is to produce as much increase in the voltage impressed upon the grids of successive tubes as possible, and in order to do this it is necessary that the voltage drop across the elements of the external plate circuit be as great as is consistent with stable operation.

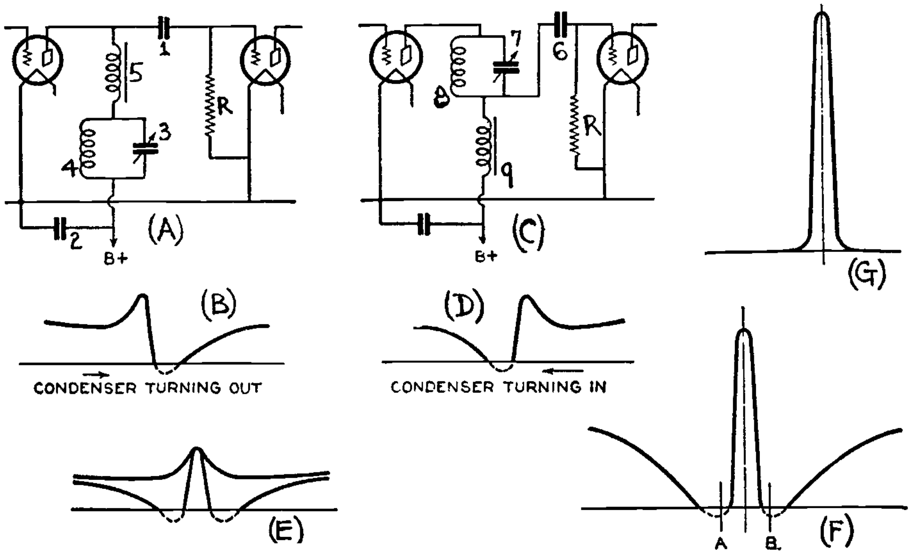


Fig. 254—Hopkins band rejector system. With the circuit at (A), the tuning response at (B) is obtained. With the circuit at (C), the tuning response at (D) is obtained. This is the exact opposite of (B).

With screen-grid tubes the high plate resistance makes it necessary to greatly increase the impedance of the external plate circuit, over that necessary with the -27 type, in order to create a high voltage drop for impression upon the grid of the following tube. A parallel resonant circuit, of the type sometimes called a wave-trap, is employed as the best means for supplying the high impedance, in spite of the fact that such a system, as usually employed, presents problems due to the tendency of such circuits to oscillate and become decidedly unstable when as many as three stages are used.

A form of coupling means which may be used in the Hopkins system is shown at A of Fig. 254. The plate circuit i seen to consist of a combination of a choke coil in series with a parallel tuned circuit, with the plate return through these impedance elements and a fixed condenser. The fixed condenser, 1, between the plate of the first tube and the grid of the second, is for the sole purpose of isolating the grid from high plate voltage. A leak, R, is provided to prevent blocking of the second tube. The choke coil, designated as 5 in the diagram, is so designed that it has a large value of inductance with a very small distributed capacity. At the same time the capacity is sufficient to tune the circuit to a frequency much lower than the frequency used in the amplifier, so that the choke acts as a capacitive reactance to this frequency, and functions as a very small condenser; that is, a condenser having high capacitive reactance.

Two fundamental electrical laws enter into the analysis of the working of this system. The first is that when a capacity and an inductance are in series and the reactances are mutually balanced (circuit is in resonance) at some particular frequency, the current at that frequency meets with no impedance other than the ohmic resistance of the circuit, and consequently no voltage drop will occur across them. The second law is that when a circuit, such as that incorporated in inductance 4, and condenser 3, is brought into parallel resonance at a certain frequency, there is no reactive impedance at that frequency, but the ohmic resistance is extremely high.

Now, if the trap circuit comprising the inductance 4, and capacity 3, is tuned slightly higher than the frequency of the radio signal, the impedance across the circuit becomes highly inductive, and, if it is tuned slightly lower in frequency, the impedance becomes highly capacitive. The combination of elements in the plate circuit, when arranged as shown, therefore offers to the amplifier plate current either inductive reactance, capacitive reactance, or series resonance (no reactance) because of the fact that one of the elements is variable.

Due to the fact that the adjustment may be such that the reactance of the plate circuit cancels out, there will be a frequency at which there is no voltage drop and consequently no voltage swing impressed on the grid of the second tube. In other words, the signal may be shorted out or shunted back to the input of the first tube. Under these circumstances the ohmic resistance of the choke coil, the only remaining coupling impedance, would not be sufficient to afford a voltage drop great enough to pass the signal to the following tube. At the same setting of the tuning element there will be another frequency at which the trap circuit offers extremely high resistive impedance, and the voltage drop across the trap is all impressed on the succeeding grid. The form of the response curve obtained by adjusting the capacity of the tuning condenser is shown at (B). It is evident that the impedance of the plate circuit is very high at the setting that gives the peak in the curve, so that a high voltage amplification is obtained.

It will be seen that with the arrangement of (A) signals of one frequency are passed along to the second tube, while signals of another and higher frequency will be shorted out, or shunted back. There is thus provided a circuit which has a high degree of selectivity on one side of the desired band of frequencies, but, because of the non-symmetrical shape of the curve has a less than normal degree of selectivity on the other side. Therefore, the system must include a circuit to give a means for eliminating stations on the other side of the band.

A circuit arrangement which gives a curve which is the reverse or complement of the curve is shown at (C). Here again we shall consider the tubes as the first and second, although they are actually the second and third tubes of the circuit. Note that the resonant circuit 7-8, and the choke coil 9, are connected as at (A), except that their relative positions are reversed. The lead to the grid of the second tube is taken from the common connection between the trap circuit and the choke, instead of from the plate of the first tube, as in the previous stage. Here it is the voltage drop across the choke, 9, that is impressed on the second tube.

If the adjustment of the trap is such that its reactance is inductive, it is apparent that it will tend to cancel out the capacitive reactance of the choke coil in the same manner as discussed in connection with the circuit of (A), but it is fundamental that when a capacity and an inductance are brought into series resonance for a given frequency, a very great voltage drop occurs across either of these reactance elements.

If the circuit shown at (C) is set up and the condenser is rotated, the signal strength will change in just the same manner as it did in the case of the arrangement shown at (A), except that the steep cut-off occurs on the other side of the "hump". The curve for this second stage is shown at (D). In this case the reason for the drop in the response curve is that the trap circuit 7-8 blocks or rejects signals of the frequency to which it is tuned. The parallel tuned circuit, instead of being in a path which is common to the plate circuit and the grid circuit, is in but one of these circuits, and it, therefore, prevents the signal current from flowing in the choke. As a consequence of this trapping action there is no current in the common impedance element (the choke) and, therefore, no voltage drop to be impressed on the next tube.

Superimposing the curves shown at (B) and (D), one upon the other, the resulting curve will be as shown at (E). The portion of the spectrum which is transmitted through the tubes is seen to form a comparatively straight-sided, narrow band. The width of the band or channel can be narrowed or widened by adjusting the setting of the condenser, 7. Experiments have shown that the band can be made so narrow that the quality of the reproduction is greatly impaired by side-band trimming, to such an extent, in fact, that a violin can nearly be tuned out due to the narrowness of the band, which will not allow the higher frequencies of the violin to pass through. Therefore, it will be seen that it is readily adjusted so as to obtain ten kilocycle station separation. The shape of the curve of (E) shows that an adjustment for band width of 10 kc. will afford extremely high rejectivity for channels on each side of the desired one. It will also be seen that the top of the curve maintains practically the full band width, which means that the fidelity will not suffer even with great station separating ability.

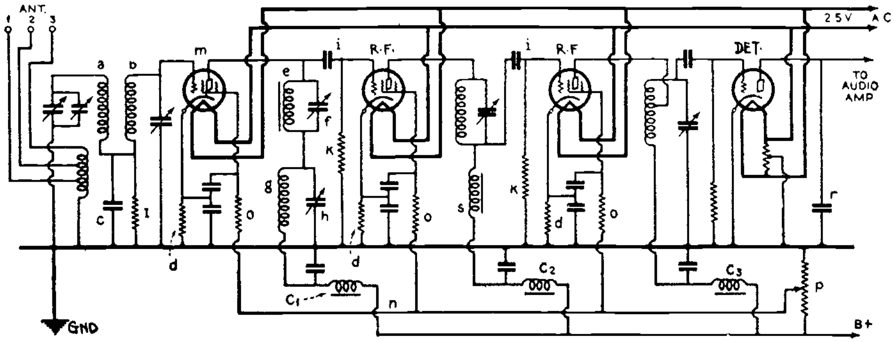


Fig. 255—The circuit of a four tube tuner employing three stages of tuned r-f., two of which employ the Hopkins band-pass system described; while the antenna stage makes use of a standard pre-selector circuit.

This system for securing station separation may be used in t-r-f receivers and in superheterodyne receivers. It will be understood that in t-r-f sets the condensers which tune the trap circuits are ganged to tune together over the broadcast band, whereas in a superheterodyne, using this system in the i-f stages, these stages are set permanently so as to give the desired band width.

Evidently, when the amplification of the stages is taken into account, the response curve of the two stages combined will be somewhat different from what is shown in the curve at (E). The figure at (F) shows what might be expected from two stages, and it will be seen that the cut-off at each side of the signal becomes steeper as the high part of the curve goes up. The low or no-signal parts of the curve remain fixed at the same distance from the signal frequency, regardless of the amplification or the strength of the signal. This is because the low points A and B are positioned by the wave traps, and these points cannot be moved apart or nearer each other by changes in signal strength.

It will be seen that we have here a means for eliminating undesired signals which are on frequencies close to the frequency of the desired signal, and that strong signals do not broaden the response curve, but merely raise it.

At points on the curve of (F) somewhat distant from the frequency of the desired signal the curve rises to perhaps one-third or one-half of its height at the signal frequency. In the sets which are built using two stages such as shown and described above, one or more additional tuning circuits of the usual types are usually employed. When the input to the first tube is tuned in the usual way frequencies somewhat removed from that of the desired signal are "tuned out" ahead of the first tube, while those close to the desired signal are prevented from passing through the receiver by being trapped or rejected in the amplifying stages. In some cases it has been found practical or advisable to employ a band-pass type of tuning ahead of the first tube."

Fig. 255 shows a circuit diagram of the r-f amplifier and detector of a practical receiver employing the Hopkins band rejector system and using a-c screen-grid tubes in the radio-frequency stages, these tubes being of the indirectly-heated cathode type. In this particular set, there is sufficient amplification ahead of the detector to permit the use of but one audio-frequency stage. In this receiver it will be noted that double tuning is used ahead of the first tube. The two coils *a* and *b* are shielded from each other, the coupling between the two tuned circuits being given by the fixed condenser C which is common to both tuned circuits. A leak resistor is provided across the condenser to prevent blocking of the grid of the tube.

"The grids of the radio-frequency tubes are biased by means of the resistors *d* between the cathode and "B" minus or ground, as usual with heater-type tubes. In the plate circuit of the first tube is located a choke coil *e*, with a small variable condenser *f* connected across it. The purpose of this condenser will be explained later. In series with the choke coil is a trap consisting of coil *g* and condenser *h*. The connection to the grid of the second tube is made through a fixed blocking condenser *i*. The condenser is connected directly to the plate of the first tube. A grid leak *k* is provided because the condenser *i* would otherwise block the grid. The screen grid of the first tube *m* is connected to line *n* through a resistor *o*. The screen grids of the other radio-frequency tubes are also connected through resistors to this line, and a potentiometer p controls the voltage applied to the screen grids and acts as a volume control.

The condenser *f* is usually placed on the shaft of the tuning condensers and thus forms a part of the gang, but if more convenient it may be placed at some point distant from the condenser gang and operated by means of a belt or link movement. This condenser turns in, so as to increase in capacity, as the set is tuned to longer wavelengths. It will be remembered that choke coil *e* acts as a small condenser. It has been found that in order to maintain the shape of the response curve the same at all wavelengths to which the set may be tuned, it is necessary to add extra capacity across the choke as the set is tuned up the scale, that is to say, to longer and longer wavelengths.

Going now to the plate circuit of the second tube, it will be seen that the arrangement is the same as that shown at (C) of Fig. 254. The response curve of this stage by itself would be the same as at (D). The coupling means employed between the third radio-frequency tube and the detector may be the familiar tuned-impedance coupling, or it may be of an untuned impedance type or it may be the usual tuned secondary with untuned primary. The detector and audio amplifier need no explanation, as they may be of conventional types.

(G) shows the overall response curve of the complete receiver. With the input to the detector tuned as shown, the curve tends to become somewhat peaked at the top, but not to such an extent as to noticeably impair the tone quality. As has been pointed out, the system of band-pass tuning as described here is applicable not only to t-r-f receivers but also to superheterodyne construction."

360. The band selector: The purpose of the *band-pass filter* or *band selector* is to present a low impedance to, and allow the passage into a circuit of, currents of a narrow band of frequencies which it is desired to receive; and to offer a high impedance to, and exclude all others, whether higher or lower than the limits of this band. The general theory of ordinary band-pass filters or selectors was explained in Article 187, and formulas for their design were given there, but since the band-pass tuners or filters, employed in t-r-f and superheterodyne receivers differ somewhat in form from these, they will be considered here. We will consider the form used in some t-r-f receivers first.

In the ordinary band selector, two tuned circuits are loosely coupled by means of a small mutual inductance or a rather large mutual capacitance. The elements of the circuit are arranged according to the general circuit at (A) of Fig. 256. The tuning coil and condenser L_1C_1 are tuned to the same frequency as similar coils and condenser L_2C_2. M is the mutual coupling reactance, which in this case is a small coil, but as we shall see later this may be a condenser, or simply magnetic coupling between the

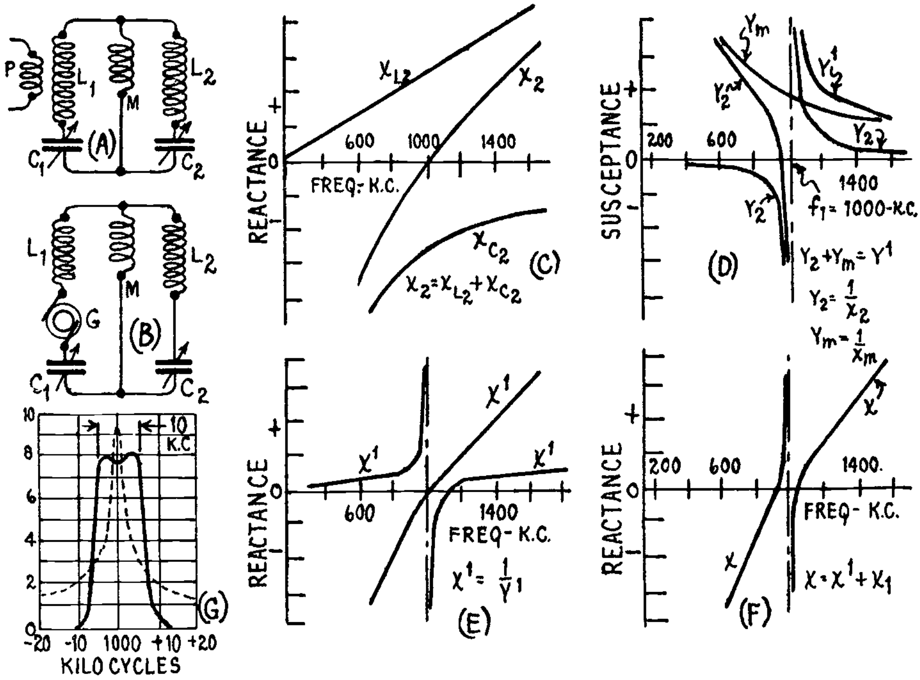


Fig. 256—Circuit arrangements and reactance variations in a band-pass filter.

coils, etc. The input voltage E may be introduced by coupling L_1 by means of a primary coil as shown at (A), or by connecting L_1 directly in the plate circuit of the amplifier tube as shown at G of Fig. 257. The output may be taken directly from L_2 or C_2, or by inductive coupling from the circuit of L_2. Inducing a voltage in L_1 is comparable to placing the voltage in series with the coil, so that the equivalent circuit is as shown at (B), with the a-c generator G in series with L_1, supplying the input voltage.

A study of this diagram will reveal why the band-pass effect is obtained. Even though coils L_1 and L_2 are similar, and C_1 and C_2 may be set at exactly the same capacitance, the circuits in which they are placed are not tuned to exactly the same frequency simply because these circuits are not similar, due to the mutual coupling inductance or capacitance M, in the circuit.

The theory of all these filters is the same. One resonance frequency is determined by the circuit disregarding the coupling device. For example, in (A) the first maximum is determined by the two inductances L_1 and L_2 connected in series and the two capacities C_1 and C_2 connected in series. The circuit then consists of L_1, L_2, C_1 and C_2. The resonance point determined by these four impedances is exactly the same as that determined by one L and one C. The reason for this, is that the inductance of the two similar coils in series is twice the inductance of either coil, and the capacity of the two equal condensers in series is equal to one-half the capacity of either. The second resonance frequency is determined by each half of the circuit in which the common or coupling impedance enters. For example, in (A) the second resonance frequency is determined by L_2, C_2, and M. Evidently this resonance frequency differs from the first one and will be more and more different as the coupling impedance M is made larger and larger.

We may make use of the reactance diagrams for the two parts of the circuit to find out just what happens in it for input voltages of various frequencies. It will be remembered from Article 175 and Fig. 116, that a reactance diagram shows how the reactance of an inductive or capacitive circuit varies as the frequency is changed. For any given similar settings of the tuning condensers C_1 and C_2, which in the case shown corresponds to a resonance frequency of 1,000 kc, the reactances of the inductance and capacity elements are calculated, plotted and combined to obtain the total reactances X_1 and X_2 of the circuits L_1 C_1 and L_2 C_2 respectively. Inductive reactance, equal to $2\pi fL$, is directly proportional to the frequency and when plotted for L_2 at (C) is a straight line (X_{L2}) through the crigin. For capacitive reactance, the inverse relation $\frac{1}{2}\pi fc$ gives rise to the curve X_{C2} for condenser C_2. Since these two elements L_2 and C_2 are in series, their resultant reactance is obtained by adding algebraically the two curves, which determines the curve X_2. Curve X_2 indicates the well known series tuned circuit action; at the frequency to which the current is tuned, the reactance drops to zero.

In parallel with the branch "2" is the mutual reactance M, an inductance in this case. When elements are in parallel, the total susceptance is obtained by adding algebraically the individual susceptances, where any susceptance is given by the reciprocal of the corresponding reactance; that is, susceptance, Y, is equal to $\frac{1}{X}$. The reactance of **M** is a positive, straight-line function of frequency; when plotted as susceptance, it takes the inverse form of Ym in (D). The susceptance of the "2" branch is derived **from** the $\mathbf{X_2}$ curve of (C). Where this reactance became zero at 1,000 kc, the susceptance goes to infinity. The sum of the two susceptances shows the curve Y^1, the total susceptance for the combination of M, C_2, and L_2. The construction shows that at 1000 kc the susceptance is infinity, and at a slightly lower frequency is zero; or, at respective frequencies, the reactance X_1 for the combination is zero, and infinity. The remaining circuit elements are C_1 and L_1, which are in series with the MC_2L_2 combination. The reactance curve for L_1 and C_1, in series, is X_1, similar to that for C_2L_2. Adding both series reactances yields the final overall curve, X, for the reactance of the band selector, which is drawn by itself for clearness at (F). The curves are plotted for a rather large mutual inductance, which is many times the actual inductance necessary in the common branch. If plotted for a smaller inductance, the points of zero and infinite reactance would merge indistinguishably close. As can be seen from (F), the reactance is zero at two values of frequency close together. At a frequency in between these, the reactance goes to infinity, and if reactance alone were considered, the current at this frequency should be zero. However, the resistance which is unavoidably present in the circuit limits the impedance so that it can never go to infinity, just as it can never go to zero. The consequence is a smoothing out of the current curves so that two resonant peaks occur at the points of zero reactance, and a more or less pronounced dip between them at the point of infinite reactance. The proximity of the peaks is determined by the value of the mutual impedance, or putting it another way, by the closeness of the coupling. As the value of the mutual inductance is increased, for any given frequency value, the coupling impedance goes up, and the peaks spread further apart as shown at (C), (D) and (E) of Fig. 257. On the other hand, increasing the capacity, when such is the common reactance, lowers the value of the coupling and the peaks come closer together. That changing the value of the common reactance changes the width of the selected band may be seen from the reactance curves. At (D) the point of zero susceptance, at f_1, is determined where the susceptance of M is equal and opposite to the susceptance of the C_2L_2 branch. The higher the susceptance of M, the closer this point moves into the frequency f_1, and the narrower becomes the overall width of the selected band.

Because the band width varies with the value of the mutual reactance, for any given coupling inductance or capacity, the band width will vary for different broadcast carrier frequencies. Suppose the coupling has been adjusted for the desired band width at one particular carrier frequency; the band will be wider or narrower at higher or lower carrier frequencies, respectively, if the mutual reactance is a coil,—vice versa if a condenser—for the reason that the value of the reactance varies proportionally with the frequency. The voltage must be introduced in L_1 as shown.

At (G) of Fig. 256, is shown the sharp peaked tuning curve (dotted) produced by a single sharply tuned circuit of the ordinary type. The solid curve shows the characteristic almost flat-topped curve 10 kc wide produced by a well-designed band selector.

In the band selector system described above, the two tuned circuits may be coupled together by an inductance as at (A) of Fig. 256 or they may be coupled by a condenser M as at (A) of Fig. 257. The degree of coupling is changed by changing the capacity of condenser M. Making this smaller, increases the capacitive reactance, and this makes the response curve broader due to the increased coupling, i.e., the peaks are further apart as shown at (B), (C), (D) etc. The closer the coupling, the further apart are the peaks and the greater is the dip between them. The opposite effect is secured by making the capacity larger. The reactance of a coupling coil increases with increase of frequency while that of a coupling condenser decreases with increase of frequency. Therefore the tendency of a coupling coil is to broaden the tuning at high frequencies and that of coupling condenser is to broaden the tuning at low frequencies. Since the lower frequencies naturally tune more sharply than the higher frequencies, the effect of using a condenser for coupling is to compensate for this frequency effect, with resulting more uniform width of response curve for all frequencies. Consequently, most band selectors of this type use a condenser for coupling. When used with tuning coils of the size generally employed for broadcast band reception, the coupling coil M need have only about 1.5 microhenries inductance, four to six turns of wire on a one inch diameter form being about right.

The selectivity of the circuit depends on the sharpness of the tuning in the two tuned portions, because sharp tuning preserves the steepness of the sides of the response curves. Sharp tuning depends on the reduction of all forms of resistance in the tuned circuits. The broadness of the response depends on the degree of coupling used between the two circuits, the closer the coupling, the broader the response curve. The width of the response curve depends also on the frequency being received, the curve being broader at high frequencies and narrower at low frequencies.

One of the simplest band selector circuits is shown at (G) of Fig. 257. In the plate circuit of the first tube is the parallel tuned circuit including L_1 and C_1. The plate circuit is completed through the condenser C_3, and the direct plate current for the tube is supplied through the choke. In the grid circuit of the second tube is another tuned circuit with a similar coil and condenser, L_2 and C_2. If coils L_1 and L_2 are separated, each tunes to the same frequency if C_1 and C_2 are equal, and of course no band-pass effect is obtained. If the coils are placed near each other so that the magnetic field set up by the current in L_1 links with the coil L_2, the two are *magnetically coupled* (designated by M) and a band-pass effect is produced, the arrangement becoming resonant for two different frequencies as explained for the previous circuits, the width of the band increasing as the coupling is increased.

The Vreeland band selector system is shown at (H) of Fig. 257. Here, two tuned circuits are coupled together through a mutual inductance consisting of a third coil L_3. The tuned circuit in the plate circuit of the first tube consists of C_1 L_1 and L_2. The tuned circuit for the grid circuit

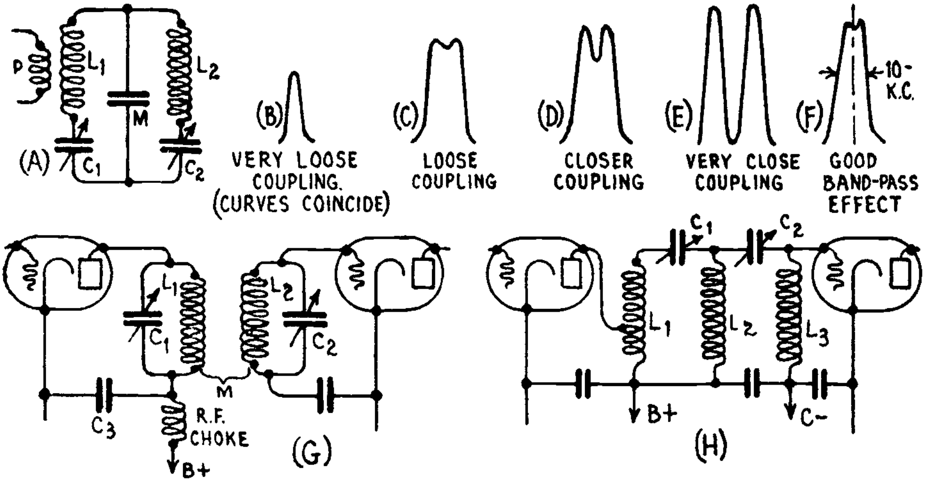


Fig. 257—Effect of coupling, on the resonance curves of band-pass filters. Several band-pass filter circuit arrangements.

of the second tube, consists of tuning condenser C_2, coil L_2 and coil L_3. In general, the action of this system is similar to that just described.

The capacitively coupled filter of (A) of Fig. 257 has one advantage in that the band width increases toward the low-frequency end of the tuning range where a somewhat wider transmission band is desired for equal transmission of the side frequencies. This is undoubtedly the principal reason why this type of filter is used in most commercial receivers that use band passing at all. Another reason for its use is that it is somewhat simpler, especially as compared with the common coil-coupled filter.

361. Applications of band selector system: The various band selector arrangements just described may be used in several ways in radio receivers. The arrangements shown in Fig. 256 and at (A) of Fig. 257 are often employed ahead of the first radio-frequency amplifying tube of tuned r-f amplifiers. In this position they are commonly called *pre-selectors.* They are also employed in a special type of receiver which will now be described. The arrangement of (G) is used extensively in the intermediate amplifiers of superheterodyne receivers. We will study this system later.

In the radio-frequency amplifier systems thus far described in this chapter, selectivity and amplification are secured at the same time by using successive amplifier tubes with a tuned circuit between each. Some receivers are designed to obtain this selectivity first, and then the amplification later. An example of this system is shown in Fig. 258. In this case, a band selector composed of several tuned circuits coupled together by means of coupling inductance M, is used to separate the signals of any wanted station from those of all other stations, and to transmit the wanted signals to an amplifier consisting of vacuum tubes coupled by untuned transformers, usually of 1 to 1 ratio.

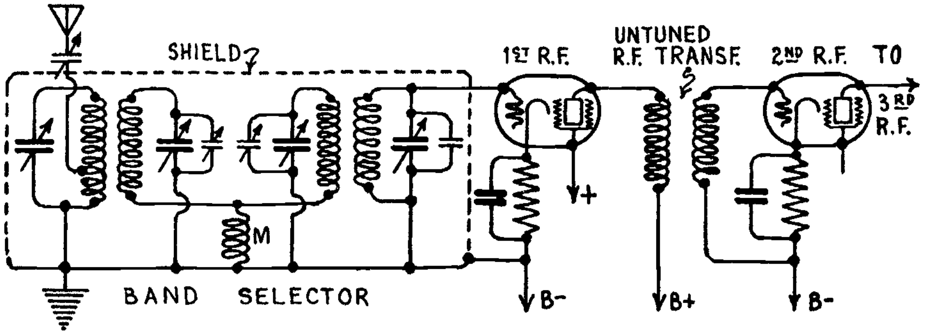


Fig. 258—A band-selector circuit employed in some receivers. All tuning is accomplished in the band selector. This is followed by untuned r-f amplifier stages.

Such an amplifier has no frequency discrimination, it amplifies all frequencies applied to it alike. It is not tuned at all—all tuning takes place in the band selector. An ordinary power detector and audio amplifier are used with the receiver. The outline diagram of this type of receiver was shown at (B) of Fig. 245. This type of circuit has been used successfully in many models of the Sparton and other commercial receivers. The practically "square-topped" tuning curve produced by the band selector eliminates sideband frequency suppression and aids in maintaining good audio tone quality.

362. Cross modulation and pre-selection: In the circuit diagram of the simple t-r-f receiver shown in Fig. 247, the signal voltages from the antenna circuit are fed to the grid circuit of the first r-f amplifier tube after being transferred to the tuned circuit L_2 C_2 by means of the antenna coupling transformer. In many receivers manufactured several years ago, a stage of fixed, untuned, radio-frequency amplification was employed between the antenna and the first r-f tube. This took the form of a resistor as shown at (A) or an r-f choke coil as shown at (B) of Fig. 259, connected directly in the antenna circuit and arranged so the varying voltage drop across it was applied directly to the grid circuit of the first r-f tube. The purpose of this arrangement was to eliminate the necessity of a tuned stage between the antenna and first r-f tube, since the tuning coil of such a stage would naturally be affected differently by the different inductances and capacitances of various antennas to which it might be connected, thus causing its tuning to be way off and preventing proper synchronizing of each section of the gang tuning condenser employed for single tuning control. Such a stage did not harmfully affect the operation of the receiver when a '27 type tube was used in the first r-f stage. The high negative grid bias (13.5 volts) used with this type of tube allowed quite a large signal voltage to be applied to the tube without danger of running the grid positive or operating on the curved portion of the E_g - I_p characteristic of the tube (see Figs. 243 and 244). With the adoption of the '24 type screen grid tube as an r-f amplifier, troubles immediately arose. Modern broadcast receivers no longer employ the fixed input stage, but employ a tuned input stage loosely coupled to the antenna circuit in order to overcome the effects of antenna variation. The reduction in the strength of the signal transferred to the receiver, is offset by the increased amplification of the screen-grid type tubes employed. The '24 type of screen-grid tube operates with a negative grid bias of only 3.0 volts (see Fig. 214). This means that a signal voltage having a "peak amplitude" of over 3.0 volts (see Art. 343), will drive the grid positive during each positive half of the cycle, with the result that a grid current will flow in the grid circuit and this will reduce the selectivity of the receiver. To understand how this takes place, let us refer to Fig. 259:

The condition of the grid circuit when a sufficient grid bias is employed to prevent the grid from ever becoming positive due to the signal voltage, is shown at (C). The grid-cathode path acts as a small condenser and as such has no loss effect on the connected tuning circuit. But if this grid become plus, due to excessive signal voltage, electrons will flow from the cathode to the grid circuit, and this whole grid-cathode path becomes a resistance each time the grid becomes positive, as shown at (D). This resistance is located directly across the tuning circuit and broadens the tuning characteristic to that shown in curve "C" in Fig. 179. Unfortunately this broadening effect takes place on strong local stations right where the greatest amount of selectivity is desired. The overloading of the grid of the '24 type tube so that it becomes positive on strong signals is illustrated by the E_g - I_p curves at (E) of Fig. 259.

With a standard '27 type tube or other low mu tube, a much larger negative grid bias voltage is employed than is used with the '24 type. For instance, the '27 type tube calls for a 13.5 volt bias, when it is operated as an amplifier with 180 volts on the plate. Such a negative bias permits a 13.5 volt maximum "peak signal-voltage" swing in the radio-frequency circuits before the grid swings positive. For the '24 type tube at a plate voltage of 180 volts, a negative grid bias voltage of about 1.5 volts must be used. Therefore this tube can only handle signals having a maximum "peak voltage" of not over 1.5 volts, otherwise the grid goes positive and broadness of tuning and other things explained a little later on, will give trouble. There is a considerable difference between 13.5 volts and 1.5 volts when it comes to allowable peak signal voltage.

The plate-current, grid-voltage characteristics of both the '27 and '24 type tubes are plotted on the same scales at (E). Since the '27 type tube has a much longer straight portion of the characteristic than the '24, it is evident that it can handle a much stronger signal without distortion, as shown by the signal curves below. Of course, the screen-grid type of tube is used in spite of this because of the high amplification that may be obtained with it, and also because it has much less tendency to oscillate, due to its low plate-grid capacitance. Granting that the screen-grid type of tube is to be used on account of its high amplification factor and freedom from grid-plate capacitance, several precautions must be taken in the circuits in which it is employed if distortionless amplification is to be obtained.

First, due to the rather crowded lower part of the characteristic of the '24 type tube as shown at (F) strong second harmonic frequencies are produced if the strong signal of a local station acts directly on the grid of the first r-f tube. If no tuning circuit is used,—or even if only a single tuned circuit is used,—between the antenna and the first r-f tube, the grid of this tube will have impressed upon it, the signals of practically all stations at all times, no matter where the tuning condensers of the following stages are set. Thus, a strong powerful local broadcasting station may be pounding onto the grid of the first tube with sufficient signal strength to actually cause the tube to work over the curved lower portion of its characteristic and cause rectification in the plate circuit of that tube. We know that any rectification or detection will create audio currents which represent the program on the carrier wave. In fact, this is the

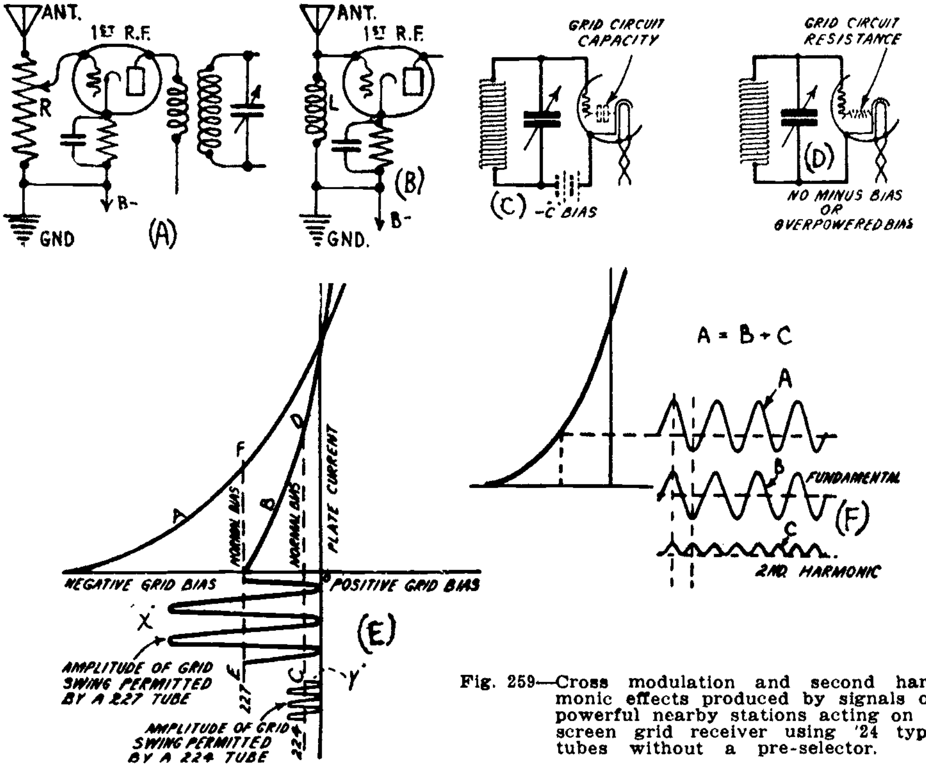


Fig. 259—Cross modulation and second harmonic effects produced by signals of powerful nearby stations acting on a screen grid receiver using '24 type tubes without a pre-selector.

entire action of the ordinary detector tube, and any tube, no matter how operated, will detect to some extent when the carrier signals are of sufficient strength to operate the grid at the lower bend. Thus, detection actually occurs in the first tube, and in appreciable amounts when the set is located near powerful local stations. The result of this is an effect commonly called *cross modulation* or *cross talk.* The local program may be tuned out all right on its own wavelength, but it will cause audio changes in the plate current. These will modulate the r-f variations caused by the signals of the station the receiver is tuned to. Thus the undesired local station program will be heard as part of the programs of all other stations received. This takes place regardless of how sharp the tuned circuits of the *following* stages are.

Another objectionable action which may take place is that of the production of second harmonic frequencies. We are already familiar with the fact that a curved E_g - I_p characteristic produces unequal amplification of the positive and negative halves of the incoming carrier signal voltage. This produces a lopsided amplified voltage in which the upper half is greater than the lower half as shown by curve (A) in (F). Such a voltage can be resolved into two voltages, both of which are symmetrical voltages. One has the proper frequency of the incoming signal and the other has twice the frequency. The latter is known as the *harmonic.* This second frequency which is just twice the frequency of the proper one, is actually created in the tube and the amount of it, for a given strength of signal, depends on the steepness of the characteristic curve. Obviously, the '24 type screen-grid tube is a much more prolific source of second harmonic disturbance than the '27 type tube, since the latter has a "flatter" curve—see (E).

A study of (F) shows that curve A, which represents the actual plate current variations produced in the plate circuit of the tube, is the signal of the frequency of the station which it is desired to receive, and to which the receiver is tuned. This, of course is resolved into curves B and C. Curve B being of the same frequency, is the one which will be selected by the tuning circuits set for this frequency or wavelength. The new voltage of curve C which exists due to the fact that the original voltage waveform has been distorted, is exactly twice the frequency of the original signal voltage. Twice the frequency, means one-half the wavelength, and when the tuning condensers are set at one half the wavelength, possibly while tuning for another station, this new wave will be picked out and the program will be brought in again at this new setting. The result is that due to the second harmonics produced, the strong local

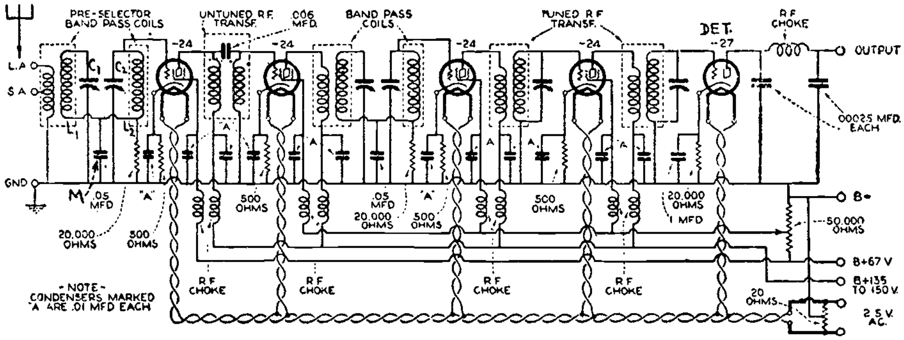


Fig. 260—A 5-tube t-r-f amplifier using screen-grid tubes and a pre-selector ahead of the first r-f tube. The pre-selector consists of a band-selector tuner.

station may be tuned in on two settings of the tuning condensers. Thus, even though it is say a high wavelength station, the fact that it is received again at a low wavelength setting may cause it to interfere with another low wavelength station operating near that frequency.

The remedy for these two effects, second harmonic generation and cross-modulation, is evidently to increase the selectivity ahead of the first r-f amplifier tube by coupling the antenna input through several tuned circuits to the grid circuit of the first tube. In this way, adequate selectivity will be obtained so that the signals of unwanted stations, even though they be powerful local stations, will not be strong enough after passing through the pre-selector tuner to either cause the grid of the first r-f tube to become positive, cause operation on the lower bend of the curve with resulting rectification and cross modulation, or cause second harmonics due to operation over the curved portion of the characteristic. The tuner arrangement is called a *pre-selector* because it "pre-selects" the wanted signals before they reach the first r-f amplifier tube.

Pre-selector circuits take several forms in practice but in most cases they consist of a band selector circuit with mutual inductive or capacitive coupling. A typical arrangement of this kind used in the r-f amplifier of an a-c operated receiver employing screen-grid tubes as amplifiers, is shown in Fig. 260. The audio amplifier and power supply unit of the receiver are not shown. Tuning coils L_1 and L_2 and condensers C_1 and C_2 form the band selector with the common coupling condenser M. It should be remembered that all pre-selectors cause some reduction in the signal voltages of the stations they are tuned to, also due to the losses in the tuned circuits, loss of energy through imperfect coupling, etc. Of course the losses in well-designed circuits is less than in poorly designed ones; in the latter a reduction of signal strength of as much as 75 per cent may take place. The loss caused by well-designed circuits is not objectionable, since it can be made up for by more amplification in the r-f amplifier.

It is not to be inferred that all screen-grid receivers without pre-selectors suffer from cross-modulation. There are installations where small receiving antennas with resulting small signal pick-up are employed, with the result that the signals from local stations are not picked up strongly enough to cause cross-modulation. Also many receivers are operated in districts far enough away from all local stations so that extremely powerful local signals are not received. Also if variable-mu type screen-grid tubes are employed, the effects of cross-modulation and second harmonic production are very much reduced, due to the fact that this type of tube can handle an extremely large signal voltage without rectification or second harmonic distortion, due to its long E_g - I_p characteristic (see A of Fig. 230). Many receivers using variable-mu type r-f tubes are constructed without any pre-selection other than a single loosely coupled tuned stage between the antenna circuit and the grid of the first r-f tube. Cross modulation effects are very seldom troublesome in these, due to the characteristic of the variable-mu tube. This important feature has resulted in the extended uses of these tubes in modern radio receivers.

363. Variable tuning condensers: Variable condensers which are used extensively for tuning the fixed inductance coils in radio-frequency tuning circuits, to any carrier frequency within the receiving range of the set, consist of a group of stationary plates (stator) arranged so that a set of movable plates (rotor) can be moved in and out between them without touching. The dielectric (the space between them) is air.

Condensers of this type were described in detail in Articles 150 to 154. The reader is advised to review these at this time. When the plates are fully meshed, as shown at (A) of Fig. 98, the full areas of the plates are exposed and the *maximum* capacitance exists. When they are all out of mesh at (B), the minimum capacitance exists; and for any intermediate position between these as at (C), various intermediate values of capacitance exist. Tuning condensers are usually made with thin brass or aluminum plates supported by a rigid framework of brass or aluminum. The stator plates are held in position and insulated from the frame by insulating strips (see Fig. 99). The stator and rotor plates should not touch, for a short-circuit would then result. Rotor bearings should work smoothly and the entire condenser should be rigid.

The end of the tuning circuit which connects to the control grid of the r-f amplifier tubes, should always be connected to the *stator* plates of the tuning condenser. The other end is connected to the *rotor* plates, which are usually grounded to the metal shaft and frame of the condenser. Since this latter end of the tuning circuit goes to the B- or ground side of the circuit, connecting it this way automatically places the shaft and frame of the tuning condenser at or near ground potential. Then no capacity exists between the condenser shaft and the body of the operator (which is also at ground potential), when it is to be rotated during the process of tuning. If the rotor shaft of the condenser were connected to the *grid end* of the tuning circuit, the capacity action between the body of the operator and the condenser shaft and rotor side of the tuned circuit, would form a capacity which is in effect really across the tuned circuit, since the other end is at ground potential through the B- line and ground. This would cause the resonance frequency of the tuned circuit to vary, de-

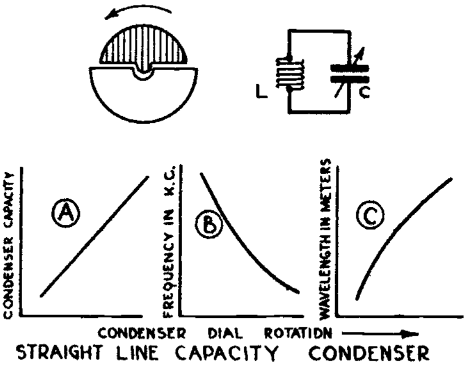


Fig. 261—The capacitance of a condenser may be made to vary directly as the angle of rotation of the rotor plates, by using semi-circular rotor and stator plates.

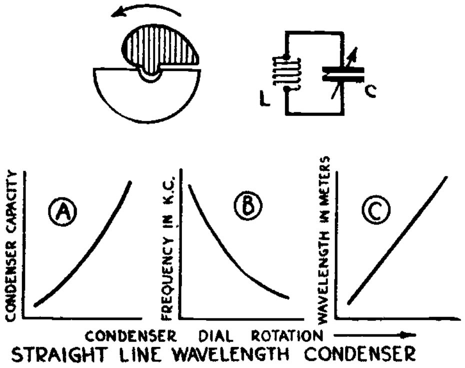


Fig. 262—By tapering off the diameter of the advancing edge of the rotor, the angle of rotation may be made to vary directly as the *wavelengths* of the tuned circuit.

pending on how near the hand was to the condenser shaft, and this would cause a de-tuning action known as *hand-capacity* effect. This condition was very troublesome in old forms of receivers in which the condenser shaft was not grounded. On some receivers, after a station was tuned in, it would fade out completely (be de-tuned) as soon as the hand was removed from the tuning knob which was fastened to the rotor shaft.

364. Shapes of condenser plates: The capacity-variation of the usual form of variable condenser is caused by changing the amount of interleaving of the plates and hence the area between them. The rate at which the capacity changes as the plates are rotated depends on the shape of the plates. There are four well known shapes at the present time, devised to secure certain tuning characteristics when used with a coil in a tuned circuit. Each of these has certain definite applications either in radio receivers or testing equipment, etc.

365. Straight line capacity condenser: Fig. 261 shows a condenser with semi-circular rotor and stator plates.

In a condenser of this type it is obvious that the capacity is proportional to the angle of rotation of the rotor, or settings of the condenser dial. That is, for equal increases of rotation, equal increases of capacity are obtained. Therefore, it is called a *straight-line* capacity condenser. If a graph is plotted with dial settings against capacity, it is a straight line. Now if this condenser is connected to a fixed tuning coil L in the usual way, as the condenser is varied the circuit is tuned to various frequencies.

The variation of the resonant frequency with condenser dial settings is shown at (B). The curve becomes steeper at the lower end of the scale, showing that a given rotation of the dial near this end produces a much greater change in frequency or wavelength of the tuned circuit it is used in, than an equal rotation at the upper end of the scale. Therefore, since the carrier frequencies of broadcasting stations in the same vicinity differ by at least 10 kilocycles, it will only require a small rotation of the condenser shaft and rotor plates to change the resonance frequency of the tuned circuit 10 kc to tune from one station to the next, at the lower end of the scale (high frequencies). Hence, if a tuning condenser having semi-circular plates is employed in a radio re-

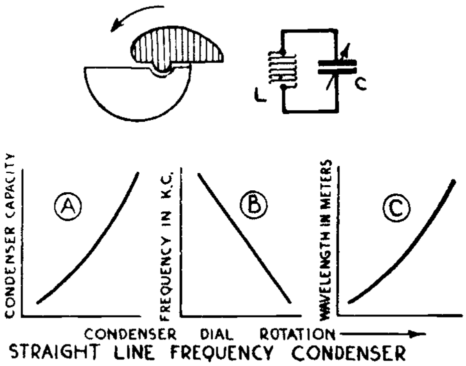


Fig. 263—By properly shaping the plates the *resonance frequency* of the tuned circuit may be made to vary directly as the angle of rotation of the rotor plates.

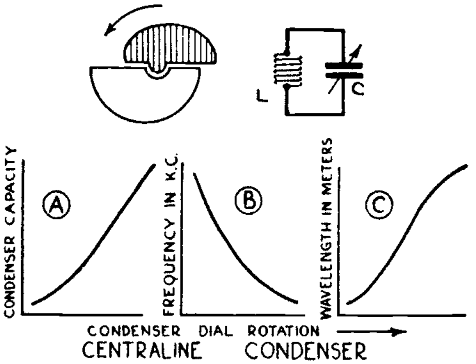


Fig. 264—Proper shaping of the plates produces a *"Centraline"* or *"Midline"* tuning curve which is most suitable for the tuning circuits of radio receivers.

ceiver, a great many stations will be received over a small crowded portion of the dial at the low wavelength end, making it necessary to set the tuning condenser extremely accurately if only a single station is to be received at a time. Therefore this simple plate shape is used very little in modern radio receivers. It is useful however, in laboratory and testing work where equal increases of capacitance are desired for equal angles of rotation of the rotor plates.

366. Straight line wavelength condenser: Many years ago, a type of condenser having a plate shape such, that equal angles of rotation of the rotor plates produced equal changes in the *wavelength* of the tuned circuit, (see Fig. 262), was used extensively in wavemeters, designed to measure the wavelength of transmitting stations, etc. This is called a *straight-line wavelength* condenser. This made a convenient form of condenser for the purpose, since the dial could be calibrated directly in wavelength and equal divisions on it would represent equal changes in wavelength.

An attempt to reduce the crowding of stations at the low wavelength region of the tuning scale in broadcasting receivers, was made by using tuning condensers having plate shapes designed to produce straight-line wavelength tuning variations. Since the wavelength-rotation curve is a straight line as at (C), a given change in dial setting anywhere produces the same change in wavelength. But the carrier waves of broadcasting stations are not separated by equal wavelengths, so that actually with this type of condenser the low wavelength stations are still crowded at the lower end of the dial, although there is a decided improvement over the S. L. C. type. The stations at the upper wavelengths are also crowded. However, the separation of the stations around the middle of the dial is practically perfect. This type of condenser is useful in wavemeters or oscillators where it is desired to have the dial reading proportional to the wavelength.

367. Straight-line frequency condenser: The *straight-line frequency* variable tuning condenser (S. L. F.), is designed with a plate shape which makes the rotation of the dial proportional to the resonance *frequency* of a tuned circuit in which it is used. With this type of condenser (Fig. 263) stations separated by 10 kilocycles in frequency come in at equally separated points on the dial. The trouble is that the high power broadcasting stations are distributed, in general, over the upper end of the scale. Hence it is of great importance that the latter be separated properly. The S. L. F. condenser does not do this, but rather crowds both the higher wavelength stations and those around the middle band, under the present station locations and frequency separations. Therefore it does not quite solve the problem of spreading the received stations out uniformly over the tuning dial of the receiver. This type of condenser is useful in oscillators and wavemeters or frequency-meters, where it is desired to have equal divisions on the dial indicate equal changes in the frequency.

368. Centraline tuning condenser: Condensers having rotor and stator plate shapes such as to produce a desirable compromise tuning curve when used in the tuning circuits of radio receivers, have been designed and are in common use. These condensers commonly known by such names as "Centraline" "Midline", etc., are designed to eliminate the disadvantages possessed by the other forms described by employing special plate shapes which give a composite tuning curve, that is, give approximately S. L. F. tuning at the low end of the dial, S. L. W. tuning at the center region, and S. L. C. tuning at the upper wavelengths. A study of the curves in Fig. 264 will show this.

These desirable tuning characteristics can be secured by irregular shaping of either the rotor plates, stator plates, or both. The physical dimensions of the condenser should be kept small, so that not much space will be required when installed in a receiver. A rotor plate shape designed to produce this effect is shown in Fig. 264 and at the right of Fig. 265.

It is evident that the effect of the S. L. W., S. L. F., and Centraline condenser plate shapes is strictly a slow-motion action on the capacity variation, having a variable reduction and gradually changing as the condenser is advanced. The same result can be accomplished by a slow-motion vernier dial constructed to automatically vary its reduction ratio to give the effect of any of these shaped plates when used with an S. L. C. condenser, but shaping the plates to produce the desired result is a much cheaper and simpler method for it costs no more to punch out condenser plates with special shapes than it does to punch out semi-circular plates, after the proper punching dies have been made up.

The illustration of Fig. 265 shows one of each of the types of condensers described, showing the shapes of the plates used in each. As explained in Article 150, variable condensers used in receiving sets are made in various capacitance values, some of which have become fairly well standard in the United States. Also they are made in single sections or in gang form, with 2 or more sections arranged to be varied in capacity by the movement of a common rotor shaft as shown in Fig. 100 and at the left of Fig. 268.

369. Reduction of tuning controls: A study of the circuit diagrams of multi-stage t. r. f. amplifiers already studied shows that the

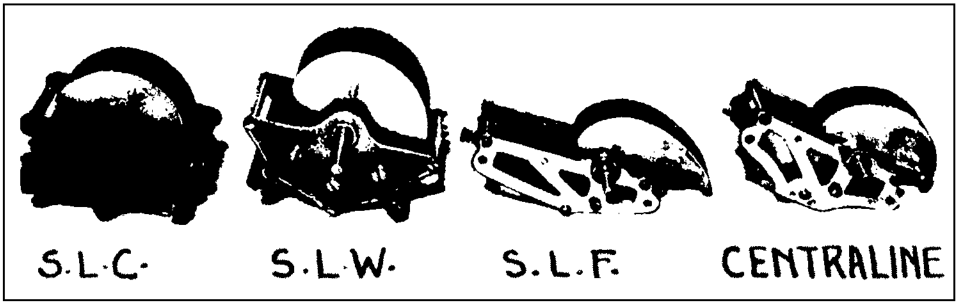


Fig. 265—Four tuning condensers designed to produce various definite capacity-variation and tuning characteristics by using the various plate shapes shown.

tuning of the receiver from one station to another is accomplished by rotating the rotor plates of the several tuning condensers. Referring, for instance to the simple 3-stage t-r-f amplifiers of Fig. 247, we see that in order to tune from one station to another, the shafts and rotor plates of condensers C_2, C_3, and C_4 must be turned in order to obtain the proper capacitance value *in each tuned circuit*, to tune the receiver to the frequency of the new station. If three condensers with separate shafts and controls were used for C_2, C_3, and C_4, this would mean that three condenser knobs or dials would have to be manipulated simultaneously.

It is rather awkward to manipulate 3 things carefully, and in step with each other, with two hands. Now the tuned circuit L_3 - C_3 works out of the plate circuit of the first r-f tube and into the grid circuit of the second one, (a similar tube). The same thing is true of tuned circuit L_4 - C_4. Therefore, if the coils L_3 and L_4, the condensers C_3 and C_4, and all stray capacitances and inductances associated with the tuned circuits are exactly similar, the two condenser settings will be exactly similar when any station is tuned in. Therefore some means can be employed to mechanically couple or *gang* the rotor shafts of these two condensers together, so they may be turned exactly in step with each other by a *single* knob or tuning *control*. We will consider the various mechanical schemes possible for ganging, presently.

It is important at this point to see just what stray inductances and capacitances may be present in either of the two tuned circuits considered. If we analyze the simple tuned grid circuit shown at (A) of Fig. 266, we find that actually it is not as simple as it seems. There are several additional capacities acting in the circuit, as shown at (B). Here we have the pure tuning inductance L, and the total circuit capacitance C consisting of the sum of the following capacitances.

d=effective capacitance from coupled input circuit.
e=distributed capacitance of the coil winding.
f=capacitance of the tuning condenser proper.
g=input grid-cathode capacitance of the vacuum tube and the capacitance between all wiring to the grid and cathode.
h=capacitance between the coil, wiring and any metal near the coil, such as shielding, etc.

Now the capacitance d, will vary with the degree of coupling and the type of input circuit, i.e., whether it is an antenna or the plate circuit of a preceeding tube; e and h will vary with type of coil winding, shape of coil, spacing, size of coil, size of shield, etc.; g will vary considerably with the type of plate loading. It is evident that in order to obtain practical single-control of the tuned r-f stages, in the receiver, *not only must the tuning coils and condensers be accurately matched, but these various stray circuit capacitances must also be kept similar in value in each stage.*

When we come to the antenna input stage several other factors enter into the problem of single-dial tuning control.

370. Effect of antenna on single-dial tuning control: It has already been shown in Fig. 179 that an antenna acts together with the earth to form a condenser. For high frequency currents there is some inductance in the straight aerial, lead-in and ground wires. It follows that an antenna has both inductance and capacitance, distributed along the length of the wire. Therefore the antenna really forms a series tuned circuit as shown at (B) of Fig. 179.

The *fundamental frequency* of an antenna is that for which the maximum possible current will flow, when no additional coils or condensers, etc are connected to it. It can be shown mathematically that when the length (in meters) of an antenna of the single wire vertical or L type is approximately one-fourth of the wave length (in meters), the fundamental frequency is that for which the sum of the inductive and capacitance reactances are zero. The length of an L type antenna includes the length of the horizontal portion plus the total length of the lead-in and ground wires.

Example: It is desired to erect an inverted L antenna which is to have a fundamental wavelength of 400 meters. What must be its total length?

Solution: 1 meter equals approximately 3.3 feet. Therefore 400 meters equal approximately $3.3 \times 400 = 1{,}320$ feet. Therefore the total distance from the ground up through the ground lead, the antenna lead and the horizontal top portion, should be about $1320 \div 4 = 330$ feet. In practice the length may vary considerably from this value.

The wavelength to which any resonant circuit is tuned may be increased by increasing either its inductance or capacitance. The wavelength of an antenna is therefore increased by connecting an inductance or *loading coil* in series with it, since then the actual inductance in the circuit is the sum of the inductances of the antenna and the coil. If a condenser is connected in series with the antenna, the wavelength is decreased, since now the combined capacitance of the antenna itself and the capacity in series with it is less than that of either alone.

When we connect the receiving antenna to the input tuning coil therefore, we have the condition shown at (C) of Fig. 266. The antenna capacitance C_A and the antenna inductance L_A are acting in series with the primary winding P of the antenna coupling coil. It is evident that the tuning circuit consisting of L_1 C_1 must work under somewhat different conditions than L_2 C_2 due to the effect of the antenna capacitance and inductance on the circuit. The capacitance of the antenna circuit acts like a similar condenser C_s connected across a portion of the secondary. Therefore, to tune the antenna system through the broadcast band, and yet use a gang condenser for all the tuned circuits including the antenna, a different type of tuning condenser would be required for each individual an-

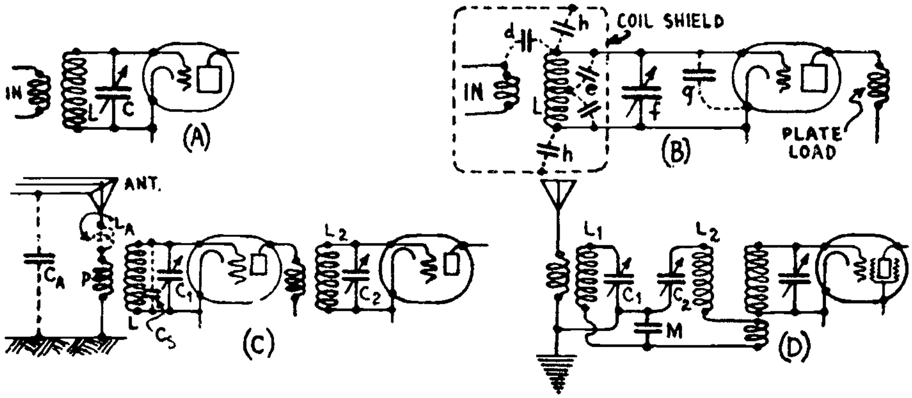


Fig. 266—Study of the effect of antenna circuit capacitance, and stray capacitances, on the tuning circuits of a t-r-f amplifier. These are important in single-control receivers.

tenna system which the set might be used with. This would be commercially impractical.

371. Antenna coupling systems: One remedy for this condition would be to leave the antenna stage untuned, and couple it to the first r-f tube by any of the arrangements shown in Fig. 267.

At (A) the first r-f tube is coupled to the antenna by a resistance of about 2,000 ohms. The varying voltage drop appearing across the end of the resistor due to the flow of the varying antenna circuit current, is applied to the input circuit of the first r-f tube commonly called the "coupling tube". This tube does not add any amplification to the circuit, but acts merely as a coupling device. With this arrangement the antenna constants have little or no effect upon the tuning of the following circuit. However, an untuned antenna stage usually produces harmonics and "cross modulation" due to rectification being set up in the first r-f tube by strong local signals as explained in Article 362. The audio currents produced in its plate circuit modulate the incoming r-f signals of all other stations, and thus the local station signal is heard as a modulation on all other stations received.

If a variable resistor R is employed as at (B) it can also be used as a volume control by varying the fraction of its total resistance and voltage drop which is included in the grid input circuit of the tube. Another method where an r-f choke coil is used to produce a potential difference between the grid and cathode is shown at (C). In some cases it has been possible to secure a small voltage step-up in the coupling tube T by utilizing a choke coil connected between the antenna and ground which, in conjunction with the average antenna (capacity about 150 to 300 mmfd., inductance from 50 to 100 microhenries, and resistance of 25 to 100 ohms), tunes to approximately 200 or 300 meters, and provides a voltage step-up in the neighborhood of four at resonance, and diminishing to about one for the remote frequencies. Unfortunately all that can be said for all of these types of antenna coupling is that they solve the single-control problem. They contribute nothing to the selectivity of the receiver, since they accept signals of all frequencies, excepting the case of the choke coil coupling. The latter may contribute some voltage gain if the inductance of the choke tunes the antenna capacitance to some frequency in the broadcast band. The amplification thus secured is confined, however, to a narrow band of frequencies around this fixed resonant frequency. At all other frequencies the gain is practically nil. Also the frequency at which some gain is obtained due to resonance will vary with different antennas.

All of these methods are very liable to cause "cross modulation" as explained above and they are seldom used in modern receivers, although many receiver models manufactured several years ago did employ them on account of their simplicity and effectiveness in eliminating the effect of the antenna circuit on the tuning of single-control receivers. In recent models of commercial receivers, the problem has been met in two ways. One is to use a variable inductance or "variometer" having a high ratio of maximum to minimum inductance, in the place of the fixed choke coil at (C), this variometer tuning the antenna circuit to resonance for the frequency of each station being received. While this type of tuned antenna input circuit applies about 3 times as much signal voltage to the grid of the first tube as the untuned antenna system does, it has the objection of adding an extra tuning control to the receiver. Many receivers now use an aperiodic (untuned) antenna circuit with an r-f transformer as shown at (C) and (D) of Fig. 266.

There are two types of antenna transformers in use, one having a high-impedance primary and the other a low-impedance primary. Both of these transformers, when properly designed, give good selectivity characteristics, gain, and practically freedom from cross-talk. They also satisfactorily meet the problem of antenna-stage tracking for single-control sets. In the high-impedance primary type, the primary of the transformer is usually slot-wound and has an inductance of the order of 400-700 microhenries. It tunes the antenna capacity to a low frequency just outside the broadcast band. Long-wave gain due to resonance is therefore high in comparison to the short-wave gain. Very loose coupling of the order of 10 per cent is employed. Antenna reaction reduces the effective secondary inductance, but owing to the very loose coupling employed, this is of small magnitude, and easily compensated. The gain of

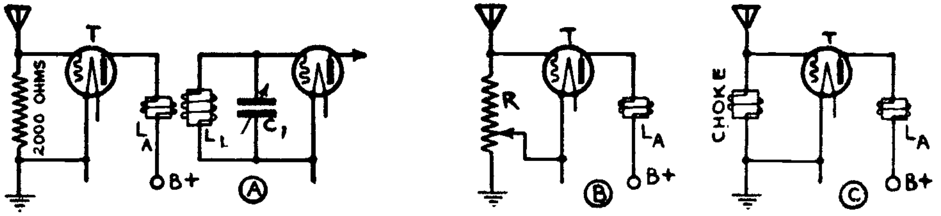


Fig. 267—Several methods of "direct coupling" the antenna circuit to the grid circuit of the first r-f amplifier tube.

this system decreases with increasing frequency, but this tends to straighten out the over-all gain curve of sets employing conventional type r-f interstage transformers.

The antenna transformer with low-impedance primary, was the most widely used system in battery sets, some years ago, especially two-and three-control sets. The primary consisted, generally, of about 6 to 20 turns (depending upon the type of transformer employed). The coupling coefficient was as high as 40 per cent and it was necessary to resort to very tight coupling in the antenna stage in order to get better transfer of signal voltage at the upper wavelengths. However, this tight coupling was unsatisfactory at the lower wavelengths. First the capacity reflected from the antenna circuit into the secondary was so great that it was not always possible to tune the first stage down to 1500 kilocycles. In the second place, the loading due to the antenna, and the dielectric loss between the primary and secondary were both increased, resulting in very poor selectivity characteristics for the first stage. It was, therefore, necessary either to reduce the coupling by reducing the primary turns by means of a tap on the primary, or to shorten the antenna electrically by the use of an antenna series condenser. The use of a single antenna connection was therefore not satisfactory over the entire frequency band.

Of course, loose coupling between the primary and secondary of the antenna coupling transformer means that only a small portion of the signal energy in the antenna circuit is transferred to coil L_1 and the grid circuit of the first tube. It does however, effectively reduce the effect of the antenna on the tuning of the first tuning condenser C_1 to such an extent, that this condenser may be ganged with the other tuning condensers. Designers of broadcast band receivers at least, have preferred to make up for this loss by employing more radio-frequency amplification in the set—this being a rather simple matter when high-gain screen-grid variable-mu vacuum tubes are employed. When a pre-selector or band-selector system is used, as shown at (D) of Fig. 266, the same loose coupling between the antenna circuit and secondary L_1 of the tuning coil may be employed.

In some cases a small variable condenser is connected in series with the antenna as shown in Fig. 258. This not only reduces the effective capacitance of the antenna (since it is in series with the antenna capacitance), but also permits some adjustment of the effective total antenna capacitance when different lengths of antenna are used. This condenser usually takes the form of a "midget" condenser of from .0001 to .0005 mf.

372. Condenser ganging: After the circuit arrangements and constants of the r-f amplifier have been satisfactorily worked out in accordance with these conditions to permit simultaneous tuning of all stages by a single control of the tuning condensers, the problem resolves itself into devising some mechanical arrangement for turning the rotor shafts of all of the tuning condensers simultaneously by means of a *single tuning control.*

Several mechanical arrangements have been devised for this purpose, but only two of them are still employed to any extent. Arrangements in which the shafts of the separate tuning condensers were connected through racks and pinions, systems of parallel arms and levers or cranks, or by flexible metal belts and pulleys have been used. Of these methods, the latter is the only one which has survived. In this, each condenser shaft is provided with a pulley which is driven by a flexible phosphor bronze belt with tension adjustment, from the main driving pulley. This in turn is controlled (usually with a step-down ratio), by a single tuning knob.

The more common method because of its cheapness, compactness and simplicity, is to build all of the condenser sections into a single frame and with a common rotor shaft, so that motion of this single rotor shaft turns all of the rotor plates simultaneously. This is called a *gang condenser.* Of course, a condenser of this type may be built with as many sections or gangs as desired. A 4-gang condenser of this type was shown in Fig. 100. A 5-gang tuning condenser is shown at the left of Fig. 268. A grounded flat metal plate (electrostatic shield) between each section of the gang reduces the capacitance which exists between adjacent stator sections when the rotor plates are turned out. As will be seen from the chart of radio symbols in Appendix A, a gang condenser is indicated by the common stator-plate line. In some cases, the condenser sections are each shown separately, but the rotor plates are connected by a dotted line. At (B) of Fig. 268, the connections of the secondaries of five r-f transformers to the individual sections of the 5 gang condenser are shown. The primaries are omitted for simplicity. The connection of each tuned stage to the grid of the amplifier tube is also shown. Note that the rotor and frame of the condenser form the common grid-return side for all the tuned circuits. A 5 tube t.r.f. amplifier in which several tuned circuits are tuned by a gang condenser is shown in Fig. 260. This permits the simultaneous tuning of all the circuits at once by merely turning a single knob or dial fastened to the condenser shaft.

373. Equalizing the circuits: In order to obtain maximum sensitivity in receivers using gang control of tuning condensers, it is absolutely essential that every tuned stage in the amplifier be tuned to exactly the same frequency for any one setting of the dial. This means that when once the various stages are adjusted to tune in step with each other, they should continue to "track" together over the entire range of the receiver. If one or more of the stages tunes to a higher or lower frequency than the rest, that stage is not set at exact resonance to an incoming signal when the others are, and therefore it produces less amplification than it otherwise would. In order to make the various tuned stages track up perfectly, it is necessary that the total of the capacitances and inductances in each tuned circuit be exactly equal. This means not only the capacitance of the tuning condenser and the inductance of the tuning coil but also all of the stray inductances and capacitances which may affect the tuned circuit, as shown at (B) of Fig. 266.

The first essential of success with gang-controlled receivers is that all the condenser sections in the gang have the same *rate* of *capacity change* at all settings, that is, over the entire tuning range of the circuit. All the condensers do not have to have the same maximum capacity, for any differences in this respect can be compensated in the inductances. But it is preferable that all the sections be equal, for if they are, there is a better chance that all the sections will have the same rate of capacity change at every setting.

If condensers having semi-circular plates (S.L.C.) are used for tuning, the adjustment for bringing various stages into step can be made by providing suitable adjustments enabling the entire set of rotor plates of any one condenser to be advanced or retarded in order to increase or decrease the capacitance at all settings or by adding small compensating condensers in parallel with the tuning condensers. If this is done with condensers having other plate shapes (as S. L. W., S. L. F., and Centraline), the capacities become unbalanced as the tuning dial is advanced. This is due to the fact that in these forms of condensers the *capacity variation per dial division increases* as the condenser is turned toward maximum capacity, and the unit which was advanced gains capacity more rapidly than the others. This can be partly avoided by keeping all the rotor plates exactly in step and making up for any inequalities by means of small compensating condensers which can be set and left fixed, thus adding a constant capacity to each circuit, as explained in Article 152. This method is not entirely suitable however, for it is very possible that the tuned circuits may be adjusted to be exactly in step for one frequency and they will be out of step at other frequencies if the various sections of the gang condenser do not vary in capacity *at similar rates* as the condenser setting is varied. This action was very noticeable on the early forms of single control receivers which employed simple gang condensers, with a small compensating condenser built into each section of the condenser. The tuned stages could be adjusted to track perfectly at any one small range of frequencies but they would be out of step for frequencies above and below this. As a compromise, receivers of this kind were tracked up accurately at but one setting at the center of the tuning range, but of course the sensitivity for all settings above and below this was much lower.

One way of eliminating this very objectionable feature, is to have one of the end rotor plates of *each section* split radially or fan-wise to form about 5 or 6 segments, as shown in the condenser of Fig. 268. The tuning of each of the various circuits can then be aligned at 5 or 6 separate points equally distributed over the entire tuning range by slightly bending the slotted segment which is just entering the stator plate area. If it is bent toward the stator plate the capacity is raised; if it is bent out, the capacity is lowered. This may be done while a station of that frequency is being re-

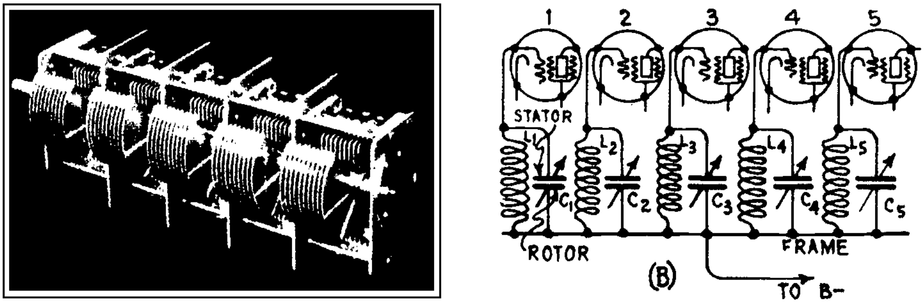


Fig. 268—Left: A 5-gang tuning condenser. Notice the slotted rotor plate at the end of each section.
Right: Connections of the secondary windings of 5 r-f tuning coils to the 5 sections of a 5-gang condenser in a single dial receiver.

ceived, or while a signal from a local test oscillator is being impressed on the receiver. The condensers are considered to be adjusted properly when maximum output is obtained. Since the ear is rather insensitive to changes in intensity of sound, more accurate adjustments may be made by employing an output meter such as that shown in Fig. 153 for indicating the output of the set during the adjusting process rather than relying on the loudness of the sound issuing from the loud speaker as judged by the ear.

As it is rather difficult to bend the segments delicately and accurately by hand, one form of gang condenser employs a set-screw arrangement shown in Fig. 269. The set screws go through a solid plate fastened to the rotor shaft. They are arranged so that the end of one screw presses against each section of the slit plate. By turning the screw, the segment it rests against can be pushed in or out by a very small amount if necessary. Adjustment is usually made with the receiver tuned to 1120, 840, 700, 600 and 550 kilocycles. The five positions of the rotor for these adjustments are shown in the illustration.

When a gang condenser is used, the coils must be carefully wound and matched, in order to minimize any inequalities between them. In spite of careful manufacture, they are bound to differ slightly so the coils must be tested and the inductance value adjusted before they leave the factory.

One simple way of doing this is to wind the coils with the inductance slightly larger than the value required. Then they are tested and the inductance may be brought down to the exact value required by sliding a few of the end turns outward toward the end of the coil so they are more widely spaced, thus placing them in the weaker part of the field and thereby slightly decreasing the inductance. This is shown at (G) of Fig. 79, and is a very simple and effective means of producing slight reduction in the inductance. Of course if the inductance is much too high, some turns of wire must be removed altogether, if it is much too low, turns must be added. A coil having too low an inductance requires more tuning capacity for any given frequency than those of proper value do. One whose inductance is too high requires less tuning capacity than those of proper value do.

If metal shielding is used around the coils, it will also affect the inductance, as does any metal object or conductor which may be in the field of the coil. The fact that the surroundings of a coil affects the inductance indicates the necessity of putting all the coils in similar settings. For example, shields around or near a coil will change its effective inductance, and this change depends on the frequency. The change is usually a decrease in the inductance, because of the bucking effect of the induced *eddy* currents in the shielding. The remedy for any inequality from this effect, obviously, is to mount every coil in the same manner with respect to shielding. And since different metals will react differently it is important that every shield should be of the same type and thickness of metal. (Note: Shielding is discussed in Arts. 412 to 414.)

Still another reaction effect is that of the primary on the secondary. The mutual inductance between the primary and the secondary will change the effective induc-

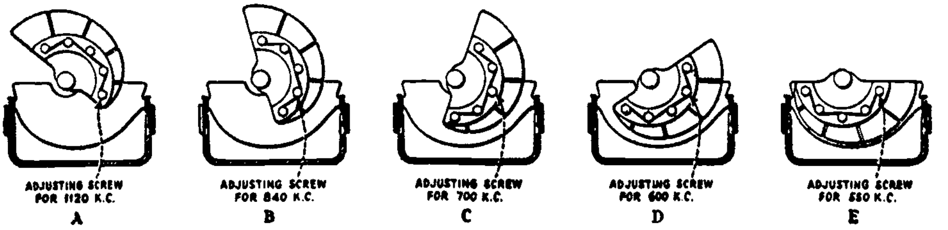


Fig. 269—Slotted condenser end-plate construction with set-screw adjustment for tracking up the tuning. The rotor is shown in 5 different positions at which the segments are adjusted to align the tuned circuits.

tance of the secondary and hence the required capacity to tune the secondary to a given frequency. This demands not only that the primaries be equal but that they be placed in the same manner with respect to the secondaries, unless loose coupling is employed between the primary and secondary coil as in the case of the antenna coupling transformer. Not only that, but it demands, as a rule, that the primaries be preceded by the same type of tube similarly operated. This effect also depends on the frequency and therefore it is somewhat troublesome. The inductance value of a coil is changed by the presence of other conductors in the field. The distributed capacity is constant as long as the coil is fixed in position, and therefore the distributed capacity adds to the zero setting capacity of the condenser and can be compensated for by the trimming condensers.

The actual procedure to be followed in adjusting or "aligning" the tuned stages in receivers employing gang condensers will be considered in detail in Articles 632 to 639 in Chapter 35. Illustrations and circuit diagrams of receivers employing gang condensers for single-control will be found in the chapters on Superheterodyne Receivers, The Battery Operated Receiver and Electric Receivers.

374. Purpose of the volume control: We have proceeded with our progressive study of tuned radio-frequency amplification to the point where we are ready to consider the various forms of volume or gain controls which may be utilized to control the loudness of the sound issuing from the loud speaker.

Assuming that our receiver employs a detector preceded by several stages of radio-frequency amplification, and followed by one or more stages of audio-frequency amplification (which will be studied presently), it would seem that some form of volume control device could be introduced either in the r-f amplifier or in the audio amplifier, so as to reduce the signal voltages applied to the amplifier tubes. The volume control in a complete radio receiver is seldom placed entirely in the audio amplifier for the simple reason that even if it were turned down to a low setting when a strong local station were being received, the last r-f amplifier tube, or the detector tube, would be overloaded, with resulting distortion, since the full amplified r-f signal-voltage is being applied to these. The volume control

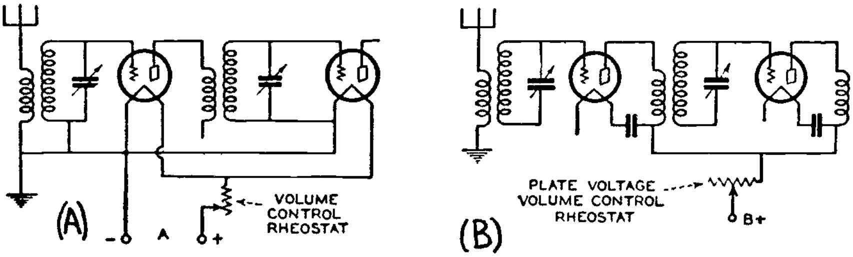


Fig. 270—(A) Simple battery receiver volume control by varying the filament voltage. (B) Volume control by varying the plate voltage.

is therefore placed before the detector tube, in order to prevent overloading of these tubes under such conditions.

The volume or gain control unit in a receiver is utilized in most cases to reduce the volume of strong signals. For weak signals, it is usually set at maximum. Volume control methods and arrangements have passed through a series of changes in the past few years due to changing designs of receivers and the change from battery operation of receivers to a-c electric operation.

Receiving sets are being designed with sensitivities of the order of 1 microvolt per meter. That is, when a signal voltage of 4 millionths of a volt is produced in the receiving antenna, a "normal" (mildly comfortable) loud speaker signal is produced when the volume control is set at its maximum volume position. Such an antenna signal might conceivably be produced in an antenna located several hundred miles from a powerful broadcast station. This same antenna and receiving set located in a more favorable position, say one-half mile from the broadcast station, might conceivably have induced in it as large a signal as 1 volt or more, at least 250,000 times as great a signal as in the preceding case. Obviously such a signal would cause severe overloading of all the tubes unless it were controlled. In order to obtain a "normal" signal from the loud speaker with this 1 volt input signal, a signal reduction or *attenuation* of 250,000 would have to be caused by the volume control in one way or another. Also, when the volume control is set at its minimum-volume position, no signal should be heard. The volume control must then introduce additional attenuation to completely extinguish the "normal" signal produced after attenuating a 1 volt antenna signal 250,000 times. If we assume this additional required attenuation to be four, the total attenuation required of the volume control amounts to 1,000,000. In other words, the volume control must be able to effectively control various signals which may differ as much as 1,000,000 to 1 in intensity.

375. Volume control arrangements: Volume control should not be obtained by detuning the tuning condensers from the exact point of resonance when a station is being received, for that is apt to bring in interference from other stations which are thereby being tuned in. It should be obtained by a form of control which does not affect the tuning. Various volume control arrangements using non-inductive resistors will now be described.

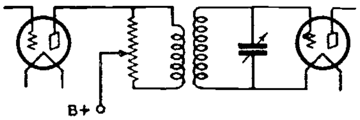
Possibly the most simple form of volume control used extensively in battery operated receivers, consisted of connecting a simple wire-wound rheostat of the order of

4 to 20 ohms, depending on the type and number of tubes controlled, in series with the filament circuit of the radio-frequency or detector tubes, as shown at (A) of Fig. 270. By controlling the filament current, the emission and amplification of these tubes was controlled. While this method of volume control is satisfactory for use with battery operated receivers, it is unsuited for those using separate-heater type tubes, because the cathode element has such high thermal inertia that there is an appreciable time-lag between the filament current changes, and the temperature and emission. When the signal became too loud, the vol.-control would be adjusted. Owing to the thermal inertia nothing would happen for a while. When the cathode finally reached its constant temperature corresponding to the changed current, the signal would suddenly drop and it would then probably be too low. The volume control would then be turned up and the same thing would happen, except that now the signal might now be too great or still not loud enough. After a few adjustments, the proper setting would be found. Obviously, such a control would require a rather objectionable amount of manipulation.

In receivers of this kind, the problem permits of either of two practical solutions. Either the reduction in signal voltage must be accomplished between circuit elements, such as for example between the antenna and first tuned circuit, or between tuned circuits and tubes. This may be accomplished by connecting a simple non-inductive potentiometer, or variable resistance, across one of the circuit elements. The other method consists in providing a control of the amplification of the amplifier tubes. This latter method is used extensively, especially when variable-mu tubes are used as r-f amplifiers, for the amplification factor and mutual conductance of this type of tube can be varied over wide ranges simply by varying the control-grid bias voltage.

At (B) of Fig. 270, a variable resistance of some 100,000 ohms maximum value (depending on the type and number of tubes controlled) is connected in series with the "B" supply of the r-f tubes. This controls the volume by raising or lowering the plate voltage applied to the tube. This system has little to be said in its favor, for as the resistance is changed, the plate current in the tube, as well as the actual voltage applied to the plate is varied. If too low a voltage is applied to a radio-frequency tube, it becomes a detector, and consequently distortion takes place. Also it is difficult to reduce the volume down to very low values, when powerful local stations are being received.

At (A) of Fig. 271, another system somewhat similar to the preceding one is shown, except that in this case a variable resistance of the order of 10,000 ohms is in parallel with the primary of one of the radio-frequency transformers. This gives a smoother control of volume, but in addition to the disadvantages of the previous method, the sharpness of tuning of the secondary of the radio-frequency transformer is reduced unless the resistor has a high value. This is because of the increase of load on the secondary when the primary is partially or totally short circuited by the volume



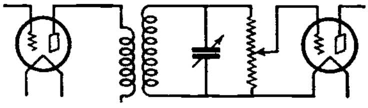


Fig. 271—(A) Volume control by means of a potentiometer connected in the plate circuit of an r-f amplifier tube. (B) Volume control by means of a potentiometer connected across the secondary of an r-f transformer.

control resistor. If a high value of resistor is used to avoid this shunting effect, the plate voltage of the tube will be reduced considerably.

At (B) of Fig. 271 a volume control potentiometer is connected across one of the tuned circuits of the receiver in such a way that any proportion of the total signal voltage developed across the tuned circuit may be applied to the grid circuit of the amplifier tube. The objection to this is the fact that the shunting effect of the resistor across the tuned circuit tends to reduce the volume and cause broad tuning. To reduce this it is necessary to use potentiometers having a resistance from ¼ to 1 megohm. The need for such high variable resistances which must be noiseless—as far as possible—and which must vary non-uniformly with respect to angular rotation, prohibits the use of wire-wound resistances, and has led to the extensive use of the graphited-paper type of unit. With the volume control connected across a tuned circuit or its equivalent, the condition should be met that the loading introduced across the tuned circuit should be constant, even though the volume control is varied. This condition obviously eliminated the use of a straight variable resistance across a tuned circuit, for as the volume is gradually reduced a smaller and smaller resistance shunts the tuned circuit, with consequent elimination of the selective and gain properties of the circuit. With the volume control in this position of the circuit, it was there-

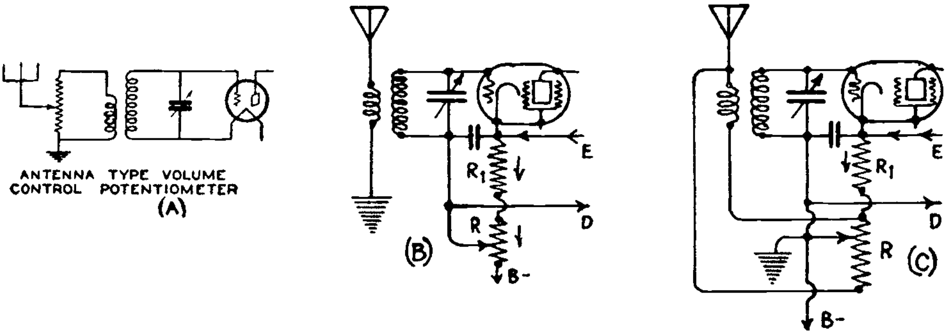


Fig. 272—(A) Antenna type volume control.
(B) and (C)—Volume control by means of a variable grid-bias resistor in the cathode circuit of the first r-f tube.

fore essential that a potentiometer type of control be used, which imposes a fixed resistance load across the tuned circuit. Another objection to this form of volume control is that all potentiometers have some capacity across their terminals, 8 mmfd. being a real low value for this. This means that besides a resistance being placed across the tuned circuit, a capacity is also added. In the case where a number of tuning condensers are being run from the same shaft, as is the case in single-control receivers, the tuning of this circuit would be thrown out of alignment, and small capacities would have to be placed across all the other variable condensers for exact alignment. Of course, this is not an insurmountable difficulty, but simply one which is objectionable in quantity production of radio receivers.

In the old forms of receivers using untuned directly-coupled antenna circuits, the volume control shown at (B) of Fig. 267 was quite popular. With this arrangement, a potentiometer of 2,000 ohms or so acted both as the untuned coupling device and the volume control. In receivers using an antenna coupling transformer, the arrangement shown at (A) of Fig. 272 has been extensively used. The potentiometer of about 25,000 ohms resistance, makes it possible to apply any fraction of the total signal voltage induced in the antenna circuit, to the primary of the coupling transformer. This type of volume control is effective only if the receiver is completely shielded so that no signals can be picked up without an aerial. Otherwise, signal voltages from local stations may be set up in the r-f coils and wiring in the set. Obviously, in such cases, the stations will be heard even if the volume control is set at minimum value. Another objection is the fact that when this form of volume control is employed, the ratio of noise to signal may be very great when the volume is turned down. The reason for this will be evident from the following considerations. Noise which appears in the output of a receiver is the result of noise picked up outside the receiver and noise which originates in the receiver proper. The former is independent of the circuit position of the volume control, while the latter is not. Receiver noise, apart from hum, is a combination of tube noise and circuit element noise, and is more or less a fixed quantity for any given receiver. These noises modulate the carrier wave which is present in the receiver, and they therefore show up in the loud speaker output. When volume is adjusted by an antenna control only, the signal amplitude fed into the receiver *input* is reduced, whereas the amplitude of the noise originating in the receiver is at its full value (since receiver amplification is maintained at its maximum value), and we have a high degree of "noise modulation." If however, a stronger signal is fed into the input of the receiver, and the volume is adjusted by a control located in the radio frequency amplifier beyond the antenna, the relative degree of noise modulation is smaller (since the noise is the same but the signal amplitude is greater); and secondly, the volume adjustment reduces the noise and the signal together, so that the ratio of noise to signal is reduced. It should be noted that the volume control is effective in reducing the noise-signal ratio to the extent that it is removed from the antenna stage, since it is effective in reducing noise (for a given output) originating ahead of it, but not that originating in the parts of the receiver circuit following it. Hence the nearer it is located to the detector circuit the less will be the noise present.

A realization of this fact has led some circuit designers to favor a dual volume control consisting of one part placed in the r-f amplifier circuit and one part in the audio circuit, both being operated from the same shaft. The idea is, that when the volume is reduced by reducing the r-f signal, the audio amplification, noises and hum due to the a-c operation, are also reduced. While this arrangement has many commendable features it has not been generally adopted on account of the increased cost and wiring complications and the fact that since the trend of receiver design is toward greater r-f amplification and less a-f amplifiication, the advantages gained by the control in the a-f amplifier become less.

When separate-heater screen-grid type r-f amplifier tubes are used, there are several additional methods of controlling volume. Volume can be controlled in this type of tube (as it can also in the '27 type tube) by varying the grid bias voltage applied to the r-f tubes as shown in the simplified method at (B) of Fig. 272. By increasing the grid bias voltage (making it more negative), the mutual conductance and therefore the amplification of these tubes is reduced, thereby diminishing the volume. By using this control on the r-f tubes in a receiver, almost complete control of any signal encountered in practice may be obtained. For this purpose, a variable resistor R is used in the cathode-return circuit as shown. If two '224 screen-grid tubes are controlled, R should be about 10,000 ohms. If four are controlled it should be about 5,000 ohms, etc. As more resistance is inserted into the circuit by moving the contact arm, the negative grid bias voltage is increased and the amplification factor and mutual conductance are decreased. In series with this variable resistor is a fixed resistor R_1 for limiting the minimum bias voltage, (which is the bias value prescribed by the tube

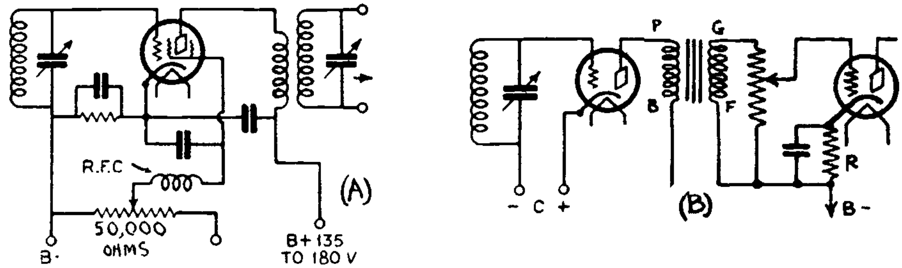


Fig. 273—(A) Volume control by screen-grid voltage control obtained by the use of a potentiometer in the screen-grid circuit. (B) Volume control in the audio circuit by means of a potentiometer connected across the secondary of the first a-f transformer.

manufacturers). If this resistor were omitted, when the volume control resistor was turned to the end at full volume position, no resistance would be in the circuit, the grid bias voltage would be zero and the signal would cause grid current to be drawn by the tube, with resulting distortion and broad tuning. An improvement on this form of volume control is shown at (C). The peculiar connection from the bottom of R to the primary of the antenna coupling transformer helps to give excellent control for very low volumes. As the moving contact on R is moved downward to decrease the volume, a smaller and smaller proportion of the antenna-to-ground voltage is being applied to the primary coil because the slider, (which is connected to ground) is moving toward the antenna end of resistor R, and therefore the signal *input* to the receiver is reduced. This combination control reduces the antenna pickup enough so that the usual modulation effects due to strong local stations are greatly diminished. A resistor having a tapered variation of resistance should be used for circuits of this kind. If this antenna-shorting action is not desired, the bottom end of R should simply be connected direct to B minus as shown at (B). In both (B) and (C), the wire marked E connects to the cathodes of the other r-f tubes, and wire marked D connects to the grid-return circuits of these tubes.

The volume can also be controlled by varying the screen grid voltage as shown at (A) of Fig. 273 when screen-grid tubes are used. Moving the arm of the potentiometer of 50,000 ohms or so, varies the voltage applied. Either of these last two methods give satisfactory control when ordinary screen-grid tubes are employed, only provided the signal input to the first tube is not too great. For loud signals, such as are produced in the vicinity of local broadcasters, either of these methods is unsatisfactory, not because they do not give complete control, but because distortion is introduced. As the volume is reduced by varying the negative bias, a point is reached at low output where the tube is operated at the lower bend of its E_g - I_p characteristic, and the tube acts as a grid bias detector, producing severe distortion of the signals. This can be corrected only by reducing the input signal to the first r-f tube by means of an antenna volume control, which must necessarily be used in conjunction with the C-bias or screen-voltage adjustment in order that complete control of loud signals may be secured. This requires a double volume control which is of course undesirable.

When variable-mu type screen-grid tubes are employed, the volume control method of (B) of Fig. 272 works very satisfactorily, without the troubles encountered when it is used with ordinary screen-grid tubes. In order to utilize the full volume control range of the '35 or 551 type tube, the volume control resistor should be of such value as to apply a maximum grid bias voltage of approximately 50 volts depending upon the circuit design and operating conditions. It will be remembered that one of the features of this tube is that the mutual conductance and amplification factor for high negative grid bias voltages are very low, (see Fig. 230).

Volume control in audio amplifiers used for public address work or for phonograph-amplifier combinations usually consist of a 500,000 ohm potentiometer connected across the secondary winding of the first audio transformer as shown at (B) of Fig. 273. This provides a smooth volume control since any fraction of the signal voltage induced in the secondary winding may be applied to the grid circuit of the tube.

This resistance will actually tend to improve the tone quality of the receiver, since, if a rather poor transformer is being used, it will smooth out the amplification curve and make it quite flat. This unit should have a maximum resistance of about 500,000 ohms, and should always be placed across the first audio transformer. It is then possible, on strong signals, to cut down the volume and prevent overloading of even the first audio tube. However, if the resistance were connected across the second transformer, it would not be possible to prevent overloading of the first tube. Connection across the first transformer is therefore advisable.

The ideal volume control is one which smoothly and uniformly controls the sound emitted from the speaker from a whisper to a maximum intensity. The control should not allow any of the tubes in the set to overload, and in fact it should not change the electrical characteristics of any part of the receiver in any harmful way.

The resistor used must provide a smooth control, so that it can be operated without audible evidence of its use beyond that of changing the volume. There must be no scraping, rustling, or clicking, and at no point must there be a sudden increase or decrease of volume. The change of volume as judged by the ear must, as far as possible, be spread out uniformly over the full range of the control.

376. Automatic volume control: In all of the volume control systems just described, the control must be operated manually by turning a volume control knob. Automatic volume control systems have been designed for use in radio receivers, in order to reduce the necessity for continual manipulation of the volume control knob. The use of automatic volume control means that once the adjustment for the desired sound output level is made normally, by setting the volume when the loudest local station is being received, tuning the receiver through local and distant stations will not produce sudden loud blasts of sounds when tuning in the carrier wave of a strong station. If the distant station is much weaker than the local station, so that the maximum amplification of the receiver will bring the signals up to the necessary strength, the station will be heard at the desired volume level, otherwise it will be heard faintly. The very weak stations are not brought up to the volume of the strong one unless the receiver is capable of amplifying their signals enough to bring them up to this level. This is an important point to remember. In this sensitive condition, the receiver will of course greatly amplify all stray electrical disturbances that may come in with the signal and noisy reception may result.

In receiving programs from certain stations, "fading" causes a great deal of annoyance. With good automatic volume control, the receiver sensitivity is shifted simultaneously with the received field strength of the transmitter, so as to maintain a constant output level. The disadvantage of course, is that the "noise" output due to stray electrical disturbances which may also be received, remains constant.

One automatic volume control system which has been used, employs a two-element detector tube whose direct current component of plate current is made to flow through a resistor and the voltage drop thereby obtained is made to vary the grid bias applied to the r-f amplifier tubes and so vary the amplification, (see latter part of Art. 313). The audio-frequency variations in the detector plate current are filtered out from the steady direct current. A stronger signal strength tends to increase this direct current. This changes the voltage drop across the resistor, thus changing the bias voltage applied to the control-grid circuits of the r-f tubes so as to decrease the amplification (see explanation referring to (B) and (C) of Fig. 272).

A simple automatic volume control arrangement devised by Mr. A. C. Mathews, Jr. and which can be used on existing receivers employing '24 type screen-grid tubes is shown at (A) of Fig. 274. This employs a '27 type tube whose function is to automatically vary the *screen grid* voltage applied to the '24 type tubes used in the r-f amplifier. It is connected to the receiver by simply breaking the screen-grid voltage supply lead at the r-f tubes and connecting the lower wire to the screen-grid instead. The top wire is tapped on to the grid of the detector tube.

In order to properly control the volume, the screen grid potential must be made variable over a considerable range. Manual variation under this system is achieved by adjusting the bias of the volume control tube by means of the 50,000-ohm potentiometer provided. The plate current passing through the resistance in the plate circuit provides the necessary drop to vary the voltage over the required range. The voltage on the screen grids, and in consequence the volume, is thereby reduced. A signal applied to the grid of the control tube reduces the bias and consequently increases the plate current, providing an automatic decrease in gain. The constants of the circuit must be so proportioned as to function rapidly—but the electrical inertia must still be great enough to avoid any possibility of "swamping out" low-frequency modulations, as these are slow changes in the amplitude of the signal. Since the volume-control tube must have its plate at the same potential as the screen-grids of the r-f amplifier, it is necessary, in order to obtain the correct plate voltage on the '27 volume-control tube, to take off voltage taps at —60 and —80 volts on the power-supply unit. This puts a potential of approximately 135 volts on the plate with respect to the cathode.

Since it is rather difficult with a system of this kind to know when the receiver is tuned exactly to resonance, because the volume seems the same over several divisions of the dial, a 0-5 d-c milliammeter is usually included in series with the plate of the volume control tube, so as to give visual evidence of the resonance point, by a maximum deflection of the pointer. In a commercial receiver of this design a shunt across the speaker terminals is used while tuning, so that the volume is reduced to a mere whisper. With the meter to indicate whether the circuits are in resonance with the carrier, the speaker gives evidence as to whether that carrier is modulated, for the meter will show a reading on the unmodulated carrier. This enables the person operating the receiver to tune the set exactly to the desired carrier, even if it is at an extremely low output level.

At (B) of Fig. 274 a different version of an automatic sensitivity

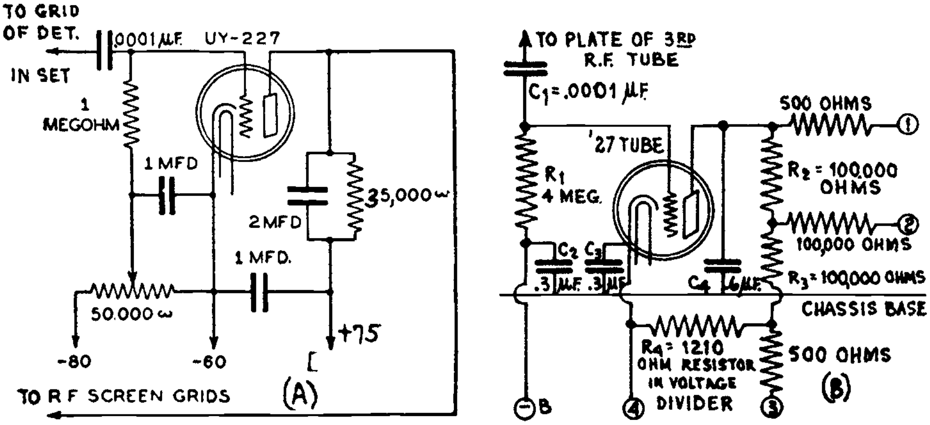


Fig. 274—(A) Automatic volume control system for screen-grid receivers. An additional '27 type tube is used. (B) System used on Stromberg Carlson models 12 and 14 screen-grid receivers.

control is shown. This is a simplified diagram of that used in the Stromberg-Carlson models 12 and 14 receivers, in connection with the 3-stage t. r. f. screen-grid amplifier employed in them.

In this the control tube is a 227, the grid of which is connected through a 0.0001 mfd. condenser to the plate of the third radio-frequency tube, which is a 224 screen grid tube. The grid return is connected to B minus, the most negative point in the circuit, and the cathode (4) is connected to a point on the voltage divider which is positive with respect to B-minus, but negative with respect to ground. The voltage between B minus and (4) is the steady bias on the control tube, which makes it a grid-bias or plate-bend detector.

The signal voltage impressed on the grid varies the direct current component in the plate circuit of the control tube and the drop in the resistors R2 and R3. Point (1) is connected to the grid return of the first screen grid radio-frequency amplifier, point (2) to the grid return of the second, and point (3) to the grid return of the third tube. It is only the bias on the first two 224 type r-f tubes that is varied automatically, the first by the amount of drop in the two resistors R2 and R3 and the second by the amount of drop in R3 alone. Thus the degree of control varies for the two tubes, being greater for the first tube than for the second. This is called "tapering of the bias."

A condenser C4 of 0.6 mfd. is connected across the plate circuit of the control tube to filter the carrier from the direct current component. Other by-pass condensers to aid in the filtering are C2 and C3, each of which has a value of 0.3 mfd.

The resistors of 500 and 100,000 ohms in the leads to the r-f tubes, are included to suppress any oscillations which might be set up in them. Terminal (1) connects to the grid return of the first r-f amplifier tube; (2) connects to the grid return of the second radio frequency amplifier tube; (3) connects to a point on the voltage divider 3 volts negative with respect to the chassis and the ground. The resistance between (3) and ground is 100 ohms and is in the main voltage divider; (4) connects to a point 1,210 ohms below (3) on the main voltage divider; (B–) connects to the negative side of the B supply circuit, which is separated from (4) by 260 ohms.

A point to observe in this control arrangement is that the most negative point of the B-power supply unit is not grounded as is customary, but the ground is placed at a point 1,750 ohms higher up. This is done so as to get the proper voltages on the control tube with reference to the voltages applied to the tubes in the amplifier.

The voltage between any two taps depends, of course, on the current taken from the various taps, and the circuit is not applicable without suitable change to any receiver. The receiver in question contains three 224 screen grid radio-frequency amplifiers, one plate-bend 227, high signal detector, one 227 audio-frequency amplifier, and two 245 power amplifiers in push-pull, transformer coupling being used throughout the audio amplifier. A milliammeter connected in the cathode circuit of the secondary r-f tube acts as a visual tuning meter as described for the previous system. This type of control gives excellent signal input voltage. The output remains practically constant at 100 arbitrary units between inputs from 100 to 5,000 microvolts. Below 100 microvolts the output drops rapidly and therefore 100 microvolts has been set as the input at which the control tube "takes hold." At 5,000 microvolts the output begins to rise rapidly as the input increases, but even at 10,000 microvolts the output has not yet doubled.

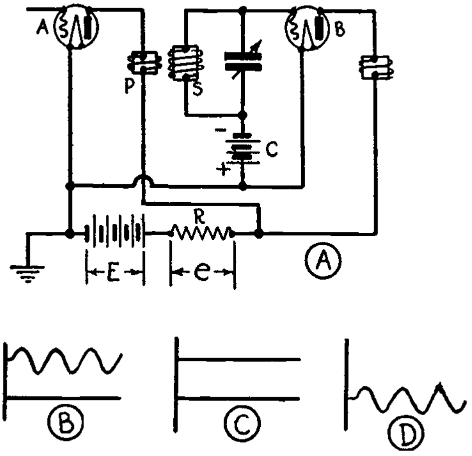
The advantage of the automatic feature is obvious. A signal of 100 microvolts is a very weak signal and one of 10,000 microvolts is a comparatively strong signal. Yet the variation in the output does not vary as much as 2 to 1. If the normal signal intensity of a station is around 2,000 microvolts, there is practically no variation in the output even if the input falls as low as 100 microvolts and rises as high as 5,000. Fading under these conditions will practically be absent and the only effect that the fluctuations would have on the received signals would be a rise and fall in the proportion of stray noises, (rising as the signal faded out and falling as it came back).

It is evident that the automatic volume control feature in a receiver is much more effective if variable-mu (super-control) type tubes are used in the r-f or i-f amplifier than if ordinary screen grid tubes are employed (see Art. 313).

377. Coupling in the "B" supply: When a receiver utilizes a single source of plate voltage for more than one stage (as is almost always the case) coupling between stages may take place through the resistance of this voltage source, as shown in (A) of Fig. 275. New "B" batteries have a very low internal resistance, but when they become old and discharged their internal resistance may increase to as much as 1,000 ohms. This is due to resistance of the active material between the zinc cylinder and carbon rod of each of the small dry cell units. In a 45-volt "B" battery there are 30 of these cell units connected in series, so the total internal resistance is equal to 30 times the resistance of each unit. Layerbilt batteries have a much lower resistance due to the wider cross-sectional area of the active material.

"B" power supply units used in electrically operated receivers, all use some form of resistance for a voltage dividing device, and the plate currents of the various tubes must flow through this resistance, which often amounts to several thousand ohms (see Articles 509 to 511). In either case the internal resistance may be considered as a resistance R in series with the power supply device (here shown as batteries for simplicity).

The resistance R is included in the common plate circuit of both tubes A and B. It should be remembered that R is really in the "B" voltage supply unit but it is shown outside for simplicity in the diagram. The plate current of either of the tubes varies somewhat in the manner shown at (B) due to the signal. This is a varying current flowing in one direction. This varying plate current flowing through R will produce a varying voltage drop *e* across it. The effective voltage acting on the plate at any instant is equal to the *e. m. f.* of the "B" voltage supply minus the voltage drop due to its internal resistance, that is, E — e. Therefore the effective plate voltage applied to the tubes is also varying, thereby varying the plate current. The varying plate current of tube B, when flowing through R produces a varying voltage drop across R which causes variations in the plate current of tube A. These are transferred to the secondary S, by the primary P, and are therefore re-impressed on the grid circuit of tube



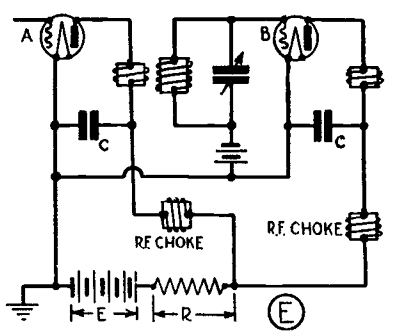


Fig. 275—How interstage coupling may occur in the common impedance of the "B" power supply unit. It may be prevented by means of the choke coils and by-pass condensers shown at (E).

B. In other words, signal-variations in the plate circuit are re-impressed on the grid circuit and are re-amplified. *Regeneration* is thereby produced. If the coupling resistor R is large enough and the circuit losses are low enough, the tube may act as an oscillator thus interfering with reception. The same action occurs among the various other tubes in the receiver. Also in screen-grid tubes, since the positive screen-grid voltage is also obtained from the "B" power supply unit, coupling of this kind can also take place in the screen grid circuit.

Obviously the cure for this interstage coupling is to eliminate the pulsations in the current flowing through the "B" power device E. This is accomplished by the simple low-pass filter arrangement shown at (E), where an r-f choke coil is connected in each plate lead, and a by-pass condenser C connects around to the B– side or cathode of the circuit. Since the action is the same as has already been described for the choke and condenser filter connected in the plate circuit of a detector, this will not be considered again. The condenser merely acts to smooth out the variations in the current flowing through the "B" power unit, thereby preventing the *varying* coupling.

R-F chokes for this purpose are usually of about 85 millihenry size, as shown at the right of Fig. 124. In r-f circuits, by-pass condensers of from .2 to .5 mf. are commonly employed. Condensers for this purpose are shown in Fig. 276.

In order to serve as an efficient by-pass to prevent undesirable coupling, the impedance offered by a condenser to currents of any given frequency must be considerably lower than the impedance of the apparatus around which it is desired to by-pass the current.

For most efficient operation, it is important that the by-pass condenser be connected as close to the points between which the current is to be by-passed as possible. While the use of by-pass blocks which include two or more condensers in one unit is economical in by-passing several circuits or circuit branches, this method should only be used when the circuits which are to be by-passed are close together so that long leads are not required to connect the condensers across the points to be by-passed. In general, better results will be obtained if individual by-pass condensers are connected *directly* across the terminals to be by-passed.

In audio circuits the same action may take place. The use of a filter in the plate circuit also helps here. The size of the chokes and condensers employed must of course be larger, since the frequency of the pulsations is much lower than in r-f circuits.

In general, common coupling in the B– power supply unit is more serious in receivers designed for high amplification per stage than in others, because any stray varying voltage getting back into a previous stage is amplified greatly and may cause the entire circuit to oscillate.

378. Automatic tuning and remote control: Automatic tuning of radio receivers either by rotating selector dials or by push-buttons or levers, has been accomplished by several systems which are in use. These are of two general types—those in which a separate lever is provided for selecting each station which the receiver has previously been adjusted to receive; and those in which a selector dial controls the tuning to any point on the dial. In both systems, the tuning condensers are rotated by an electric motor to the exact position required for reception of the station. In the former, the number of stations which may be received depends on the number of plungers provided, although additional stations may be brought in at points in-between by means of an ordinary tuning dial provided. In the latter, any number of stations (within the range of the receiver) may be tuned in at any point on the dial at will. These systems have not become generally popular for use in homes, due to their complications and cost. Midget type receivers are so inexpensive that it has been found more practical to use several such receivers in a home in which it is desired to provide radio reception in several rooms. These provide the

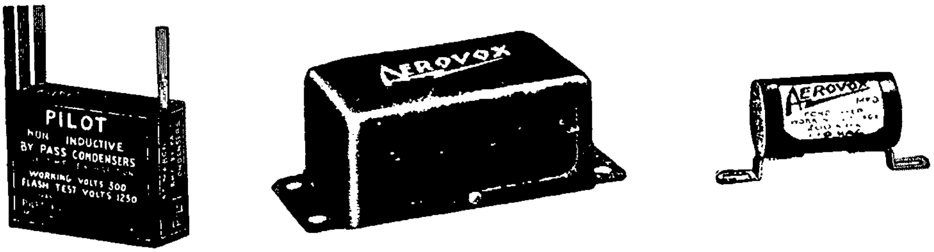


Fig. 276—Several by-pass condensers used in radio receivers. Left: 3-section condenser, each section is .2 mf. Middle: 4-section condenser with common terminal. Right: Compact, tubular form of by-pass condenser made in sizes from .01 to .1 mf.

added advantage that different programs may be received on the different sets in the various rooms at one time.

379. The superheterodyne receiver: While the superheterodyne tuner may be properly classed as a special form of radio-frequency amplifier system, it will be considered separately in the next chapter on account of its special circuit features and importance. Then, in the following chapter the design of inductance coils, tuned circuits, and shielding methods will be studied.

REVIEW QUESTIONS

1. What is meant by the term "radio-frequency amplification?"
2. Why is r-f amplification used in most modern radio receivers? What other form of amplification could be used?
3. What factors determine how much r-f amplification is required in a receiver?
4. State and discuss the requirements of a radio receiver for receiving broadcasted programs, for home entertainment.
5. What is meant by the term (a) microvolts per meter, (b) field strength?
6. What signal strength in microvolts-per-meter is required at the receiving antenna for year-round high-class reception?
7. An antenna 100 feet high has induced in it a signal voltage of 30 microvolts. What is the strength of the field surrounding the antenna?
8. Draw an outline diagram of the main parts of a simple t-r-f. receiver system and explain the advantages and disadvantages of the system.
9. Repeat question 8 for a receiver employing a band selector followed by several stages of untuned r-f amplification.
10. Explain (with diagrams) three methods of coupling successive amplifier tubes in t-r-f amplifiers and discuss the advantages and disadvantages of each.
11. Why is the variable-mu tube considered such an excellent r-f amplifier?
12. Since the resistance-coupled amplifier is so simple and inexpensive, why is it not used in r-f amplifiers?
13. Draw a circuit sketch illustrating the use of parallel-feed plate supply in the plate circuit of an r-f amplifier tube. What are its advantages?
14. Explain why the use of several similar tuning circuits in a receiver increases the selectivity.
15. Why is a straight-sided square-topped tuning response desirable in radio receivers?
16. Explain the operation of one form of band-pass tuner or "band selector".
17. What is the effect on the width of the band passed, as the frequency is increased in a band selector using (a) capacity coupling; (b) inductive coupling?
18. Explain in detail what is meant by cross modulation, and how it may be produced. What are its effects? What must be the form of the E_g - I_p characteristic of a tube which produces severe cross modulation effects. What must be the form for one which does not produce them. What type of tube fulfills (a) the first condition; (b) the second condition?

19. What is a S. L. C.; S. L. W.; S. L. F.; Centraline frequency, condenser?
20. How is single-dial tuning control obtained in receivers employing a number of tuned stages of r-f amplification?
21. What is a gang condenser? What is a compensating condenser and what is it used for?
22. How may the tuned circuits in a single control receiver be matched practically?
23. Why must the tuned circuits in a single control receiver be matched exactly? What happens if they are not matched exactly?
24. What is the reason for slitting one of the end plates in each section of a gang condenser?
25. What effect does the antenna have on the tuning of the first condenser of a receiver employing a tightly coupled antenna coupling transformer? How may this effect be reduced by changing the design of the transformer?
26. Why is a volume control used in radio receivers? What is the difference between a manually operated volume control and an automatic volume control?
27. Draw circuit diagrams for five types of volume controls which have been used in radio receivers, and explain the operation, advantages and disadvantages of each type.
28. Draw a desirable volume control circuit for a t-r-f receiver employing three variable-mu screen-grid r-f tubes.
29. What are the relative advantages of (a) placing the volume control ahead of the detector; (b) placing it after the detector?
30. Explain how coupling between amplifier stages can take place in the "B" power supply unit and how it may be eliminated. Why is it objectionable?

CHAPTER 22

SUPERHETERODYNE RECEIVERS

REVIEW OF T-R-F SYSTEM — THE SUPERHETERODYNE SYSTEM — ADVANTAGES OF THE SUPERHETERODYNE SYSTEM — "BEAT FREQUENCIES" — THE "BEAT" ACTION IN A SUPERHETERODYNE — THE R-F AMPLIFIER IN THE SUPER — IMAGE FREQUENCY — DESIGN OF THE R-F AMPLIFIER — THE OSCILLATOR — SINGLE CONTROL OF THE TUNING CIRCUIT — CHOICE OF THE INTERMEDIATE FREQUENCY — THE INTERMEDIATE AMPLIFIER — THE SECOND DETECTOR — "REPEAT" POINTS — THE "AUTODYNE" — FREQUENCY CHANGERS — ADJUSTING THE CIRCUITS OF A SUPERHETERODYNE — REVIEW QUESTIONS.

380. Review of t-r-f system: In the tuned radio-frequency amplifier system, which we studied in Chapter 21, a number of tuned amplifier stages are adjusted, usually by a single dial, to the different frequencies of the stations it is desired to receive. Considering receivers of this type designed to work on the usual broadcast band, it is evident that the tuned circuits are so designed that they may be adjusted to tune to any frequency between 1500 kc (200 meters) and about 545 kc (500 meters). The signal voltage is induced in the antenna circuit; is then amplified by the r-f amplifier; is detected or demodulated (changed to audio-frequency) ; and is finally amplified further by one or two stages of audio amplification, the output from the audio amplifier supplying the loud speaker. This system is shown in simplified form at (A) and (B) of Fig. 245. It is important to remember that in the t-r-f amplifier system the signal is amplified *at its own carrier frequency.* It is difficult to design a receiver of this kind to give high amplification, perfect selectivity and ideal fidelity of reproduction. Due to the high frequencies of the signal voltages being amplified, it is difficult to obtain amplifications of more than 40 or 50 per stage even when screen grid tubes are employed. This necessitates the use of many stages, if high sensitivity is to be obtained. Also since the primary of each r-f transformer induces a higher voltage into the secondary at the higher frequencies than at the lower ones, due to the more rapidly varying magnetic field, the r-f amplification is not uniform over the entire broadcast band unless special circuit arrangements for constant coupling are employed. These have not yet been developed to a point where they are simple, inexpensive and generally satisfactory. Also, in order to obtain a satisfactory r-f tuning curve consistent with adequate selectivity, band-pass tuning circuits must be employed (see Fig.

257). Since these band-pass circuits must be of the variable tunable type, tunable to any frequency in the frequency range the receiver is to cover, they cannot be built with as great efficiency as they would have if designed to work at one single frequency. This brief summary of the operating features of t-r-f receivers will enable us to better appreciate and understand the advantages of the superheterodyne circuit.

381. The superheterodyne system: In the superheterodyne circuit, instead of selecting and amplifying the signal at its own particular

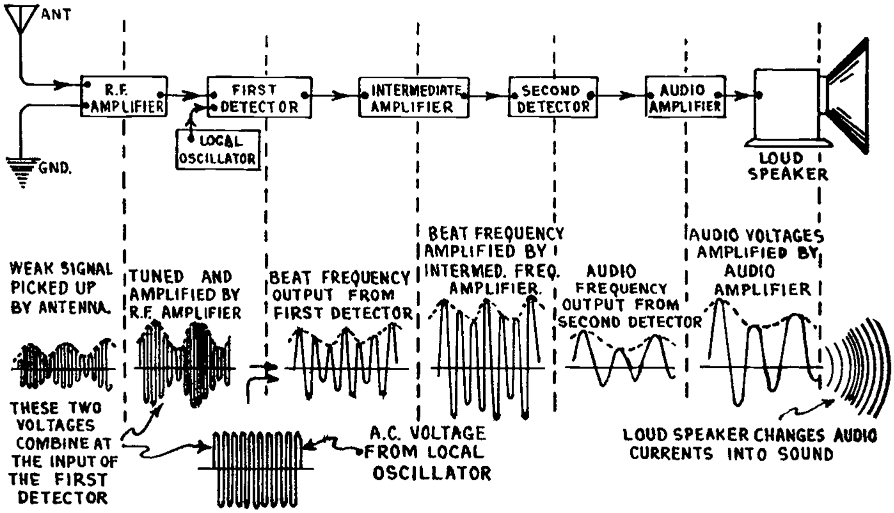


Fig. 277—Functional diagram of the various parts of a superheterodyne receiver showing the changes which occur in the signal voltage in each part of the receiver. The weak signal voltage induced in the antenna circuit is tuned and amplified, combined with the output from the oscillator, demodulated, amplified and tuned again, demodulated again, amplified again at audio frequency, and then reaches the loud speaker, which converts it into sound waves.

carrier frequency (which is a high frequency) by means of circuits which must be adjusted to that particular frequency, the high carrier frequency is changed to a lower fixed frequency, so it can be amplified and the signals of unwanted stations eliminated much more efficiently. The fixed frequency at which the signals are amplified is usually called the *intermediate frequency* sometimes abbreviated "i-f". Probably the single greatest difference between the t-r-f amplifier system and this one, is that in the former the receiver is tuned to the frequency of the signal and the signal is amplified at that frequency, while in the superheterodyne, the signal is tuned in and then changed in frequency to the lower value to which the intermediate amplifier is "fixed-tuned", and is amplified at that frequency.

The main parts of a superheterodyne receiver and the changes which the r-f signal undergoes are shown in Fig. 277. The fields of many stations induce modulated r-f voltages in the antenna circuit. The signal of the unwanted stations are usually tuned out or separated somewhat from that of the wanted station by the antenna tuning circuits, and the latter is amplified by a stage of tuned r-f amplification. Then it is fed to the mixer circuit, where it is "mixed" or combined with a *steady* signal of a definite frequency generated by the "local oscillator" tube. This operates at a frequency differing from the signal frequency by an amount equal to the fixed frequency of the intermediate amplifier. After passing through the first detector, this produces a resulting beat frequency voltage having the same frequency as that to which the intermediate amplifier is tuned, and essentially equivalent in modulation to that of the original signal frequency. This single frequency modulated voltage is then amplified by the intermediate amplifier, then fed to the detector where it is demodulated or changed to audio frequency, is amplified further at audio frequency by the a-f amplifier, and finally fed to the loud speaker. The use of an r-f amplifier stage ahead of the first detector tube is not essential to the operation of the superheterodyne receiver, but it is used for several special reasons in modern supers as we shall see. We will now proceed to a detailed study of the operation of the various parts of the receiver.

382. Advantages of the superheterodyne system: The superheterodyne tuner possesses two advantages which the t-r-f type of tuner can never possess. One is the fact that in the super, so called "arithmetical" selectivity is obtained during the heterodyning of the incoming signal with the local-oscillator signal. This will be explained later. Also, the amplifying is done at the comparatively low fixed-frequency to which the intermediate amplifier is tuned (excepting the amplification obtained in the r-f amplifier stage ahead of the first detector tube). Since this is usually around 460 kc in modern superheterodynes, each intermediate amplifier stage can easily be made to produce an amplification of about 60 to 80, when screen grid type tubes are employed. Contrast this with the amplification of about 40 per stage usually obtained when the amplification is carried out at the high frequencies (1500 kc. to 545 kc.) at which the signals are amplified in the ordinary t-r-f receiver. This is because of the serious effects of stray and tube capacitances at these high frequencies.

However, it should be understood that t-r-f receivers can be built to be just as sensitive as superheterodynes. It is just a question of providing enough amplifier stages. The point is, that in the superheterodyne system the same sensitivity or amplification can be produced with *less* amplifier stages.

Also, since the intermediate amplifier stages in the super operate at the one *fixed* "intermediate frequency," it is possible to use band-pass tuning in them, of a form designed to have much more nearly the ideal straight-sided flat-topped tuning characteristic desired, than is possible where the band-pass tuner must be tunable to various frequencies over a wide frequency range as in the case of the t-r-f receiver. This means that in a well designed superheterodyne it is relatively easier to obtain the high degree of selectivity required in receivers for use under present congested conditions. While these are possibly the most important advantages of the superheterodyne, others will be pointed out as we proceed with our study.

383. "Beat" frequencies: Since the superheterodyne receiver depends for its operation on the production of "beat" frequencies, it is essential that we understand this action first. The phenomenon of the production of "beat frequencies" in electrical circuits is somewhat similar to the production of "beats" or beat frequencies, with sound waves.

Suppose we strike the note C in the bass of a piano, we hear a certain note due to this particular frequency of vibration. Now if we strike one of the adjoining keys,

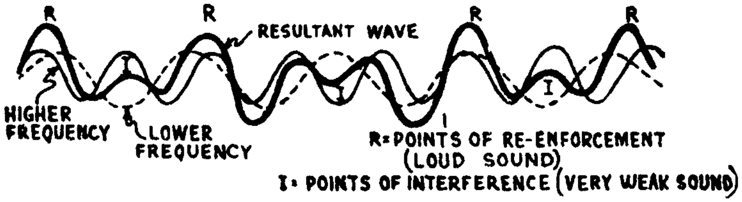


Fig. 278—Phenomenon of "beats," produced by the combination of sound waves of slightly different frequencies. The two light curves represent sets of simple sound waves having a vibration frequency ratio of 8 to 5. The heavy curve, represents the resultant sound wave obtained by adding the amplitudes of the individual curves together at various points, due regard being taken of the relative directions at these instants. Four points (R) of reinforcement (*beats*) and three of interference (I) are produced.

we hear a different note. If we strike both together, a note which differs slightly from both of these will be heard, and the sound will be found to swell and diminish at regular intervals. At regular intervals the two separate sound waves are in such phase relation that a condensation of one combines with a condensation of the other, reënforcing it and producing a louder sound or "beat note". At intermediate instants, condensations combine with rarefactions and their interference produces weak or even inaudible sounds. Hence, the effect is a succession of loud sounds called *beats*, separated by intervals of relative silence as shown in Fig. 278. Such beat notes can be produced by any two musical instruments when notes differing slightly in frequency are played. The number of beats produced per second will equal the difference in frequency of the two sets of vibrations. Thus with two sounds having frequencies of 256 and 260 vibrations per second respectively, four beats will be produced every second.

Now let us consider the production of "beat frequencies" in electrical circuits. Whenever two voltages or currents of different frequencies are combined, periodic reinforcement and weakening of the voltage or current are produced. Let us see just how this happens.

Let us suppose that we have an a-c generator producing voltage or current of a frequency of 10 cycles, rising and falling during one second as shown at (A) of Fig. 279. Let us suppose that we have another a-c generator producing another a-c voltage or current of 8 cycles, rising and falling during one second as shown at (B). We will assume that they are both introduced into a common "mixer" circuit as at (E), say by electromagnetic induction between the primaries and secondaries of the two transformers L and M shown. At the instant represented by the vertical line 1 - 1 the 10 cycle voltage induced in coil L is at its peak value, and in the positive direction. At the same instant, the 8 cycle voltage induced in coil M is almost at peak value in the opposite direction (negative) as shown. If we assume for simplicity that the peak value of the 10 cycle voltage is slightly greater than that of the 8 cycle voltage, then a small net voltage in the positive direction, equal to the difference between these peak values, acts in the "mixer" circuit at that instant as shown by the height of the "combined voltage" wave above the axis line O - O at (C) where 1 - 1 crosses it. Thus at each instant the voltages induced in L and M combine (with regard to their directions at the instant) to produce a resulting voltage equal in value to the algebraic sum of their individual values. At the instant represented by 2 - 2, the negative voltage of the 10 cycle current and the negative voltage of the 8 cycle current have combined with each other to form a much stronger negative voltage amplitude in the combined curve at (C). At the instant represented by vertical line 3 - 3, the positive voltage peaks of the two upper frequencies have combined to form a new positive peak of much greater positive amplitude as shown at (C), etc. Now, close study of the curve at (C) reveals that between the instants represented by 1 - 1 and 3 - 3, the various *peak values* of the *combined voltage* rise steadily from a minimum to a maximum value. Then from instant 3 - 3 to 4 - 4, the peak values of the

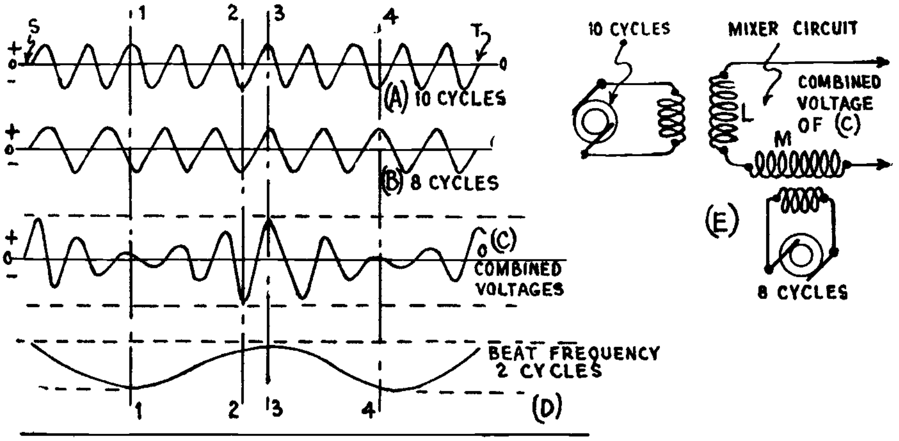


Fig. 279—The production of a "beat frequency" (D) in an electrical circuit, by the combination of two currents or voltages (A) & (B) of differing frequencies. The "beat frequency" is equal to the **difference** between the frequencies of the two voltages or currents which have been combined.

combined voltage fall steadily to a minimum value again. This rise and fall in *amplitude* of the *peak values* is represented by the curve at (D). Curves (A) and (B) are drawn to scale, that is, during the interval from S to T, there are 10 waves or cycles at (A) and 8 waves or cycles at (B). We find that during this time there are 2 waves or cycles produced at (C), that is, the new resulting current or voltage produced (shown at (C), varies in "amplitude", *the cyclic variation of its amplitude* taking place at a frequency equal to the *difference* between the two original frequencies at (A) and (B). This point is a very important one to remember, for it is a condition which has been confused somewhat by loose consideration of the subject of beats by some writers.

There is one additional important point to understand here. Referring back to Fig. 279, and by actually counting the number of cycles at (A), (B), and (C) we find that during the time the current or voltage at (A) goes through 10 cycles, that at (B) goes through 8 cycles, and that at (C) goes through *9 cycles.* In other words, when two voltages or currents are combined, what we really get, is a current or voltage having a *resultant frequency which is the average of the two frequencies.* This resulting current or voltage however, varies in *amplitude*, the cycle of its *amplitude variations* taking place at a frequency equal to the difference between the two original frequencies. In the diagrams in Fig. 279 simple sine-wave voltages or currents were considered in order to make both the illustrations and the action easy to understand. If one of the voltages or currents considered were modulated, the same action would take place, only in this case, the amplitude of (C) would be modulated by this modulation at each instant. Its *peak* values would vary at the difference in frequency, but would not vary in simple sine-wave form as shown at (D). They would vary according to the modulation of this one wave. This is too complex to be shown in a simple diagram.

384. The "beat" action in a superheterodyne: An actual example of the "beat" action in a superheterodyne receiver will be considered now. Suppose the modulated carrier signal voltage of a broadcasting station transmitting on say 1,000 kc is being received. Let us further suppose that this was modulated by a 3,000 cycle sound in the broadcasting station. Let us suppose also that the intermediate-frequency amplifier of this superheterodyne receiver is designed to amplify at a fixed frequency of 175 kc, permitting of course, a band of frequencies 10 kc wide (170 kc to 180 kc) to pass through it freely, so that the sideband frequencies will not be cut or weakened. We will forget about the sideband frequencies for a moment and consider simply the carrier frequency. Now the desired signal is separated from those of other stations by the r-f tuning circuit, and is amplified by the single r-f stage. From here it goes to the "mixer" circuit where it is combined with a steady a-c voltage of 1175 kc produced by the oscillator tube in the receiver. (The oscillator has been adjusted to generate a voltage of this frequency for this particular case. When receiving stations of other frequencies, the oscillator must generate a different frequency in order to produce the 175 kc beats). The result is, that in the mixer circuit the 1,000 kc modulated signal voltage and the 1175 kc oscillator voltage combine to produce a resultant voltage having a frequency equal to the average of these, that is 1087.5 kc. This new resulting voltage makes cyclic variations in amplitude, at a rate of 1175 — 1000, or 175 kc every second (beat frequency). These variations in amplitude are in exact accordance with the modulations of the incoming signal voltage. Now this 1087.5 kc resulting voltage is applied to the grid circuit of the first detector tube, this being either of the "grid leak and condenser" type, or the "grid-bias" type. The effect of the detector, is to demodulate the 1087.5 kc voltage, removing the 1087.5 kc variations by the detector action (see Figs. 236 and 237). The output of the first detector is therefore a current or voltage possessing the 175 kc cyclic variations modulated in accordance with the original signal modulations. After passing through the primary of the first coupling transformer, this is an a-c voltage of 175 kc modulated as above. It is then amplified by the intermediate amplifier, and finally fed to the second detector where it is demodulated again, only this time, the 175 kc variations are removed and the audio-frequency modulations are left. These are amplified by the audio amplifier and fed to the loud speaker. The various changes which the incoming signal undergoes are shown at Fig. 277. It is interesting to note that the first detector really performs the function of detection or demodulation, notwithstanding the assertions of some writers to the contrary. It removes the variations of the *average* frequency resulting from the mixing of the incoming signal frequency and the oscillator frequency, and preserves the beat modulation. The second detector removes the intermediate-frequency variations, leaving only the original audio-frequency modulations. Without the first detector, we would have simply the radio-frequency of 1087.5 cycles fed to the intermediate amplifier. In this case, just as without the second detector, we would have in the audio circuit the frequency which passes through the intermediate amplifier. Now that we understand the most important action in the superheterodyne, let us proceed to study the design and operation of the various main parts, starting at the antenna circuit and proceeding through to the audio amplifier.

385. The r-f amplifier in the super: Some superheterodynes are designed with sufficient amplification so that their signal voltages may be taken from a small loop of wire. As the loop is directional, it must be turned so its plane points toward the station being received, in order to obtain maximum signal strength. Most supers of recent design are made sensitive enough to operate from a very short antenna, thus reducing the pickup of static, etc. The use of ordinary radio-frequency amplification ahead of the first detector of a super may seem rather inconsistent at first thought, when we remember that so much more amplification would be obtained by using an additional intermediate-amplifier stage instead. The r-f amplifier stage has two other purposes however, besides that of mere amplification. First, it is usually included in order to be able to reduce the strength of the incoming signals of powerful unwanted local stations before they reach the detector, to a value sufficiently low so that they do not produce cross modulation effects on weaker incoming signals which it may be desired to receive. This is the usual problem of "adjacent channel" selectivity which is also encountered in ordinary t-r-f receivers. The other reason for the use of r-f amplifier stage, is one peculiar to the superheterodyne circuit only. This is the problem of eliminating "image frequency".

386. Image frequency: The problem of eliminating image frequency effect is probably the most serious drawback of the superheterodyne system. This is caused by the following action. Since the frequency of the beats produced, is equal to the difference between the frequency of the carrier wave of the incoming signal and the frequency of the oscillator, it is evident that for any one oscillator frequency setting, there is a frequency above this and one below this such that the difference between it and the oscillator frequency is the same.

Suppose the intermediate amplifier is designed for a frequency of 175 kc and a 1000 kc signal is to be received. In order to change the carrier frequency of this signal to the 175 kc intermediate-frequency, the oscillator can be set either at 1175 kc or 825 kc, for in either case the difference in frequency is the 175 kc desired. If it is set at 1175 kc then it will not only change the 1,000 kc signal so it becomes 175 kc in the intermediate amplifier but will also change any 1350 kc signal which may be received, so it also becomes 175 kc in the amplifier, since 1350 minus 1175 is also equal to 175 kc. Therefore, both of these signals will be amplified by the intermediate amplifier and of course will be heard together. The same action would take place if the oscillator were set at 825 kc. In this case, both the 1,000 kc signal and the 650 kc signal would be present in the intermediate amplifier together, after having been acted on by the oscillator voltage and passed through the first detector. In the first case, the signal of 1350 kc is the *image frequency* signal. In the latter case, the 650 kc is the *image frequency*. It is also possible for two signals in the broadcast band, which are separated by the frequency of the intermediate amplifier, to reach the first detector, one serving to heterodyne the other to this frequency, and a modulation of one or both stations appearing at the loud speaker. This incoming signal of 1, 500 kc could heterodyne with an incoming signal of 1,325 kc to produce beats at 175 kc.

387. Design of the r-f amplifier: It is evident that both of these problems connected with "image frequency" could be solved if we could see to it that only the incoming signal which we desire to receive, gets to the grid circuit of the first detector. This problem has been successfully solved

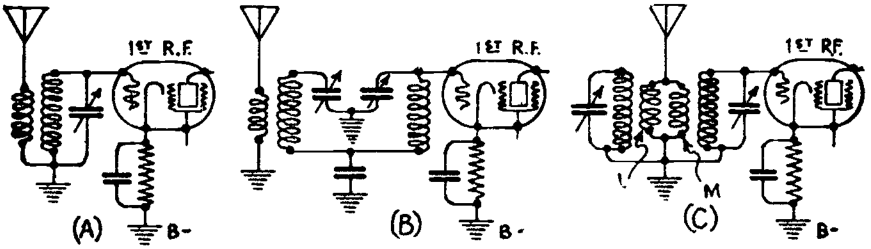


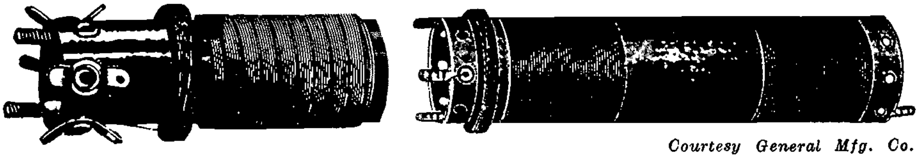
Fig. 280—Several antenna circuit tuning arrangements for superheterodyne receivers (see Fig. 281.)

in recent superheterodyne receivers, by obtaining a high degree of selectivity before the first detector through the use of a tuned r-f amplifier stage. For practical reception, it is necessary that this selectivity be such as to reduce the intensity of the interfering signal appearing at the first detector to a point where it is only one-five-thousandth or less of that of the wanted signal. Thus, the tuned r-f amplifier stage must provide a high order of "off-channel selectivity" rather than a high order of "adjacent channel selectivity" mentioned in Article 385. The latter can be obtained more easily and conveniently in the intermediate frequency amplifier, than in the preceding r-f circuits. The cross modulation effects which may occur in this first r-f amplifier tube due to strong local signals, have practically been eliminated by the development of the variable-mu type tube which may be used in this position, (see Art. 313).

Several forms of tuning circuits are suitable for the r-f amplifier. Since the action of the first tuned r-f stage in a superheterodyne receiver is exactly the same as that in a t-r-f receiver, the same forms of tuned circuits which have become popular for the first r-f stage in the latter types of sets are also used in modern superheterodynes.

Among these are the circuits shown in Fig. 280. A single tuned circuit arrangement is shown at (A). The secondary of the r-f transformer which couples this r-f amplifier tube to the first detector is also tuned. At (B) a band-pass pre-selector arrangement of the ordinary capacity-coupled type is shown. This type of circuit provides more selectivity than that at (A) and has been used extensively. At (C) is a very efficient arrangement in which the left hand or first tuned circuit is a rejector stage across the antenna and ground circuit. The action of this is to allow signal currents of frequencies above and below that of the wanted signal to flow without opposition through coil L, thus shunting them from the primary M. Between the antenna system and the r-f tube is another tuned circuit of the series resonance type. The combined selective effect of these two tuned circuits is higher than that of the conventional selector stage of (B) and, shows in addition, a higher voltage transfer from the antenna to the r-f tube, since this system does not show as much loss as the average dual-selector stage employed in most r-f circuits.

This arrangement gives a high order of both adjacent-channel and image-frequency selectivity and when used with a variable-mu type tube, results in freedom from cross-modulation. Coils suitable for the arrangements of (A) and (B) are shown in Fig. 281. At the left is that for the single tuned circuit, at the right is that for the band-pass circuit. In each case the primary winding is of the high inductance—high impedance type, lattice—wound in a narrow form. This inductance is so large that in



Courtesy General Mfg. Co.

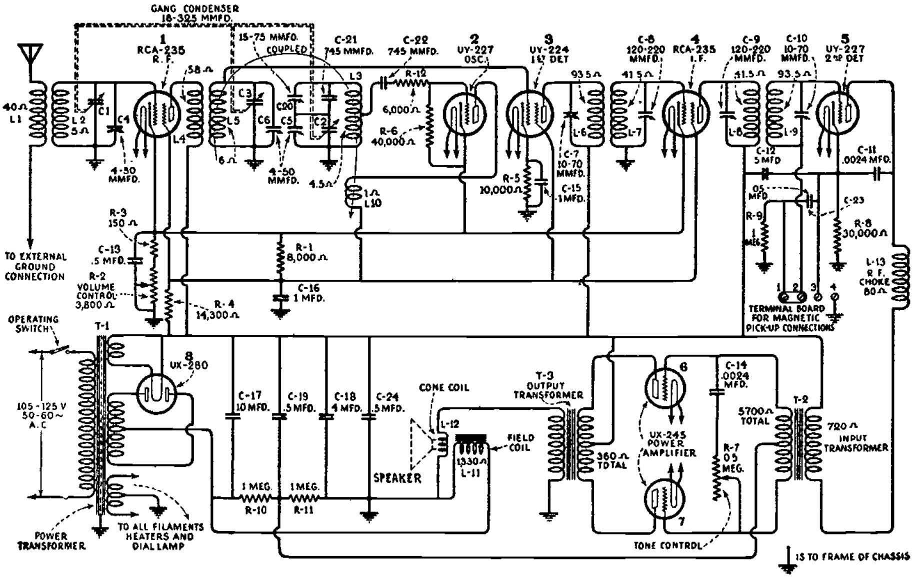
Fig. 281—Left: Antenna coil suitable for use in the circuit arrangement shown at (A) of Fig. 280.
Right: Antenna coil suitable for use in the arrangement shown at (B) of Fig. 280.
In each coil, the narrow primary at the left, is of the high impedance type, lattice-wound. The secondary is the long winding.

combination with the capacity of the antenna circuit it is in resonance to a frequency below that of any frequency to be received. At the lower broadcast frequencies where most receivers are insensitive, the use of a primary of this type results in somewhat greater gain than when a low-inductance primary is used. This was explained in Art. 371.

388. The oscillator: The function of the *local-oscillator* is mainly to generate a steady high frequency a-c voltage or current. Its frequency must be variable within the range necessary to produce beats of the fixed frequency for which the intermediate amplifier is designed, with every signal which it may be desired to receive. All forms of oscillators operate by feeding back energy from the plate circuit to the grid circuit. Since in a vacuum tube containing more than 2 electrodes, the available energy in the plate circuit is greater than that in the grid circuit, if part of this energy in the plate circuit is fed back to the grid circuit in sufficient amount and proper phase relationship of the instantaneous voltages, there will be constant re-amplification and feeding back of energy from the plate to the grid circuit. The frequency of the oscillations so produced will be determined by the inductance and capacitance of the tuned grid or plate circuit and their amplitude will depend on the shape of the family of E_g - I_p characteristic curves, the rate at which the power is dissipated in the entire circuit, and the amount of energy fed back to the grid circuit. The energy may be fed back through the plate-grid capacity of the tube as has already been explained, or it may be fed back by coupling the plate circuit to the grid circuit by the inductive action between coils connected in the grid and plate circuit (as in Fig. 282 and 283), or even by external capacity coupling with condensers. All forms of oscillators are not really suitable for use in superheterodyne receivers.

If the tuning circuit of the local-oscillator interacts with other tuning circuits in any way, there will be a change in local-oscillator frequency as these circuits are tuned. For this reason the circuit position of the oscillator is usually arranged by inductive coupling to an auxiliary winding in the cathode return, or the grid lead of the first detector circuit, so that detuning effects are negligible.

Many types of oscillator systems may be used in superheterodyne



Courtesy R.C.A. Victor Co.

Fig. 282—Complete circuit diagram of an a-c operated superheterodyne receiver employing two 175 kc intermediate frequency amplifier stages, and a t-r-f stage ahead of the first detector.

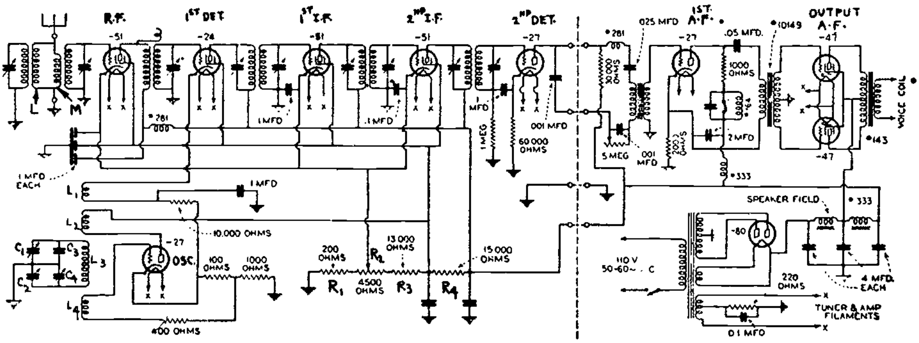
design, but the simple tuned-grid oscillator answers every requirement. The oscillator may be coupled to the mixer circuit in several ways. It may be coupled inductively by a coupling coil; by mutual induction; by means of a high resistance and small capacity in series; or by means of the screen-grid or cathode. Of these ways, mutual-induction is the simplest and the one most economical of space and material.

The oscillator should be so designed as to deliver considerable power to the frequency changer, and this voltage should be as constant over the frequency band as possible. With a little care, the voltage change over the frequency band can be made less than 3 to 1. The r-f voltage delivered to the frequency changer should be so adjusted, by varying the coupling to the oscillator, as to give maximum sensitivity without overload of the frequency changer at any frequency. The allowable voltage will depend upon the point at which the frequency changer is being worked.

The ideal local-oscillator should possess the following characteristics:

It should produce a constant frequency at any setting; should produce constant frequency free from objectionable harmonic frequencies; it should have constant power output over the tuning range; should radiate a minimum of energy into space to be picked up by other nearby radio receivers; and should produce minimum detuning action on the rest of the circuit through electrostatic and magnetic coupling. In some receivers, constant power-output of the oscillator over the full tuning range is not desired. In these, the output of the oscillator is purposely made greater for those frequencies at which the sensitivity of the receiver as a whole would be rather low. In this way, the sensitivity is made more uniform. Oscillator coils should be shielded to prevent radiation of energy to nearby receiving systems.

Two popular types of oscillator circuits for superheterodynes are shown in the superheterodyne receiver circuit diagrams in Figs. 282 and 283. In Fig. 282, the out-



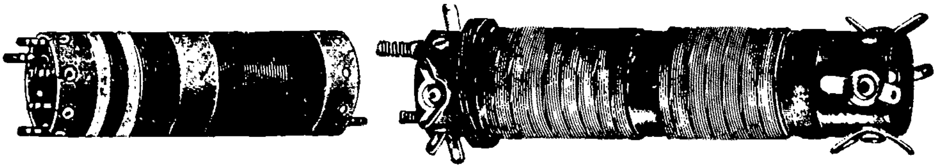
Courtesy Silver Marshall Co., Inc.

Fig. 283—Complete circuit diagram of a typical a-c operated superheterodyne receiver employing a tuned rejector antenna circuit, and two 175 k.c. tuned intermediate amplifier stages. Dual tone control is provided in the audio amplifier.

put of the oscillator is inductively coupled to the grid coil of the first detector. This is a tuned-grid circuit oscillator having a closely-coupled plate coil that gives sufficient feedback to provide stable operation. The peculiar grid circuit tuning arrangement shown is so designed that by means of a correct combination of capacity and inductance, a constant frequency difference (equal to 175 kc, the intermediate frequency) between the oscillator and the tuned r-f circuits is obtained.

In Fig. 283 the oscillator uses what is known as a "tank" tuning circuit which is substantially dissociated from the oscillator tube so far as frequency stability is concerned. Energy is fed back from plate coil L_2 to grid coil L_4 by magnetic coupling between L_2 and L_3 and between L_3 and L_4. The oscillator signal is fed to the grid circuit of the first detector tube by means of the coil L_1 connected in the cathode circuit. Since L_1 is between the cathode and the 10,000 ohm grid bias resistor of the first detector, the voltages induced in it by magnetic coupling with L_2 are impressed on the grid circuit.

Two forms of oscillator coils for superheterodyne receivers are shown in Fig. 284. The coil at the left has three windings, one for the grid tuning circuit, one for the tube plate feedback, and a small coupling coil for inducing the oscillator voltage into the grid circuit of the first detector. At the right is a single unit containing the coils L_4, L_5, L_8 and L_{10} from left to right in the order given, in the circuit diagram of Fig. 282. It is possible to operate the oscillator so that its frequency is always *higher* by a fixed amount (equal to the i-f), than the signal frequency, or operate it so its frequency is lower than that of the signal by this same amount, for in either case the frequency *difference* between the two will be the same. In practice, because of image-frequency interference considerations, the oscillator frequency is usually made *higher* than the signal frequency.



Courtesy General Mfg. Co.

Fig. 284—Left: Oscillator coil with coupling, plate, and grid windings.
Right: Oscillator coil with windings L4, L5, L3, and L10 for use in the type of circuit shown in Fig. 282.

389. Single control of the tuning circuits: The problem of achieving single-control of all the tunable circuits in a modern superheterodyne receiver is one which long defied the ingenuity of receiver designers. In the circuit of Fig. 282 for instance, C_1 and C_3 are the tuning condensers which must be varied to tune the circuits to exact resonance to the frequency of the incoming signal. These condensers may be made to track up easily enough if a gang condenser is used for tuning. However, condenser C_2 must tune the oscillator circuit to a frequency always exactly 175 kc higher than that to which the other two circuits are tuned, if the intermediate frequency is 175 kc. This problem has been solved in practice in two ways. One is to use a gang condenser in which the plates for C_1 and C_3 are similar but in which the plates of C_2 are shaped properly to give the proper tuning curve (so frequency is always 175 kc *higher* than the other two) under the circuit conditions for that section. These shapes have been worked out sufficiently close, and condensers designed especially for this purpose are available for use in practical single-control receivers.

The other solution is to use a gang condenser having exactly similar sections, but provide a "pad" circuit arrangement, which automatically balances up the inequalities in the tuning circuits.

The theoretical considerations involved in the design of these are too complex for presentation here, but it will suffice to say that a rule for the type of network shown in the circuits of Fig. 282 and 283 has been worked out experimentally. Referring to Fig. 282, this states that if tuning condensers C_1, C_2 and C_3 are alike, and C_{21} is made about twice the value of C_3 or C_2 at its maximum setting, for an oscillator inductance 22% less than L_5 (this value is not critical) the rate of change of the total capacitance in the oscillator circuit will be such as to give a tuning curve which maintains the oscillator frequency a given fixed value above the frequency of the second detector grid circuit for any setting. The two small capacitances C_{20} and C_5 are simply small midget condensers, which are employed to align the circuits at the high and low wavelength ends, respectively, of the tuning range.

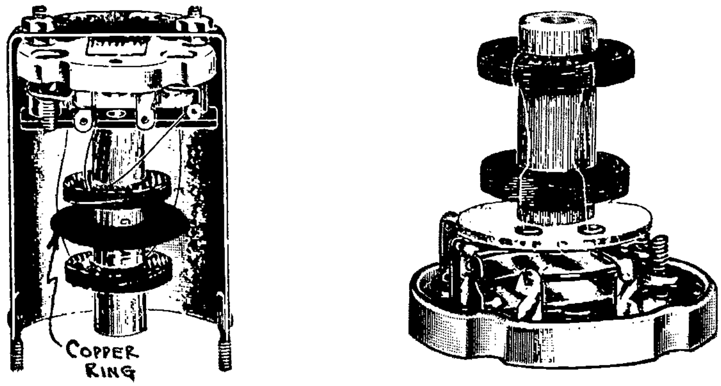
The trimmer condenser C_5, across the tuning section of the oscillator network, adjusts the minimum capacity of the system, and thus effects an alignment of the oscillator circuit at the low wavelength end of the range. The other fixed condenser trimmer C_{20}, serves to effect a similar alignment at the high wavelength end of the spectrum. Tracking throughout the mid-range will be perfect enough to avoid any necessity for the use of a manually-operated trimmer while tuning. The same form of tuner circuit is employed in the oscillator circuit of Fig. 283. If signals of any station in the broadcast range (550 to 1,500 kc) are to be received, and the intermediate frequency is say, 175 kc, the range of the oscillator must be from 550+175 or 725 kc to 1,500+175=1675 kc.

390. Choice of the intermediate frequency: The selection of the value of the intermediate frequency employed is very important. The choice of the intermediate frequency has, in the past, often seemed a matter of the set-designer's whim, but actually, it is definitely settled by the conditions of the actual problems involved. Let us see what they are.

For high amplification and good selectivity, the lower the i-f, the better, whereas for freedom from image-frequency interference, the higher the i-f the better. As the image-frequency problem is perhaps the most serious one, a high i-f might seem to be best, but another factor enters, limiting the upper limit of i-f which may be employed in practice. Any detector generates some harmonics of the r-f signal carrier applied to it, and in the case of a power detector handling high signal voltages, harmonics, up to the third, represent quite a fair percentage of the fundamental. It has been found that if the third harmonic of the i-f falls in the broadcast band, leakage in the set from second detector output back to first detector can cause serious interference problems, so that the i-f should be low enugh to keep its third harmonic below the broadcast band. The third harmonic of 175 kc, for example is 525 kc, just safely below the broadcast band, and therefore 175 kc has been chosen as the intermediate frequency in many modern receivers. The reason why 170 kc is not chosen, is that the choice of an i-f that is a multiple of 5 kc rather than 10 is desirable, since broadcasting station frequencies in the United States are separated by 10 kc, and two stations themselves separated by 170 kc or 180 kc will cause less trouble to a sharp 175 kc i-f amplifiier than they would to a 170 kc amplifier. This has been discussed in Article 386.

391. The intermediate amplifier: The function of the intermediate-frequency amplifier is to amplify a band of frequencies not more than 10 kilocycles wide (with the present broadcast and audio range of 5,000 cycles), that is 5 kc on either side of the value of the intermediate frequency it is designed for. Screen-grid tubes are commonly employed in i-f amplifiers on account of their high amplification factor. It is possible to obtain an actual amplification of 80 or so per stage in a well designed i-f amplifier. The tubes could be coupled together by resistance, transformer, or impedance coupling, but since the i-f amplifier is a fixed-frequency amplifier, it presents a splendid opportunity for the use of band-pass tuners designed to produce actual results close to the theoretical ideal. The simple form with a tuned primary and tuned secondary with magnetic coupling between the coils is commonly employed on account of its cheapness and simplicity. Fig. 282 shows the arrangement of two such stages. In Fig. 283, three are used.

The interstage transformers are designed with a large ratio of L to C, and small adjustable compression type mica condensers having a range of approximately 100 to 200 mmf. are used to tune each winding to the frequency required. Many of the smaller midget receiver designs contain only a single intermediate stage, and for this single stage amplifier the transformer should be designed so that the stage will have a gain approximately seven times as great as when two stages are used. This can be done by winding the coils with litzendraht wire, keeping the ratio of L to C higher



Courtesy General Mfg. Co.

Fig. 285—Left: Intermediate-frequency transformer for coupling first detector to first i-f amplifier tube. The coupling between the primary and secondary is made loose by means of the copper ring between.
Right: Same type of i-f coil for the other i-f stages. The tuning condensers are in the base.

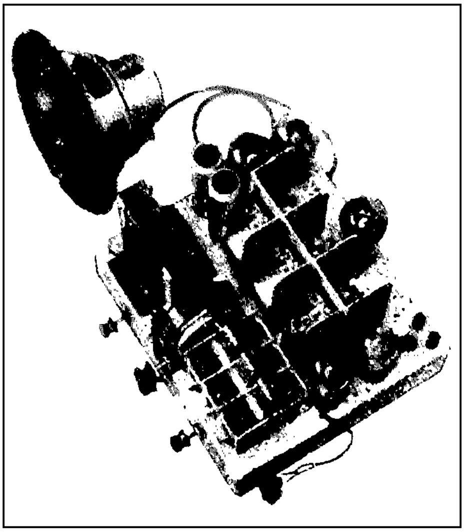
than the ratio for the two stage transformers. The mutual inductance between the windings is chosen so that the resonance curve will approximate a flat top, with band-pass characteristics.

The proper value of mutual inductance cannot be expressed as a certain distance between the primary and secondary coils, because this distance will vary with different amplifier designs. To secure the proper degree of selectivity it is necessary, as a rule, to use less coupling between the tuned circuits of the first stage than is used in the succeeding stages. In cases where the physical dimensions of the shields have prevented sufficient separation of the coils to reduce the coupling to the proper value, small copper ring shields have been used between the coils with good success. These copper rings may then be bent until the coupling is just the proper value. This ring shield is usually employed only in the first stage transformer. A unit of this type is shown at the left of Fig. 285, with its enclosing shield cut away to show the interior. One of the intermediate coils without the ring is shown at the right. The tuning condensers for each coil unit are mounted below the respective coils.

As all the circuits of the intermediate amplifier are tuned, it is vital in order to preserve the proper selectivity and amplification, that the adjustable tuning capacities have good electrical properties. They must also be mechanically correct so that they will permanently hold their adjustment without change in capacity value.

A commonly used mounting for the small universally wound coils, which are employed for the tuned intermediate circuits, is wooden doweling. There is no objection to this material provided that it is impregnated with wax, so that the wax penetrates entirely through the wood. The intermediate transformer assemblies should be shielded.

It is quite possible to properly design a superheterodyne of "midget" proportions and still retain the full amount of amplification as used in the larger receivers of this type. It can be made to perform as well as the larger receivers in everything but reproduction, and even here it would not fail if it had an equivalent amount of baffling for the reproducer. The complete chassis of a midget superheterodyne receiver of this type, complete with its electro-dynamic type loud speaker is shown in Fig. 286. The sensitivity of this particular receiver is 6 to 10 microvolts per meter. The three gang condenser which tunes the dual antenna circuit selector



Courtesy Silver Marshall Co., Inc.

Fig. 286—The chassis and loud speaker of a typical midget type superheterodyne receiver. The chassis measures only 12 inches wide. The sensitivity is 6 to 10 microvolts per meter.

and the oscillator circuit is seen at the lower left of the chassis. The chassis of this set is only 12 inches wide.

392. The second detector: The second detector employed should be of the power type. Only a single audio stage is used in most supers because the gain of the receiver is so high that a second audio stage would be of no advantage and would tend to increase the hum in a-c operated receivers. The use of but one audio stage requires less "B" power supply filtration, but more i-f gain, which however, is easier to obtain in a super than is additional audio gain. The circuit of Fig. 282 shows the connections for a '27 type power detector feeding into a single audio stage. In Fig. 283, the second detector feeds into two audio stages, used on account of the special audio tone-control employed.

393. Arithmetical selectivity: Another advantage of the superheterodyne receiver is that due to the so-called *arithmetical selectivity* which is obtained. This can best be illustrated by considering the problem of selecting a wanted station at, say, 1,000 kc and yet completely eliminating an unwanted station at 1,010 kc.

The frequency separation is seen to be 10 kc, or 1 per cent, and such separation presents problems which no t-r-f receiver (even one employing five or six tuned circuits), can completely satisfactorily meet. In the case of the superheterodyne however, where the intermediate amplification frequency may, for this purpose, be considered as a frequency of 175 kc, it is apparent that when the wanted and unwanted signals are both heterodyned, they will appear 10 kc apart at the intermediate-frequency amplifier. That is, the wanted stations will appear at 175 kc and the unwanted station will still be 10 kc away. The percentage difference in this case is seen to be about 5.7 per cent and it is apparent therefore, that the relative selectivity problem is approximately six times simpler for the super with 175 kc i-f amplifier than for the t-r-f set which must perform discrimination between original signals of 1,000 and 1,010 kc.

394. "Repeat" points: With many of the old 2-dial control superheterodynes, it is possible to tune a single station in at two separate settings of the oscillator dial, or tune in two separate stations with a given setting of the oscillator dial. This is due to the fact that the oscillator tuning control and the antenna circuit tuning control are separate and that insufficient selectivity is provided ahead of the first detector.

The incoming signal can be converted to the beat frequency when the oscillator frequency is the proper amount above its frequency (1 setting), and also when the oscillator frequency is the proper amount below its frequency (the other setting). To make this clear, let us suppose that the intermediate or "beat" frequency is to be 100 kc. If a signal of 550 kc is tuned in, the frequency of the oscillator can either be adjusted to 450 kc or 650 kc to provide this beat frequency of 100 kc. Also if the oscillator frequency were set at say 650 kc, and there were two stations operating at 550 kc and 750 kc equally powerful at the input to the receiver, both would provide the required 100 kc intermediate-frequency and both would be heard together. In modern single-control receivers, this is eliminated by providing adequate selectivity ahead of the first detector, using a moderately high i-f, and ganging the condensers together so the oscillator frequency is always an equal frequency above that of the antenna tuning circuits.

395. The "Autodyne": In the autodyne system, one tube is eliminated by combining the functions of the oscillator and the first detector. The input circuit from the antenna is coupled to the oscillator, which also acts as the detector. This is tuned so its frequency differs from the incoming frequency by the exact number of kc to which the i-f amplifier is tuned. A super of this type is called an *autodyne* because the signal is automatically heterodyned in the local oscillator or first detector, instead of requiring the additional mixing circuit and tube. Some loss in signal strength is experienced in autodynes, because the first detector is actually detuned from the incoming signal.

396. Frequency changers: The principle of the superheterodyne can be applied to any existing t-r-f receiver by adding an oscillator and a mixing tube. In a system of this kind, all of the tuning circuits of the r-f amplifier are set at some fixed frequency to give maximum amplification within the broadcast band. The tuned r-f amplifier is therefore used as the "intermediate amplifier" of the super system. The oscillator output produces beats with the incoming signals so that this intermediate frequency is generated and amplified. The signals are finally detected in normal manner by the detector in the t-r-f receiver. The oscillator must of course be designed to produce the proper range of frequencies, depending on what the intermediate frequency is to be. Superheterodyne type short wave converters are commonly used for receiving short wave programs. The oscillator produces beats at the lower frequencies to which the t-r-f amplifier of the receiver it is used with is tuned. These "frequency changers" or so-called *short wave converters* are discussed in detail in Art. 565.

397. Adjusting the circuits of a superheterodyne: In a superheterodyne receiver, it is essential that the tuning circuits controlled by the gang tuning condenser be kept accurately aligned. Also, the tuned circuits formed by the primary and secondary windings of the intermediate transformers must be adjusted accurately so as to pass a band of frequencies 5 kc above and below the i-f. The methods and apparatus used for adjusting these circuits will be considered in Art. 639.

REVIEW QUESTIONS

1. Show by means of a block diagram, the various parts of a superheterodyne receiver, and explain briefly the various changes which the signal undergoes as it proceeds through the set.
2. What is the essential difference between a t-r-f receiver and a superheterodyne?
3. What is the main advantage of amplifying at an "intermediate frequency" lower than the frequency of the incoming signal?
4. State three advantages of the superheterodyne form of receiver over the ordinary t-r-f receiver for broadcast band reception.
5. Explain in detail the phenomenon of "beat frequencies" taking place when a voltage having a frequency of 1,000 kc and one having a frequency of 600 kc are made to act together in the same circuit. What is the frequency of the beats produced? What is the frequency of the resulting voltage?
6. A superheterodyne receiver with a 175 kc intermediate amplifier is to be designed for reception of signals over a frequency range of 500 to 3,000 kc. What must be the frequency range of the oscillator in this receiver?
7. Give one example of how image frequencies might be received by a superheterodyne. By what practical arrangement could they be eliminated?

8. What is the difference between adjacent-channel selectivity and off-channel selectivity? Which is most important in (a) the r-f amplifier stage of a superheterodyne; (b) in the i-f amplifier?
9. What factors influence the selection of the i-f for a broadcast superheterodyne receiver?
10. Why is it necessary to "demodulate" the combined output of the antenna and local oscillator, in order to obtain the beat frequency?
11. What form of coupling is generally employed between the i-f stages of a broadcast superheterodyne? What is the advantage of this form of coupling here?
12. Explain the fundamental principle of the operation of a vacuum tube as an oscillator.
13. What is the function of the oscillator? How is the output of the oscillator made to combine with the input signal?
14. Why must the frequency of the oscillator be varied for each different station received in a superheterodyne receiver? How is this accomplished?
15. What is the advantage of making the oscillator frequency always higher than the signal frequency?
16. What is the advantage of using a high-inductance primary loosely coupled to the secondary coil in an antenna coupling coil.
17. Why is a special "pad" circuit arrangement, or a condenser section with specially shaped plates, required for tuning the oscillator circuit in a single control superheterodyne?
18. Explain in detail some of the factors which govern the choice of a suitable i-f for broadcast band superheterodynes. What i-f is used in most supers now? What advantages does this frequency have over others?
19. What is the purpose of the "second detector?"
20. Explain what is meant by the "arithmetical selectivity" obtained by the beat action in a superheterodyne.
21. How may an ordinary t-r-f receiver be converted into a superheterodyne, using the tuned stages of the t-r-f set as the intermediate amplifier? What additional parts are necessary?

CHAPTER 23

DESIGN OF R. F. AMPLIFIERS AND TUNING COILS

TUNING CIRCUITS — FORMS OF INTERSTAGE COUPLING COILS — CALCULATING THE INDUCTANCE OR CAPACITANCE REQUIRED — DESIGNING THE WINDING BY USE OF FORMULAS — COIL DESIGN BY MEANS OF CHARTS — DESIGN OF THE PRIMARY WINDING — EFFECT OF VARYING THE COUPLING — CONSTANT R. F. COUPLING — LOSSES IN TUNED COILS — DISTRIBUTED CAPACITY — COIL SHAPES AND TYPES OF WINDINGS — INTERSTAGE COIL COUPLING — R. F. COIL PROPORTIONS — PLACEMENT OF R. F. COILS — SHIELDING IN R. F. AMPLIFIERS — EFFECT OF SHIELDING ON TUNING COIL — GENERAL SHIELDING CONSIDERATIONS — REVIEW QUESTIONS.

398. Tuning circuits: We have seen that both the t-r-f and the superheterodyne forms of tuners used in radio receivers depend for their operation on electrical resonance produced in tuned circuits consisting usually of inductances and condensers of proper values depending on the frequency range to be received. If the circuit is to be tuned at will to any frequency within a certain specified frequency band, the coil is usually of fixed inductance and the tuning condenser is of the variable type. If the combination is always to be in resonance at some one fixed frequency, both the inductance and the condenser are made fixed, or the latter is semi-adjustable, as in the case of the i-f tuning coils in the superheterodyne. Thus far, we have referred to the coupling coils or transformers used for this purpose, in a rather abstract way, no attempt being made to study their design in detail. This will be considered now. Several forms of coils in superheterodynes were shown in Chapter 22.

399. Forms of interstage coupling coils: The tendency in modern t-r-f receivers is toward the use of the air-core type of r-f transformers in which the primary and secondary windings are on thin tubes of insulating material such as Bakelite or Formica. The use of iron cores is of course objectionable on account of the excessive eddy current and hysteresis losses at these high frequencies unless special design precautions are taken. Some interesting r-f transformers have been produced with special chemically treated compressed iron dust cores, in which each particle of iron is insulated from the next by a thin insulating film of oxide, etc., but they have not attained much commercial success. The windings consist of either cotton, silk or enamel covered copper magnet wire, the latter being used extensively on account of its lack of moisture absorption and better mechanical characteristics for quantity-production machine winding. The secondary winding is usually tuned by a variable condenser to produce resonance. We have already studied in detail, in Articles 172 to 178 and elsewhere, the actions which take place in the tuned circuit, so we will not repeat them again here. Suffice it to say, that the inductance and capacity required to form a resonant circuit at any frequency or wavelength can be calculated by formulas or may be found quickly by charts arranged especially for this purpose.

The usual procedure in designing tuning coils, is to design the tuned winding or inductance first, since this depends in any case, on the size of the tuning condensers employed, and the frequency, or frequency range, over which resonance is to be obtained. The sizes and design of tuning condensers employed for use in t-r-f circuits has been fairly well standardized in the U. S., as explained in Articles 150 to 154, variable tuning condensers having a maximum capacitance in the neighborhood of .00035 mf. being used most in broadcast-band tuners.

400. Calculating the inductance or capacitance required: Any inductance in combination with a given capacitance (as in Fig. 223 for instance), will be in resonance or in "tune" at a certain definite frequency or wavelength which may be calculated from the equations already discussed in Articles 116, 173, 176 and 177. These will be summarized here for convenience: First, the resonance frequency in cycles per second is found from the equation:

$$f = \frac{159{,}000}{\sqrt{L\ (\text{Microhenries}) \times C\ (\text{Microfarads})}} \qquad (1)$$

$$\text{from which } L = \frac{2.528 \times 10^{10}}{f^2\, C} \qquad (2)$$

$$\text{or, } C = \frac{2.528 \times 10^{10}}{f^2\, L} \qquad (3)$$

The wavelength in meters, at which resonance takes place is found from:

$$\text{Wavelength} = 1885 \times \sqrt{L\ (\text{Microhenries}) \times C\ (\text{Microfarads})} \qquad (4)$$

$$\text{from which } L = \frac{\text{Wavelength}^2}{3.55 \times 10^6 \times C} \qquad (5)$$

$$\text{or, } C = \frac{\text{Wavelength}^2}{3.55 \times 10^6 \times L} \qquad (6)$$

The self-inductance of an *air-core solenoid* coil in *microhenries*, is approximately equal to:

$$L=0.0251\ d^2\ n^2\ l\ K \qquad (7)$$

Where n=the No. of turns per inch (see magnet wire table in Fig. 288 for particular size and kind of wire being used).
d=mean diameter of the solenoid in inches.
l=the length of the solenoid when wound (inches).
K is the "form factor" (Nagoaka's correction factor), which depends for its value on the ratio obtained by dividing the diameter by the length of the winding. Values of K for various diameter-length ratios are given in the following table.

VALUES OF "K" FOR USE IN FORMULA (7), ABOVE

Diam. length	K	Diam. length	K	Diam. length	K	Diam. length	K	Diam. length	K
0.00	1.0000	1.20	.6475	2.80	.4452	5.40	.3050	16.00	.1457
.10	.9588	1.30	.6290	3.00	.4292	5.80	.2916	18.00	.1336
.20	.9201	1.40	.6115	3.20	.4145	6.20	.2795	20.00	.1236
.30	.8838	1.50	.5950	3.40	.4008	6.60	.2685	24.00	.1078
.40	.8499	1.60	.5795	3.60	.3882	7.00	.2584	28.00	.0959
.50	.8181	1.70	.5649	3.80	.3764	7.40	.2491	35.00	.0808
.60	.7885	1.80	.5511	4.00	.3654	7.80	.2406	45.00	.0664
.70	.7609	1.90	.5379	4.20	.3551	8.50	.2272	60.00	.0528
.80	.7351	2.00	.5255	4.40	.3455	9.50	.2106	80.00	.0419
.90	.7110	2.20	.5025	4.60	.3364	10.00	.2033	00.00	.0350
1.00	.6884	2.40	.4816	4.80	.3279	12.00	.1790	--------	--------
1.10	.6673	2.60	.4623	5.00	.3198	14.00	.1605	--------	--------

NOTE: This formula assumes the coil to be wound with an infinitely thin conducting tape, the edges of which touch, though electrically insulated. The correction for the commercially available conductors commonly used is relatively small and may be neglected so far as practical results are concerned.

Calculatio s involving the use of equation (1) may be simplified by the use of the table of L C values which will be found in Appendix I. By means of equations (2), (3), (5) or (6) the required value of either the inductance or the capacity may be calculated, if either the wavelength or the frequency are known. These are all derived from the same formula, but are given here in order to make the calculations convenient. It should be remembered that in a practical tuned circuit used in a radio receiver, the capacity of the tuning condenser is not the only capacity that tends to tune the inductance. As shown at (B) of Fig. 266, the mutual coupling capacity to the primary (if one is used), the distributed capacitances of the coil, and wiring, input grid-cathode capacity of the tube, etc. all act to tune the coil. Therefore if accurate calculations are desired, the sum of these must be considered as the effective tuning capacitance. For rough determinations however, only the tuning condenser capacitance is considered and one or two turn of wire less are used on the coil to allow for the other stray capacitances.

Problem: What must be the indu tance of the secondary winding of an r-f transformer if it is to tune to a wavelength of 600 meters (500 kc) when the variable tuning condenser of .00035 mf. is set at maximum capacitance?

Solution: from equation (5) we find,

$$L=\frac{\text{Wave ength}^2}{3.55\times10^6\times C}=\frac{600\times600}{3.55\times10^6\times.00035}=300 \text{ Microhenries (approx.)}$$

401. Designing the winding by use of formulas: After the value of inductance which is required is determined, the exact winding data for the coil must be found. This is really the most difficult part of the problem, for it depends on many factors. For instance, in the above problem, we found that a coil of 300 microhenries is to be used for the particular conditions mentioned. As we shall see later, there are various types of windings such as solenoid, honeycomb, torroid, etc., which could be employed. We will assume for simplicity that a simple solenoid winding is to be used, since this is the most efficient and widely used form employed in the tuned circuits of short wave and broadcast band, t-r-f receivers. The next thing to be determined, is the diameter of the coil. Here again we have a wide choice, but since modern receiver design requires small, compact coils, with very limited external magnetic fields, we will assume that our coil is to be wound say, one inch in diameter. Coils of 7/8, 1, or 1¼ inches in diameter are used extensively since they are compact, and may be shielded by metal shield cans of small size. Next, we have a choice of size of wire and kind of insulation to be employed. Enamel covered copper wire is used extensively, due to its many advantages which will be discussed later. Sizes from No. 22 B and S to No. 32 B and S gauge are being employed, the smaller sizes being used most, in order to keep the length of the coil winding short. Let us now see how the winding data is determined if the coil diameter and size to be used, are known:

From formula (7) we have: $L = 0.0251\, d^2 n^2 l K$. Since we must find l first and then find the number of turns for this length of winding from the magnet wire table, we can arrange this formula in the form,

$$l = \frac{L}{.0251\ d^2 n^2 K}$$

Now it is evident that the known factors are L and d. If the wire size is known, n may be also found from a magnet wire table such as that of Fig. 288. We do not know the value of K, because this varies as the length of the winding is varied. Therefore we must assume an approximate value for the total number of turns and proceed with the calculation on that basis. If we have had some experience in designing windings of this type, we will probably be able to assume this value for the number of turns, close to the actual value. Then the value of K corresponding the length of the coil with these turns is found from the table. The computations must be carried out on this basis. The coil diameter must then be divided by the length of the winding obtained, and the value of K for this ratio must be checked back against the value assumed. If they differ greatly, a new value for the length of the winding must be assumed, and the calculation made over again. This procedure must be repeated until the correct values are found.

402. Coil design by means of charts: It is evident that the use of the formulas for the design of a solenoid tuning coil is not very convenient because of the involved computations necessary. In order to simplify this work and obtain results accurate enough for ordinary coil design work, special charts have been devised, which enable one to design a solenoid coil in a few minutes simply by the use of a straight-edge, pencil and paper. The charts for this purpose have been arranged together with complete instructions for their use in Fig. 287. Chart No. 1 at the left may be employed to find the inductance or capacitance if the wavelength of resonance is known. Chart No. 2 is for finding the coil design data. A

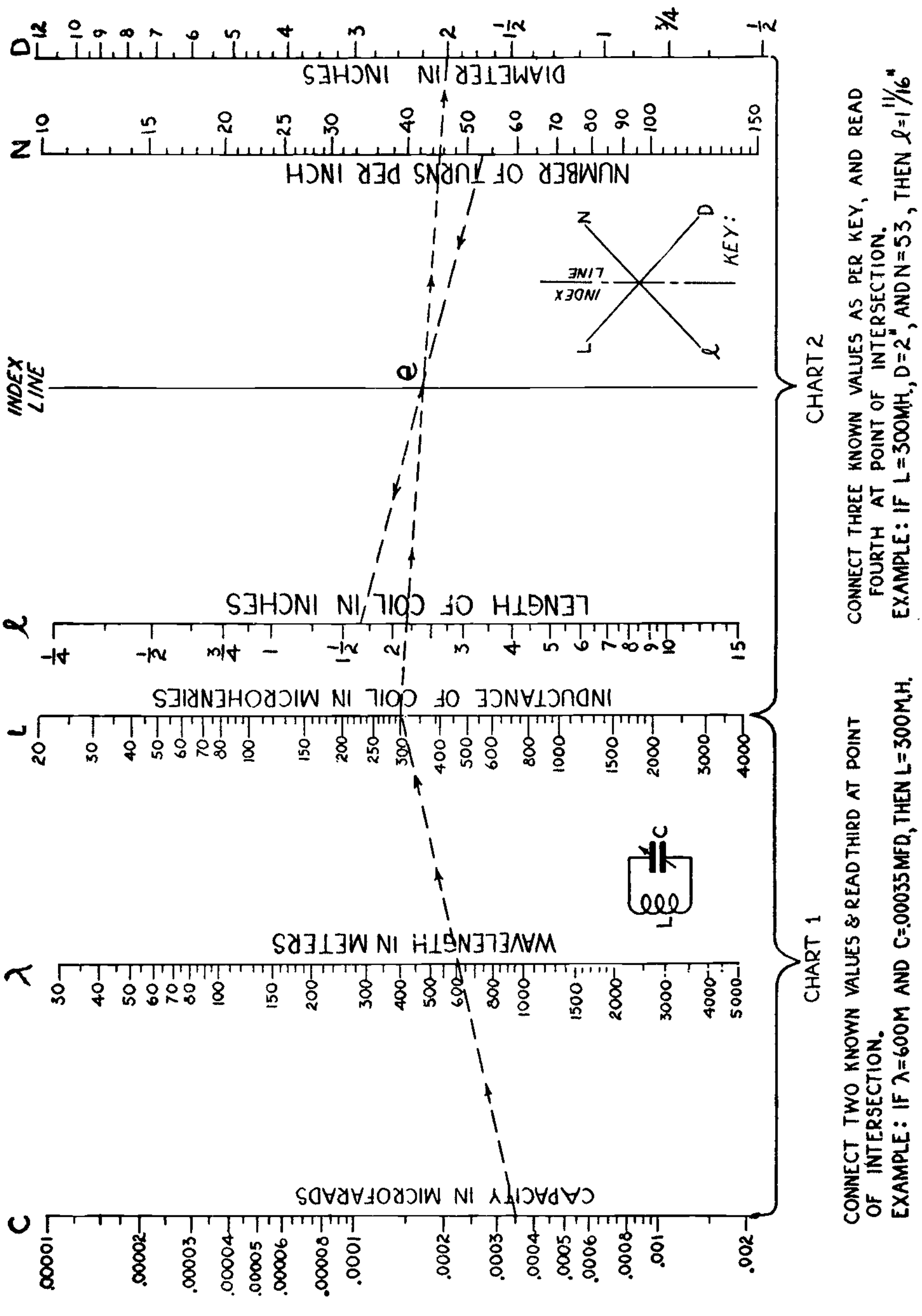


Fig. 287—Charts for rapid design of solenoid type tuning coils. Their use is explained in the text.

SIZE B.&S.	DIAMETER IN MILS.	AREA IN CIR. MILS.	FEET PER OHM	FEET PER POUND: BARE	FEET PER POUND: SINGLE SILK S.S.C.	FEET PER POUND: DOUBLE SILK D.S.C.	FEET PER POUND: SINGLE COTTON S.C.C.	FEET PER POUND: DOUBLE COTTON D.C.C.	OHMS PER 1000 FT. AT 68° F.	TURNS PER INCH: BARE	TURNS PER INCH: ENAMEL	TURNS PER INCH: SINGLE SILK S.S.C.	TURNS PER INCH: DOUBLE SILK D.S.C.	TURNS PER INCH: SINGLE COTTON S.C.C.	TURNS PER INCH: DOUBLE COTTON D.C.C.	APPROX. COST PER LB. (CENTS) ADD 5% FOR GREEN SILK: ENAMEL	APPROX. COST: SINGLE SILK (WHITE) ADD 5% FOR GREEN SILK	APPROX. COST: DOUBLE SILK (WHITE)	APPROX. COST: SINGLE COTTON	APPROX. COST: DOUBLE COTTON
14	64	4100	396	80.4					2.58	15.6	14			14	13	21			23	24
15	57	3260	321	101.4					3.25	17.5	16			15	14	22			24	26
16	51	2580	249	127.9					4.09	19.6	18			17	16	22	38	50	25	28
17	45	2050	197	161.3					5.16	22.	21			20	18	23	39	52	27	29
18	40	1620	156.5	203.4					6.51	25	23			22	20	23	39	55	28	31
19	36	1290	124	256.5					8.21	27.8	27			25	22	24	42	62	30	33
20	32	1020	98.4	323.4	319	312	311	298	10.4	31	29	27	25	27	25	25	47	67	31	36
21	28.5	810	78.1	407.8	398	389	389	370	13.1	35	32	30	27	30	27	27	51	73	34	39
22	25.3	642	61.91	514	504	493	491	461	16.5	39	36	34	30.5	34	30	26	52	83	34	42
23	22.6	509	49.09	648	645	631	624	584	20.8	44	40	38	34	37	32	27	54	89	35	47
24	20.1	404	38.92	818	795	779	778	745	26.2	50	45	43	38	41	35	28	61	98	38	51
25	17.9	320	30.86	1031	1004	966	958	903	33	56	50	47	41	45	38	29	67	109	42	58
26	15.9	254	24.47	1300	1240	1202	1188	1118	41.6	63	57	52	45	50	41	31	75	121	45	62
27	14.2	202	19.41	1639	1615	1542	1533	1422	52.5	70	64	58	50	55	45	33	81	139	50	71
28	12.6	160	15.39	2067	2023	1917	1903	1759	66.2	79	71	64	53	60	48	35	94	149	55	85
29	11.3	127	12.21	2607	2625	2485	2461	2207	83.4	88	81	71	58	65	51	37	105	167	61	93
30	10	101	9.68	3287	3325	2909	2893	2534	105	100	88	80	66	71	55	40	115	200	68	109
31	8.9	79.7	7.86	4145	3820	3683	3483	2768	133	112	104	87	71	76	58	43	133	219	83	124
32	8	63.2	6.09	5227	4876	4654	4414	3737	167	125	120	99	76	84	62	43	149	259	94	148
33	7.1	50.1	4.83	6591	6243	5609	5688	4697	211	141	130	105	83	90	66	45	174	304	107	168
34	6.3	39.8	3.83	8311	7757	7111	6400	6168	266	159	140	110	88	97	69	47	211	345	127	203
35	.6	31.5	5.04	10480	9660	8534	8393	6737	335	179	160	130	104	104	73	51	242	405	152	236
36	5	25	2.41	13210	11907	10040	9846	7877	423	200	190	140	110	117	82	58	294	488	176	268
37	4.5	19.8	1.91	16660	13474	10670	11636	9309	533	222	205	150	115	123	85	68	344	590	208	292
38	4	15.7	1.51	21010	16516	14220	13848	10660	673	250	225	160	120	130	88	83	464	746	243	353
39	3.5	12.5	1.2	26500	22260	16520	18286	11910	848	285	255	180	130	142	90	102	548	891	289	399
40	3.1	9.9	.95	33410	26950	21330	24381	14220	1070	321	280	200	140	151	92	139	693	1149	346	452

Fig. 288—Table of useful information on copper wire with various kinds of insulation, such as is employed for tuning coils, inductors, transformer windings, etc. This is useful in conjunction with the charts of Fig 287.

convenient table giving the turns per inch, feet per pound, etc. of the many sizes and types of wire is given in Fig. 288. The use of these is illustrated by the following problem:

Problem: What must be the inductance of the secondary winding of an r-f transformer if it is to tune to 600 meters when the variable tuning condenser of .00035 mf. is set at maximum capacitance? The coil is to be wound with No. 28 double silk covered (d. s. c.) wire, on a two-inch diameter form. Find the number of turns required for the winding and the length of the winding.

Solution: First use chart No. 1 in Fig. 287. Lay a straight edge on the chart so it connects the points representing the two known values, i.e., wavelength=600 meters and tuning capacitance=.00035 mfd. The required inductance is read at the intersection of the straight edge with the inductance scale (L). It is 300 microhenries (the dotted lines on the chart have been drawn to show the condition for this problem).

The dimensions of the coil can be found easily from the chart No. 2 at the right and the wire table of Fig. 288. A line is drawn from the 300 point on the common L scale, to "2" on the coil diameter scale (D), intersecting the index line at point "e". Referring to the magnet wire table of Fig. 288, we find that No. 28 double silk covered wire winds to 53 turns per inch. Another line is now drawn from this value on the "turns per inch" scale (N), through intersection point "e". It is found to intersect the coil-length scale (l) at about 1.7 inches. This means that the coil should be wound to a total length of 1.7 inches. Since this wire winds to 53 turns per inch, there will be 53×1.7 or 90 turns of wire on the coil. Ans.

The charts can be also operated in the reverse direction, always making sure that the correct pairs of scales are connected together, as shown by the "Key" at the lower right of the charts. Thus, if a coil has a certain number of turns of wire of a certain kind and size on a certain size of form, its inductance may be found.

In order to find the exact minimum wavelength (or highest frequency) to which the variably tuned circuit will tune, it is necessary to know the following factors: the minimum capacitance of the condenser; the distributed capacitance of the coil and wiring; the grid-cathode capacitance of the tube it works into; and the capacitance between the coil and metal shielding (if any is used). These capacitances all act to tune the coil. Let us suppose that in the above problem the total of all these capacitances at the minimum setting of the tuning condenser, is C=.00003 mf. Using this value for C, and 300 microhenries for L, we find from the charts, that the minimum wavelength to which the circuit will tune, is 180 meters (1,666 kc). This example shows how simple the design of tuning coils becomes, with the aid of the charts and wire table. They can be used in many ways, for finding any constant of a tuned circuit, when the other constants necessary are known.

It must be remembered that the values obtained by this method of coil design apply only to a single coil of wire isolated in space and connected to a tuning condenser. The moment another coil is brought into its vicinity, the conditions change since the magnetic fields interact and the inductance decreases. For instance, if this coil is to be used with an untuned primary coupled to it, it will be necessary to use one or two more turns on it than the number indicated by the charts. This also holds true when a tickler coil is used with it. If the coupling between the various coils is loose however, there will not be much change in the inductance of the secondary, so no correction need ordinarily be made. The same design procedure applies to the coupling devices used in impedance or tuned-plate r-f amplifiers.

403. Design of the primary winding: The design of an untuned primary winding for an r-f transformer presents several difficulties, and in most cases the final design represents a compromise between several factors. Since the function of the primary coil is to transfer energy to the secondary through the medium of its magnetic field, it would seem that best results would be obtained by a large number of primary turns so closely coupled to the secondary coil that all of its lines of force link with the secondary. This condition would best be met by winding the primary on a form and placing it inside of the secondary, either as a concentrated winding at the center or a distributed winding equal to the length of the coil. However, a consideration of the principle of pure transformer action as studied in Article 111, shows that greatest voltage step-up in the transformer is obtained by making the ratio of the secondary turns to the primary turns as great as possible. Since the secondary turns are determined and fixed by the size of the tuning condenser used and the lowest frequency to which the circuit is to tune, this would mean using only a few turns for the primary winding in order to get a large step-up ratio. However, the conditions in r-f transformers are quite different, for since no iron core is employed, not all of the lines of force of the primary link with the secondary, that is, there is a large *magnetic leakage*. Therefore, if we used only a few turns on the primary, so few lines of force would link with the secondary, that very little voltage would be induced in the secondary at all. The ratio of the number of secondary to primary turns is no indication of the voltage step-up under such conditions—in fact, in an air-core r-f transformer having say 60 secondary turns and 15 primary turns (4 to 1 turns ratio), an actual voltage step-up of only 1.2 or 1.4 might be actually obtained, due to the loose coupling necessary for selectivity. Also a consideration of the theory of the vacuum tube as an amplifier, as presented in Article 336, shows that the amplification or gain produced by the tube is equal to $G=\mu\times\frac{R_o}{R_o+R_p}$ where R_p is the plate resistance of the tube and R_o is the plate load resistance. Therefore in order to secure a large proportion of the possible amplification factor of the tube, it is desirable and necessary that the load resistance (which is the primary of the coupling transformer in this case) be as large as possible. Thus, if the load resistance is 3 times the plate resistance of the tube, 75 per cent of the mu of the tube is obtained, etc. A glance at the table of Fig. 214 will show that the plate resistance of most amplifier tubes is high, especially that of screen-grid tubes which it is desirable to use, so that the primary of the coupling transformer should have a high impedance (large number of turns) in order to secure high gain from the tube. It is evident that the final design is always a compromise between the various factors encountered. In practice the tendency has been to use primaries of 40 or more turns of wire when screen grid r-f tubes are used, in order to obtain sufficiently high plate circuit load for high amplification.

The coupling between the primary and secondary depends on the degree of selectivity required, the number of tuned stages used, etc. The

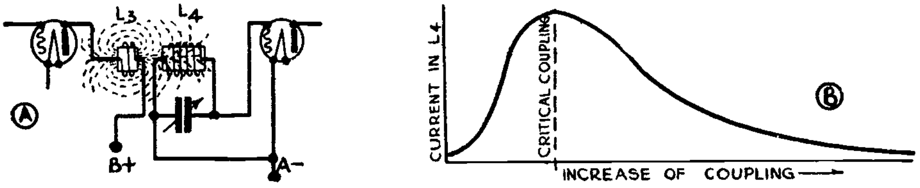


Fig. 289—Effect, on the induced secondary voltage and current, of variation of the magnetic coupling between the primary and secondary windings of an interstage r-f coupling transformer.

value of coupling used, and the exact mechanical arrangement and relation of the primary to the secondary coil is always determined finally by actual trial and experiment for any given receiver design. Two designs of r-f transformers actually used in high-gain screen-grid r-f amplifiers are shown at (B) of Fig. 290. The one at the right, with the prongs, has the primary consisting of about 40 turns of silk covered nichrome wire wound directly over the grid return end of the secondary with a strip of celluloid insulation between them. The secondary is underneath. This arrangement provides rather tight coupling and the selectivity may not be great enough for some reception conditions. The coil design at the left is more desirable in many cases. It has a high inductance primary of many turns of fine wire, wound in a slotted form placed inside of the grid return end of the secondary, but about ¼ inch away from it. This provides the high plate load impedance necessary for high amplification with the screen-grid r-f amplifier tube used, at the same time providing loose enough magnetic coupling for good selectivity. A small capacity-coupling coil C, one end of which is connected to the primary and the other end of which is open, provides a small capacity-coupling for making the transfer of energy more uniform over the broadcast frequencies. In the case of the band-pass coils such as are used in the intermediate amplifiers of superheterodynes, since the primaries and secondaries are usually similar, the primary coil design is automatically fixed by the frequency of the i-f amplifier and the small tuning condenser employed. The amount of magnetic coupling between them is determined by the width of the frequency band to be passed.

404. Effect of varying the coupling: An interesting study of the effect on the induced voltage and current, of variation of magnetic coupling between the primary and secondary windings of an r-f interstage transformer is shown in Fig. 289:

Let coils L_3 and L_4 be so arranged that loose coupling exists between them, that is, L_3 is separated from L_4 so that only a small number of its lines of force link with L_4. If the tuning condenser is varied from zero to maximum capacity, we find that the induced voltage and current in the tuned circuit varies as shown by curve A, at the left of Fig. 290, having a maximum value at the resonant point. This curve has a sharp peak if the coupling is sufficiently loose, and the tuned circuit is therefore selective; in fact, it may be too selective.

If the coils are moved closer together to tighten the coupling, we might expect that as the field of coil L_3 linking with coil L_4 is stronger, the voltage and current in coil L_4 will be greater. This may be the case, but it is not necessarily so, especially if the coupling is greater than a certain "critical" value. The current induced in L_4 sets up its own magnetic field which tends to oppose any change in the inducing field of L_3 (Lenz's Law, see Art. 104), and this effect will be stronger the greater the current flowing in L_4. As the natural frequency of the L_4 tuned circuit is increased from minimum to maximum by the variable condenser, we find that as we approach the resonance frequency the current in L_4 *gradually* rises. As the current becomes stronger, the opposing field also increases correspondingly, reducing the effective or inducing field. As a matter of fact, a condition of sufficiently tight coupling will be reached where the current in L_4 will cease to increase, or actually decrease at the previous resonance point. The closer the two coils are placed together, the more marked will this effect be, as shown by curves B, C, and D, which represent successive degrees of tighter coupling. The double-humped curve D represents an extreme con-

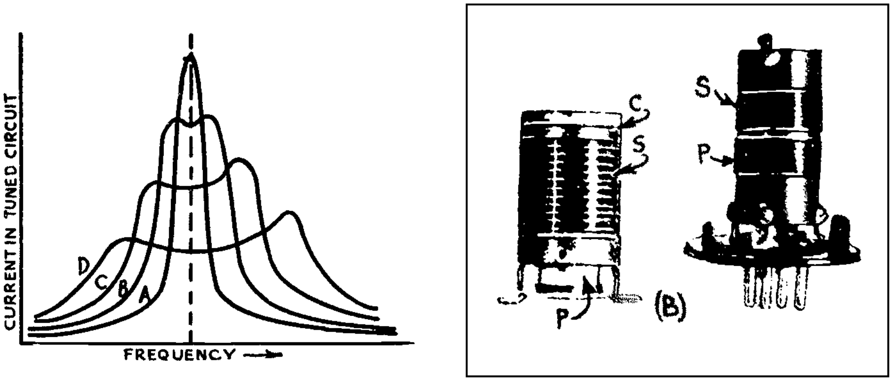


Fig. 290—Left: Effect of tightness of coupling, on the tuning curves of the secondary. Right: Typical r-f tuning coils used in screen-grid receivers. The one at the left has a high-impedance loosely-coupled primary P, a secondary S, and a capacity winding C. That at the right, has a tightly-coupled primary. Both are only 1-inch in diameter.

dition where there are two resonance points, that is, the same station is heard at two separated points on the dial. This of course is due to too tight coupling between the primary and secondary coils.

The question now arises as to just what proper value of coupling is necessary for best results. Let us consider L_3 and L_4 situated ten feet apart. Then since there is practically no linking of the magnetic field of L_3 with L_4, the coils have no effect on each other. If we now bring them together slowly we shall come to a point where the field of the primary links with the secondary, inducing a weak current in it. As the coils are brought closer together more and more of the magnetic field of L_3 links with

L_4, resulting in a gradual increase of induced voltage and current in the secondary. Finally, as the coils are brought still closer, the current in the secondary reaches such a value that it reacts seriously upon the primary, as we have described, causing the *effective* field to be reduced and the current weakened. The point where the secondary current no longer continues to increase as the coupling is tightened is called the point of "critical coupling". This is shown graphically at (B) of Fig. 289, where it is seen that as the coupling is increased from zero, the voltage and current in L_4 passes through a maximum value, and then decreases.

Therefore, for best results the coupling should be adjusted as near to the critical value as possible. Looser coupling than this results in poor transfer of energy, closer coupling results in poor selectivity, and also results in the secondary condenser tending to tune the primary coil through the agency of the reversed magnetic field. This tuning of the primary may result in oscillation tendencies due to the plate-grid capacitance of the tube. Notice, that the selectivity obtained is governed by something else besides the resistance of the tuned circuit, namely, the tightness of coupling between the primary and secondary. The calculation of the mutual inductance and coupling coefficient between coils was discussed in Articles 120 to 122.

405. Constant r-f coupling: A study of the coupling existing between the primary and secondary windings of an r-f transformer having a fixed primary, reveals the fact that for equal input, the voltage induced in the secondary is not constant over the broadcast frequency band. The induced r-f voltages in the secondary turns are proportional not only to the strength of the primary field, but also to the rapidity with which that field alternates. Thus at the higher frequencies, the r-f alternations are much faster than at the lower frequencies, and the induced r-f voltages will therefore be much greater when receiving stations around 200 meters than is the case when receiving stations around 500 meters. If such a circuit is made non-oscillating at 200 meters it has little sensitivity at 500 meters. If it is made sensitive at 500 meters by working near the oscillation point, it usually oscillates violently at lower wavelengths.

Several schemes have been developed to remedy this defect. In one, the Lord system, the primary coil is moved away from the secondary as the condenser is tuned to the higher frequencies. This is accomplished by a cam on the condenser shaft which acts on a follower attached to the primary coil. It is easily seen that the primary field, being removed from the secondary field at the higher frequencies, cuts a smaller number of secondary turns and thus induces less voltage.

In another, the King system, the primary is mounted on the condenser tuning shaft by an adjustable bracket and in such relation to the secondary coil that as the condenser is tuned to the low wavelengths the primary is rotated more and more at an angle with the secondary, thus loosening the coupling. In both these systems the plate load impedance remains substantially the same.

An arrangement credited to K. Hassel and used in Zenith receivers at one time, consists of taking a portion of the primary coil and mounting it on the condenser shaft so that it rotates inside of the secondary coil, in such a manner that the rotating portion of the primary coil opposes the coupling from the fixed portion at the low waves and adds to the coupling at the high waves. In this way the primary-secondary coupling is varied with change of wavelength and the impedance value of the load connected in the plate circuit of the tube is varied to keep it just below the critical value.

None of these systems are really simple enough for practical use in modern receivers where all of the tuned circuits must be operated by a single control. An electrical circuit method of automatically securing equal voltage transfer at all frequencies in the broadcast band is necessary. A system of this type developed by Messrs. Loftin and White, is based on the fact that the reactance of a condenser *increases* as the frequency de-

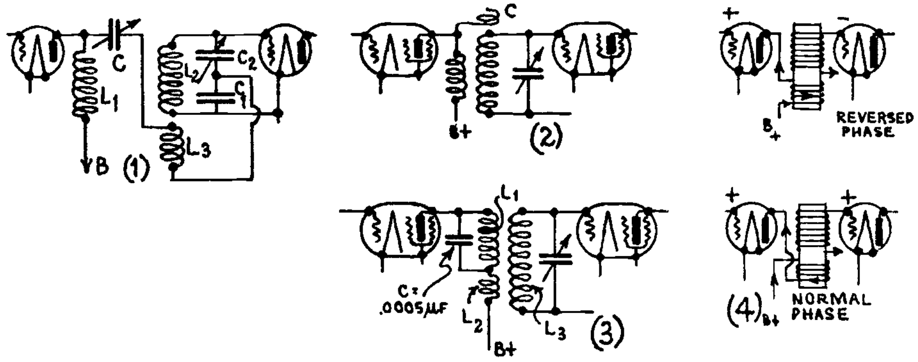


Fig. 290A—(1) Loftin-White constant coupling circuit; (2) obtaining constant coupling by capacity winding C; (3) obtaining uniform amplification by resonated primary winding; (4) primary and secondary coil connections.

creases, and that the impedance of an inductance *decreases* as the frequency decreases (exactly the reverse).

The circuit of this system, one stage of which is shown at (1) in Fig. 290A, has its inductances and capacities so connected that there is both inductive and capacitive coupling. The values of the inductances and capacities are so adjusted that as the reactance of say the inductance starts to drop off, the reactance of the condenser increases, and vice versa, so that actually the coupling resistance remains almost constant for all frequencies within a reasonably wide band. Consequently, after the associated circuits have once been adjusted to prevent oscillation, there is no change in either the amount of selectivity, sensitivity or regeneration, at any frequency. By proper adjustment the set may also be made to oscillate at either the high or the low wavelengths.

In Fig. 290A it can be seen that inductive coupling is obtained through coils L_2 and L_3, while capacitive coupling is furnished by the condensers C and C_1. Coil L_1 is an r-f choke which prevents the leakage of any r-f currents into the "B" supply circuit, and makes them all go through L_3, through C_1 to the cathode, while C is a phase-shifting condenser which is employed for the purpose of shifting the phase of the r-f plate current.

Mutual inductance is less effective for transferring energy at the higher wavelengths than at the shorter ones. Mutual capacity behaves in an opposite manner. Suppose that the set is tuned to a low wavelength and all constants are adjusted to keep the receiver at maximum efficiency. Now suppose it is tuned to a higher wavelength. The energy transfer from L_2 to L_3 by inductive coupling decreases. Also as the tuning condenser C_2 is increased in capacity for tuning to the longer wavelength, its reactance decreases, and the voltage drop across it decreases. Therefore, there is more voltage across C_1 proportionately, and hence more current is fed to the tuned circuit by the capacitive coupling, offsetting the effect of the decreased energy transfer by magnetic induction.

One of the objections to this circuit is that it is rather difficult to adjust all of these parts when the receiver is built. It is not very well suited to quantity production methods of manufacture.

In r-f coils employing high-inductance primaries, the primary inductance is usually great enough so that in combination with all stray capacities across it, it tunes to some frequency below the broadcast band (a wavelength above 550 meters). This gives rise to the peculiar effect of the gain being good at around 550 kc, but poor around 1,500 kc. The falling off at the high frequencies can be partly compensated for by placing the primary (which is really a small choke coil in this case), at the grid end of the secondary and thereby introducing capacity coupling due to the difference of potential between the primary and the grid end of the secondary. This capacity coupling is of course more effective at the high frequencies, and by careful designing, a transformer may be obtained producing almost even amplification over the broadcast band. Another way of accomplishing this is to wind one or two turns of wire over the grid end of the primary. One end is left disconnected and the other end is connected to the primary. These few turns of wire then act as a small condenser between the primary and secondary, and by shifting them slightly along the coil, the value of this coupling capacity may be varied until best operation is obtained. This open-end "capacity winding" is marked C in the coil at (B) of Fig. 290. It is also shown at (2) of Fig. 290A.

A simple circuit scheme for obtaining uniform r-f amplification, and which has been used in many receivers employing screen-grid r-f tubes is shown at (3) of Fig. 290A. Here the primary L_2 and secondary L_3 form an ordinary r-f transformer. L_1 is a separate high-inductance coil wound to fit inside of the secondary at the grid end. A condenser C connected across it, tunes it rather broadly to resonance at whatever small band of frequencies it is designed to raise the sensitivity. Since this is a parallel tuned circuit, it acts as a high impedance load in the plate circuit at these frequencies, and so results in greater effective amplification by the tube at that particular band of frequencies. In this way, the sensitivity of the receiver may be increased at any frequencies desired.

Confusion often arises when connecting the primary and secondary windings of an r-f transformer to the two tubes between which it operates. There are two possible directions in which each winding may be connected. One arrangement is called "normal phase" and the other is called "reversed phase". Let us first assume that the primary and secondary coils are wound in the same direction of rotation as shown at (4) of Fig. 290A. This is generally the case; for the same winding machine winds both the primary and the secondary. In this case the plate of the preceeding tube is always connected to the end of the primary which corresponds to the cathode end of the secondary, when a *normal phase* connection is desired; the reverse is true when *reverse phase* is desired. Both of these connections are shown at (4).

With the normal phase connection, if the grid of the preceeding tube is made say, more positive, an increase in plate current results. This increased plate current flowing through the primary winding induces a voltage in the secondary in such a direction as to tend to oppose this increase, (Lenz's law). This will make the grid of this tube more positive also, i.e., the signal impulses in the grids of the two tubes are in phase. With the reversed phase connection, the signal impulse on the grids of the two tubes is 180 degrees out of phase. When the coil is used with an oscillator tube, the plate and B+ ends of the primary go to the same tube. If the two windings are in opposite directions, the same rule applies, only the terminal connections of either one of the windings must be reversed. The calculation of mutual inductance and coupling coefficient between coils was discussed in Articles 120 to 122.

406. Losses in tuning coils: Although extreme selectivity in the r-f amplifier is undesirable from the point of view of sideband frequency suppression, unless some compensation of the audio high note response is purposely introduced into the audio amplifier or loud speaker, it is usually advantageous to keep the resistance of the tuned circuits as low as possible consistent with sensible, practical design, in order to obtain maximum voltage gain in the tuned circuits, and secure the proper amount of selectivity by proper coupling of the primary and secondary coils. Common sense should rule all attempts to reduce the resistance. It is not necessary to resort to the use of gold or silver wire because of their better conductivity, or to wind the wire to be self supporting so as to eliminate the supporting form or tubing, nor is it necessary to hang the coils up by threads in order to eliminate metal supports. Such drastic practices cost more than the results they accomplish are worth. It has been found by many tests that the most efficient form of r-f tuning coil is one wound in loose basket-weave, or simple solenoid form, somewhat like the coils shown in Fig. 290, having a ratio of diameter to length of approximately 2.5, and wound with No. 20 to 26 wire. This proportion may be departed from over quite a wide range without seriously affecting the efficiency of the coil. Actually, in the coils used in radio work this ratio may be as low as 0.75 and still the coils perform well. Due to the necessity for compact construction, American designers have reverted to the use of small tuning coils around one inch in diameter, wound with enamel-covered wire.

In order to get the 100 or more turns of wire necessary for these coils when they are used with the standard .00035 mfd. tuning condensers on the broadcast band, and still keep the length of the coil small, wire of about No. 30 B. and S. gauge is used. The efficiency of coils of this construction does not depart greatly from that of the more efficient coils which might be built with larger wire, of larger diameter, etc., especially when we consider that the coils in modern compact receivers must be mounted close together, and must therefore be enclosed by metal shielding to prevent interaction of the magnetic fields.

The losses in a coil in which high-frequency currents flow are much greater than the simple "ohmic resistance" of the wire measured for direct current conditions. All of the losses in a tuning coil at radio frequencies are usually summed up and expressed as a single loss called the *a-c resist-*

ance of the coil. This is usually considered at the particular frequency at which the coil is being employed. While this is not technically correct, it has become the accepted practice, since the final effect of these losses is to reduce the current in the tuned circuit, just exactly as if the tuned circuit itself had no resistance and we inserted a resistor equal in value to this so-called "a-c resistance" into it.

One source of loss, known as the *skin effect*, is due to the fact that at the high frequencies the currents travel only over the surface or "skin" of the wire, thus making only a small proportion of the total cross-sectional area of the wire effective in carrying the current, thus increasing the resistance to the flow of the current.

When d-c flows through a wire, the electron flow is uniformly distributed throughout the entire cross-section of the wire, that is, there is as much current flow-

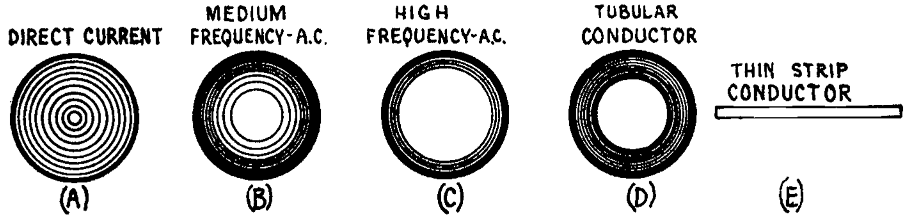


Fig. 291—Skin effect at high frequencies. Due to the high self-induced counter e.m.f. developed in the center part of the conductor, the current flows only through a thin outside shell of the conductor at these very high frequencies.

ing through a given area at the center as through an equal area near the outside surface, as shown at (A) of Fig. 291. When high-frequency a-c flows through a wire, the rapidly alternating circular magnetic field (magnetic whirls), produced around the wire (see Fig. 53), expands and collapses as the current rises and falls. This induces a counter-e. m. f. in the wire itself which tends to oppose the flow of current through it (Lenz's law). Since the field is varying most rapidly at the instants when the current goes through its zero values, during each half cycle (see Article 160), the induced counter-e. m. f. is greatest at these instants. But at these instants the magnetic whirls have either just collapsed to the center axis of the wire or are just about to spread out from there. Therefore the region of greatest counter-e. m. f. due to the field lies at the center axis and the current flow is opposed more there than at the outside regions. As the frequency is increased, the field varies rapidly even at other parts of the cycle, so the counter-e. m. f. becomes appreciable at these other times also. The result is, that at high frequencies a large proportion of the current flowing through the wire flows through the part nearest the outside surface, i.e., along a "surface shell" of the wire, as shown at (B) and (C). Therefore the conductor offers just as much resistance as it would if it had less cross-section area, i.e., the resistance is increased because the current or electron flow is crowded into a smaller cross-section area. The higher the frequency, the greater is the "skin effect". At very high frequencies, for a given weight of conductor we actually obtain better conductivity with a hollow tube having thin walls than from a solid wire, because the center of the wire only adds to the weight and cost of the conductor without serving any purpose in carrying current. If it is left out, it is not counted as part of the cross-section area and so the resistance is lower. The added resistance due to the skin effect is greater in larger wires than in small ones because in the larger wires less of the total bulk is represented by the skin or surface, so a smaller proportion of the whole bulk of the wire is being used to carry the current. A special wire called "litzendraht" has a very low skin-effect, due to the fact that it is made of 25 or more strands of fine wire each insulated individually from the others by enamel or cotton insulation. This is more expensive than ordinary magnet wire.

At broadcast frequencies (500 to 1,500 kc) the skin effect is not large enough to warrant the use of any special forms of wire for ordinary purposes. In short wave work (high frequencies) "Litz" wire is often used for receiver tuning coils. Transmitter tuning coils are usually made of copper tubing as at (D) or of thin flat-copper strip as at (E), to obtain a large surface area.

Another loss which exists in coils used in high-frequency circuits, is that due to eddy currents set up in the wires of the coil by the varying magnetic field. This increases as the diameter of the wire used is increased. The total resistance of r-f coils increases greatly as the frequency is increased. The amount of resistance increase depends on the shape of coil and size of wire. For instance, a single-layer solenoid coil of 300 microhenries inductance, consisting of about 58 turns of No. 28 D. C. C. (double cotton covered) wire wound on a 3-inch diameter tube, was measured and found to have a resistance of 3.15 ohms on direct current, 6 ohms at 500 kilocycles (600 meters), 10 ohms at 1,000 kilocycles (300 meters) and 14 ohms at 1,500 kilocycles (200 meters). When a coil is surrounded by metal shielding a loss also occurs due to the eddy currents set up in the shielding by the magnetic field of the coil. This will be studied in detail in Articles 412 and 413.

407. Distributed capacity: Another tuning coil characteristic which is usually undesirable, is known as *distributed capacity.* In a coil which has a potential difference existing between its terminals, a proportionate potential difference exists between every two adjacent turns of wire on the coil. Since the various turns of wire are conducting surfaces separated by the insulation on the wire, they form tiny condensers distributed along the turns of wire. As the adjacent turns are at different electrical potentials, small alternating currents flow back and forth in the tiny circuits formed by these distributed condensers at high frequencies. By imagining all the little distributed capacities of these condensers lumped together to form a single condenser C_D, the coil may be considered as a pure inductance with a condenser C_D in parallel. At low frequencies, the condenser effect is negligible and all the current flows through the wire. However, if the frequency is progressively increased, the reactance of the inductive part of the coil increases and that of the distributed capacity decreases, until a point is reached where practically all of the current passes through the distributed capacity, and the coil behaves like a condenser instead of an inductance. The working frequency-range of a tuning coil must be necessarily small if it is to have constant inductance. Since there are losses in these small condensers due to the imperfect insulation properties of the solid insulating material between the turns, and due to the dielectric hysteresis and absorption (see Articles 130 and 131), the apparent resistance of the coil is increased by their presence.

It is for this reason that tuning coils should not be coated with shellac and other "dope" preparations which increase the distributed capacity effect and also the losses. Distributed capacity in a tuning coil is also a disadvantage, since it lowers the frequency range over which a coil can be tuned by an external condenser; for even when the external condenser is at its minimum value, the full distributed capacity is shunting the coil. If high inductance values, necessitating the use of a large number of turns of wire wound in several layers are necessary, the windings should be bank-wound as at f and g of Fig. 292, to reduce the distributed capacity.

Just as the capacity of a condenser may be decreased by decreasing the area of the plates or increasing the distance between them, the distributed capacity of a coil can be reduced by using a smaller wire or by

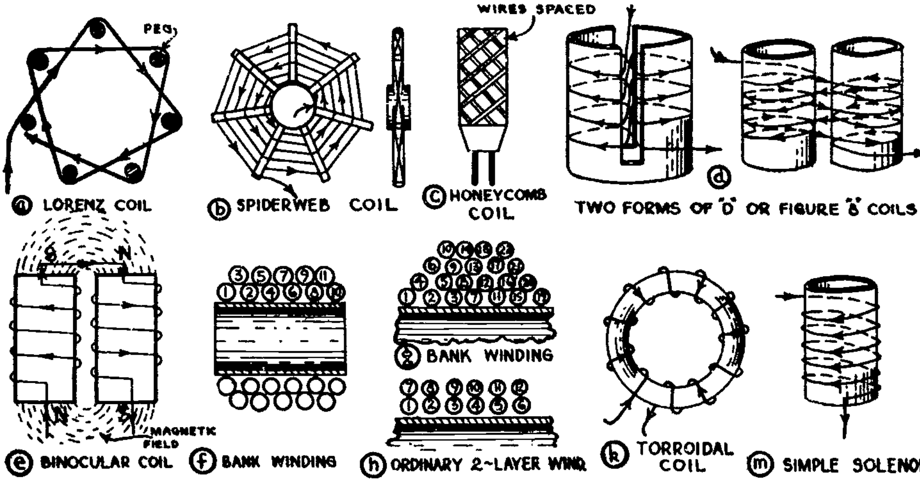


Fig. 292—Various shapes of coils and forms of windings which have been employed for r-f coils. Those at (C), (G), and (M), are most popular now.

leaving a space between the adjacent turns of a coil. The size of the wire cannot be decreased too much, for the resistance will then increase, and the distance between turns cannot be made too large, for the inductance will then be decreased, necessitating more turns for a given value with consequent increased resistance and added capacity. On a solenoid, cotton covered wire of about No. 24 B. & S. gauge wound tightly, already has enough spacing between the metal of the conductors due to the double thickness of the insulation so that the turns may be wound close together. When enameled wire is used, a spacing equal to half the diameter of the wire may be employed to reduce the distributed capacity. The wire is usually wound in a spiral groove, machine-cut lightly into the coil form. This gives accurate spacing. It is obvious that the distributed capacity increases with the diameter of the coil, since this increases the effective surface area. This is another advantage in using small tuning coils.

408. Coil shapes and types of windings: Many shapes of coils and types of windings have been developed and used, but the fact remains that for a given inductance value, the simple solenoid at (m), or the loose basket-weave coil at (a), have the lowest resistance of all of them when the diameter of the winding is approximately 2.5 times the length of the winding. This proportion may be departed from over quite a long range without seriously affecting the efficiency of the coil. Actually, in coils used in most radio work this ratio may be as low as 0.75 and still the coils perform well. However, each of the other forms of coils shown, have some particular advantageous feature which may make it particularly desirable for some special application. For coils having large inductance, the honeycomb or "universal" type winding is preferable on account of its compact form and low distributed capacitance. A discussion of various coil windings which have been developed follows. The various windings are shown in Fig. 292.

Lorenz developed a coil having a low distributed capacity. By winding the wire on a series of pegs arranged in a circle, he was able to zigzag it as shown at (a). No two turns are parallel to each other at close proximity for any distance, so the distributed capacity is lower than in the simple solenoid winding at (m). The pegs are removed after winding. Another way of reducing capacity is by winding the coils on flat strips mounted radially like the spokes of a wheel as at (b), and zigzagging the wire. This is known as the *spiderweb coil.*

The *honeycomb coil* at (c) is wound with a number of layers, the turns of each adjacent layer crossing each other almost at right angles. It is used where large values of inductance are required. It is usually mounted on a base having two contact pins for plugging into a receptacle. This construction reduces the distributed capacity. This is probably the most popular type of coil for long-wave reception, and for the intermediate-frequency amplifiers of superheterodynes. The so-called "universal" winding often used, is somewhat similar to this honeycomb type. These coils are made in various standard sizes, with inductance values, distributed capacity, etc., as given in the accompanying table.

DATA ON HONEYCOMB COILS

No. of Turns	Inductance at 800 Cycles, in Millihenries	Natural Wave-length Meters	Distributed Capacity in Mmfd.	Wavelength Range, Meters	
				0.0005-Mfd. Condenser	0.001-Mfd. Condenser
25	.039	65	30	120 to 245	120 to 355
35	.0717	92	33	160 to 335	160 to 480
50	.149	128	31	220 to 485	220 to 690
75	.325	172	26	340 to 715	340 to 1020
100	.555	218	24	430 to 930	430 to 1330
150	1.30	282	17	680 to 1410	680 to 2060
200	2.31	358	16	900 to 1880	900 to 2700
249	3.67	442	15	1100 to 2370	1000 to 3410
300	5.35	535	17	1400 to 2870	1400 to 4120
400	9.62	656	13	1800 to 3830	1800 to 5500
500	15.5	836	13	2300 to 4870	2300 to 7000
600	21.6	1045	14	2800 to 5700	2800 to 8200
750	34.2	1300	14	3500 to 7200	3500 to 10400
1000	61	1700	13	4700 to 9600	4700 to 13800
1250	102.5	2010	11	6000 to 12500	6000 to 18000
1500	155	2710	13	7500 to 15400	7500 to 22100

The manufacturer's type numbers of commercial coils of this kind usually give a key to the number of turns they contain. Thus a DL25 coil has 25 turns, a DL100 coil has 100 turns, etc.

The illustration at (d) shows a D or "figure 8" coil, so called because each of its two halves form the letter D, and the whole coil forms a figure 8. It is wound by slotting a tube, or may consist of two separate interconnected coils as shown at the right. The magnetic fields of the two coils aid each other inside the tube and oppose each other outside so that a very small external magnetic field is produced. This reduces stray magnetic coupling with other coils in the receiver.

A *binocular coil* is shown at (e). This consists of two separate coils connected in series, and having magnetic fields as shown. This also has a very restricted external magnetic field, is easier to construct and is more efficient than the D coil.

A two-layer bank-wound coil as shown at (f), and (g) shows one of 4-layers. This type of winding is also used where a large inductance is required in compact form with low distributed capacity. The reason for banking the turns of a multilayer coil lies in the fact that the capacitance between layers of the ordinary multilayered solenoid is excessive. This capacitance gives the coil a tendency to oscillate at some particular frequency and moreover increases the dielectric losses. In banked coils instead of winding on one complete layer followed by successive similar layers, one turn is wound successively in each of the layers. The voltage between adjacent wires is thus reduced, and accordingly the distributed capacitance is reduced. This decreases the currents flowing in the tiny distributed capacity circuits. Compare the banked windings at (f) and (g) with the ordinary 2-layer winding at (h). For banked windings not too great in depth as compared to diameter, a close approximation for the inductance is obtained by using Nxn for the turns per inch in the solenoid inductance formula, (where N=No. of banks). The formula then becomes $L = .0251\, d^2 N^2 n^2 lK$.

A torroidal coil is shown at (k). This has the advantage of having practically no external field, but the resistance of this form of coil for a given inductance value is so high compared to that of the other forms that it is rarely employed in radio equipment.

While these and many other forms of coils have been developed for special purposes, the fact remains that for a given amount of inductance (within the broadcast frequency range) the most efficient coil is one of simple solenoid form as shown at (m), having a ratio of diameter to length of about 2.5. This ratio can be reduced to about 1 or even 0.75, without seriously affecting the efficiency. On broadcast frequencies it makes little difference whether the coil is self-supporting or whether it is wound on a thin insulating form. The latter is preferable for its mechanical rigidity. It is not necessary to use wire larger than about 24 B. & S. gauge. No. 26 or 28 can be used satisfactorily. (See Technologic Paper No. 298 of Bureau of Standards.) Now it is evident that for practical reasons, coils must be made of a definite size and of proper rigidity. Since the position of nearby metallic objects causes losses due to absorption of energy due to the setting up of eddy currents; and interstage coupling is undesirable, the tuning coils used in modern radio receivers are much smaller in physical size than were those used several years ago, because our receivers are made much more compactly now than they were then (see Fig. 286). The illustration in Fig. 293 show this interesting historical development and constant reduction in dimensions of tuning coils. At the left, is a large 4½ inch diameter coil popular in the neutrodyne receivers used as late as 1929. A smaller 2½″ coil popular at about the same time is next. Following this is a 2-inch diameter coil, popular in 1929 and 1930. The small one inch coil at the right is typical of the type used extensively now, on account of its small size and limited external magnetic field. This illustration shows the exact comparative sizes, since all of the coils were photographed together. The inch-scale alongside of the 3-inch coil shows the comparative sizes. Precision coil-winding machinery has been developed to wind r-f coils so they are produced by the thousands, with electrical constants suitably uniform. Enamel covered copper wire is used extensively on account of its obvious advantages of being handled without damaging by finger marks, and being unaffected by atmospheric moisture.

409. Interstage coil coupling: In Article 308 we found that any voltage induced in the grid circuit by means of energy fed back from the

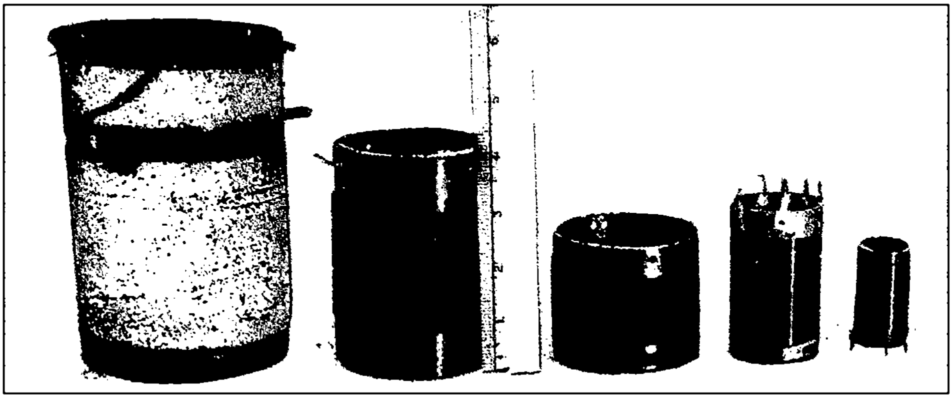


Fig. 293—This illustration shows how the dimensions of tuning coils have been reduced during the past few years. At the left is a 4½ inch diameter coil popular in 1923. At the right is a 1-inch diameter coil popular for use in modern receivers.

plate circuit of an r-f amplifier tube, would cause oscillation if it were of sufficient magnitude and proper phase relation. We found that the grid-plate capacitance of the tube was a prolific source of such feedback, and that special means for reducing or neutralizing this feedback were necessary if 3-electrode tubes were used as r-f amplifiers, on account of the comparatively large plate-grid capacitance of these tubes. The use of screen-grid type tubes removes the necessity for using these neutralization and losser schemes, since the feedback due to the p-g capacitance is very low because of the low value of this capacitance in tubes of this kind. However, feedback via the p-g capacity is not the only way in which it can take place. Energy can be fed back from the plate circuit to the grid circuit of any amplifier stage through magnetic coupling which may exist due to large stray magnetic fields, or close placement of the tuning coils. Energy may even be fed back from an r-f stage to a circuit one or two stages ahead of it in the receiver, through magnetic or capacative coupling. This fact is often overlooked by amateur set builders, with the result that despite elaborate precautions to eliminate oscillation, by using screen-grid r-f amplifier tubes, etc., persistent oscillations result due to magnetic feedback between the tuning coils, or coupling in the B power supply, etc. If the fed-back energy is in phase with the incoming signal voltages in the grid circuit of that tube, increased response will result due to the additional amplification produced, but if it is large enough, as it usually is, it will cause the tube to generate oscillations, acting as an r-f oscillator. Whistling due to beat notes will be heard when a station is tuned in, or when the tuned stages are not set exactly at the frequency of the incoming signal. If the induced voltages due to feedback are out of

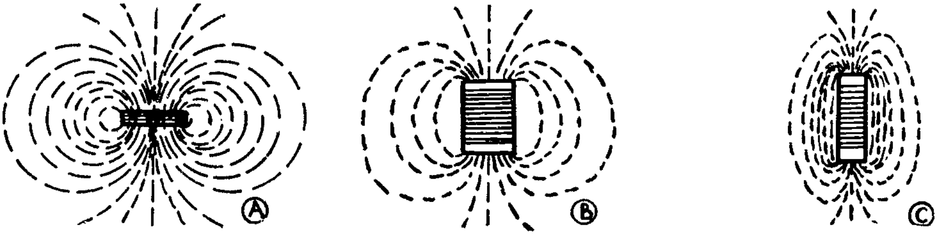


Fig. 294—The proportions of a solenoid coil greatly affect the external magnetic field. The short, large-diameter coil of (A) has a widespread field, that at (B) has a more confined field, and the long thin coil at (C) has a limited external field, making it desirable for use in compactly built receivers.

phase with the incoming signal voltages, opposition or "degeneration" will result, and the response of the set will be decreased. As r-f amplifiers of higher and higher amplification per stage are built, any stray magnetic or capacitive couplings which may exist between certain parts or circuits become increasingly important, because the fed-back energy is amplified more by the tube, and there is greater tendency to cause the r-f tubes to go into the state of oscillation.

It is not necessary to eliminate every trace of feedback or coupling, for a small amount is desirable and is often purposely introduced by receiver designers because it increases the sensitivity of the receiver due to the additional amplification produced. It is when the feedback reaches a value sufficiently great to cause oscillation or cause the set to operate on the verge of oscillation, that it is objectionable. The stray couplings may be one or more of three types, magnetic, capacity, or resistance coupling. The latter is the most prevalent in B— power supply units and in grid-bias resistors connected in the common cathode return circuit for supplying grid bias for several r-f tubes. The remedy for each of these, is to use by-pass condensers of sufficiently large capacitance across the resistors in which coupling occurs, as explained in Article 377. Inductive coupling between wires and between coils was discussed in Articles 121 to 125. Objectionable capacitive and inductive coupling between circuits is best reduced by laying out the wiring of the receiver so that all *grid* and *plate* connecting wires are as short and as far apart as possible, preferably with air (dielectric constant=1) between them. If they must be run close due to the particular design of the receiver, they should cross at *right angles* if possible. Coupling between the successive tuning coils may take place through the medium of their magnetic fields. This is by far the most prevalent form of coupling, but fortunately it can be almost entirely eliminated by proper design. The first precaution to eliminate magnetic coil coupling is to use coils having limited external magnetic fields. The torroid, D coil, binocular coil, etc., possess this characteristic, but these coils all have a much greater r-f resistance for a given inductance than the simple solenoid coil, so they are not used extensively. Satisfactory characteristics may be obtained by proper use of the more efficient solenoid form of coil.

410. R-F coil proportions: The shape of the magnetic field around a solenoid coil changes as the proportions of the coil are changed, as shown in Fig. 294. The field around a short coil of large diameter, is shown at (A). The field is nearly circular in shape, and extends out a large distance on all sides of the coil, obviously very good for interstage feedback coupling. A coil slightly longer than it is wide is shown at (B). The field is slightly elliptical in shape and does not extend out as far from the sides of the coil as the other. A long coil of small diameter is shown at (C). The field is very elliptical and does not extend far out from the coil. This is obviously the type of coil most suitable for use in compactly built radio receivers. Many of the commercial sets employ coils of this type having a diameter of about 1 inch and length of about 2 inches as shown in Fig. 290. They are wound with about No. 30 enameled wire, space-wound in a shallow spiral groove machine-cut in the coil form.

411. Placement of r-f coils: Even though r-f coils with limited external magnetic fields are employed, they must be mounted so close together in modern receivers of compact construction, that magnetic coupling between them must be eliminated either by mounting them in angular relation with each other in "no-coupling" positions, or else shielding them in metallic shields.

If the coils are all mounted with their axis lying in the same straight line, and turned so every coil is at right angles to every other coil, no magnetic coupling will exist between them. Fig. 295 shows this relation for three coils. Consider the magnetic field of coil B having a direction as shown by the arrows, at some particular instant. It links with coils A and C. Any line of force approaching the coil A from the right, cuts the wire twice and sets up a voltage in each half of every turn. These voltages are in opposite directions as shown by the arrows, and since they are equal, they neutralize each other. Hence there is no coupling to A. Similar reasoning holds for coil C, where the opposing directions of the induced voltages are shown. This

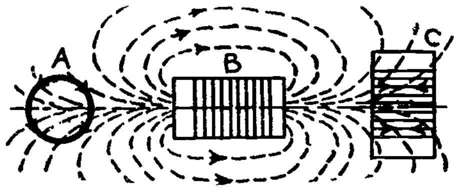


Fig. 295—Right angle coil placement to prevent magnetic coupling between coils. Axes of all coils lie along the same line.

right-angled placement of coils is simple and effective and has been used extensively in tuned r-f sets.

Another method is to place the coils parallel to each other but at such distances apart that the lines of force of each coil cut through the other coils at right angles to the axis, thus producing equal and opposite voltages in both halves of each turn, which neutralize each other. This is shown in Fig. 296. If the coils are mounted on a panel, in the manner shown at (A) to save space, it is found that the coils make angles A with

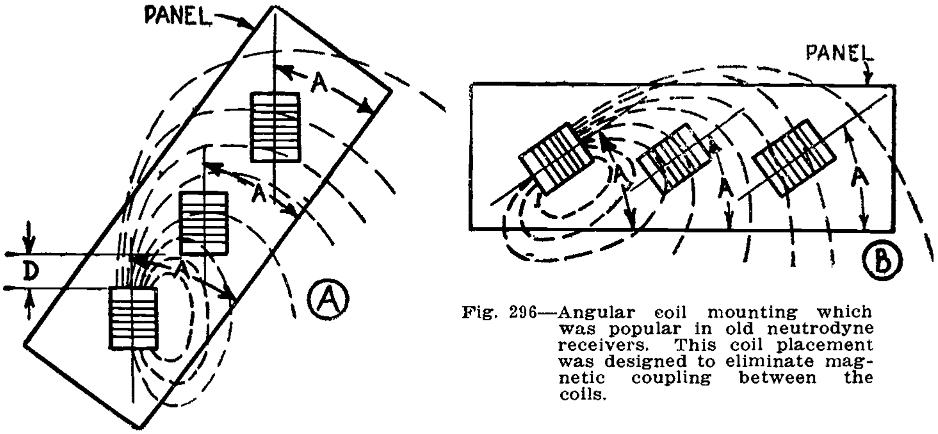


Fig. 296—Angular coil mounting which was popular in old neutrodyne receivers. This coil placement was designed to eliminate magnetic coupling between the coils.

the base of the panel. If this panel is shown in a horizontal position as at (B) you will probably recognize the familiar neutrodyne arrangement used extensively several years ago.

Obviously the angle A at which the coils must be placed, and the distance D between them, are not constant factors for all receiver designs but vary with the physical proportions of the coils used, since the shape of the magnetic fields also vary with these. Consequently, although 54.7 degrees was recommended for the no-coupling angle A in the old neutrodyne sets, it does not follow that this angle is correct when coils of different size are used. The angle must be determined for the particular coils used. This makes the right-angle placement, discussed previously, more practical for ordinary use unless metal coil shielding is to be employed.

412. Shielding in r-f amplifiers: The coil arrangements just discussed, will eliminate magnetic coupling between various coils in an r. f. amplifier but they do not eliminate the capacity coupling which will exist between the windings on one coil and those on adjacent coils. The windings really act like the plates of condensers with the air space between the coils as the dielectric. When the coils must be mounted closely together, this capacity coupling will be very great. Both the interstage magnetic coupling and capacity coupling may be reduced greatly by enclosing the coils, or the entire separate r-f stages, in metal shields made usually of aluminum or copper and connected to B— and ground. The energy of any stray magnetic fields, is dissipated in the shield metal in the form of heat, due to the fact that the rapidly alternating fields set up "eddy currents" in it (see (F) of Fig. 79). However, shielding introduces resistance into the tuned circuits due to the losses, unless great care is taken in allowing proper clearance between the coils and the shields.

A grounded plate or screen of fairly good conducting material enclosing the circuits under consideration takes care of the disturbing effects of *electrostatic fields* (see Article 309 and (A) and (B) of Fig. 225). As long as the metal enclosing the circuits is a good conductor, it may be thin and yet give complete shielding from external electric fields. If the resistance of the shielding material is very high, or if the frequency is quite high, the electrostatic shielding will be correspondingly less complete. For this reason, sheet iron, zinc, etc., are not good shielding materials for use in r-f amplifiers. It is a much more difficult problem, however, to eliminate the disturbing effects of the electromagnetic fields upon the circuits. To completely shield a space, it must be surrounded by a box of conducting material.

The question naturally arises as to the shielding efficiency of various metals. The basic factors governing the shielding efficiency of copper and brass in particular, have been investigated by Morecroft and Turner (Proc. Inst. Radio Eng. *13*, 477, 1925), while Mason (Q. S. T. *15*, 23, 1928) has measured and discussed the shielding efficiency of aluminum in reference to other materials such as copper and brass. It was found that the thickness of the shield, the frequency of the field which is being shielded and the conductivity of the shielding metal all have a bearing on the efficiency of the shielding. At low frequencies the thickness of the shield and the conductivity of the metal are relatively important factors. At the radio-frequencies used in broadcasting and at higher frequencies, however, the conductivity of the shield is not so important; very thin shields of either aluminum or copper may give practically 100 per cent shielding. Shields made of 20 gage (0.032 inch) or thicker aluminum sheet give good results mechanically and also give substantially 100 per cent shielding. This combination of high electrical conductivity, good mechanical rigidity and low weight has made the use of aluminum shielding very popular. Also it can be given a very pleasing and permanent dull silvery finish at very little cost. When copper is employed, it must be lacquered or otherwise treated to prevent corrosion and tarnishing.

Collapsable aluminum stage-shields are available with flat side pieces about 0.08 inch thick and special grooved corner pieces into which they fit. These are very convenient for making box-shields.

Shielding should be thoroughly grounded to the B– and ground circuits of the receiver. It is not considered good practice to employ the

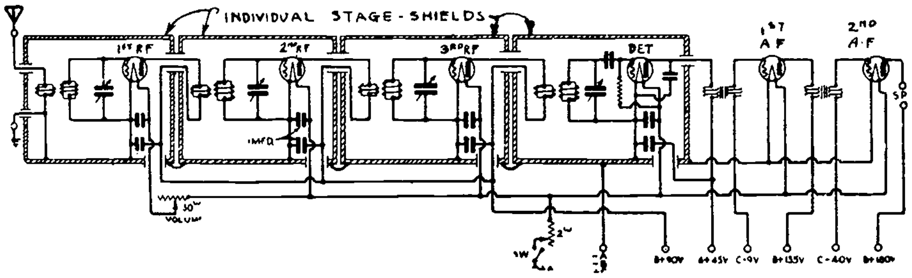
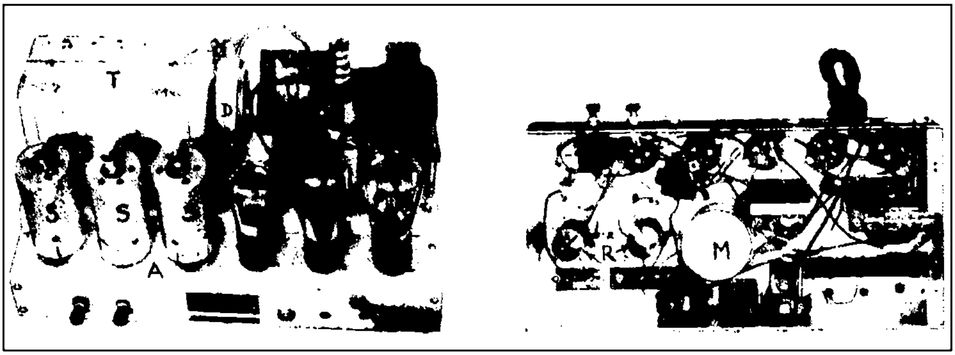


Fig. 297—Battery-operated receiver with three tuned r-f stages, in which each complete r-f stage and the detector, is shielded from the others by a separate metal enclosing "stage shield."

shielding as a conducting path for the filament, cathode, or grid return circuits, since undesirable couplings may take place between the various circuits due to high resistance joints in the path, or to the actions of the magnetic fields of the returning currents. This is the cause of oscillations in many otherwise well-designed high-gain receivers, in which all other sources of interstage coupling have been removed. It is best to provide a separate insulated conducting wire for each current path. In this way the various currents are all confined to their proper paths and are kept separate. All holes in the shields, necessary for instrument shafts, wiring, etc., should be as small as possible, since the shielding effect can be



Courtesy Pilot Radio & Tube Corp.

Fig. 298—Top and bottom views of the chassis of a typical radio receiver in which individual tuning condenser, r-f tube, and r-f coil shields are employed. M is a coil shield.

totally spoiled by a few large open holes. Where wires are brought out through the shields, it is a good plan to use small rubber bushings to prevent abrasion of the insulation with resulting short circuits.

Considering the r-f amplifier of a receiver as a unit, the question arises as to whether to shield each r-f coil and tube individually or to shield each complete r-f stage consisting of wiring, coil, tube, and tuning condenser as a unit as shown in Fig. 297. Both methods can, and have been used. If the r-f amplifier parts are to be shielded individually, the coils may be enclosed in individual shield cans, (see Fig. 299) which can be made removable to facilitate testing and repairs. The screen-grid tubes can also be enclosed in separate removable shields of the type shown at the left. (The individual stator sections of modern gang tuning condensers are already shielded from each other by grounded electrostatic shield plates built into the condenser (see Fig. 268), so this source of electrostatic coupling is taken care of.) In this way, the necessary amount of shielding can be obtained at low cost, and the design is such that the entire chassis of the receiver is open and parts are easily accessible for test and repair work.

Rear and bottom views of the chassis of a typical receiver constructed in this way are shown in Fig. 298. At the left, the aluminum shields S on the three screen-grid r-f tubes are shown, the control grid caps of the tubes projecting through the rubber-insulated holes in the shields. Directly behind these is the shielded "gang type" tuning condenser T, with its dial D, at the right. Next to this is the power pack, with its enclosing shield removed to show the power transformer U, choke V, etc. In the bottom view of the chassis, two of the r-f coils R, with their aluminum shields removed are shown at the left. Next to these is one of the coil-shields M in place over the third coil. Notice that the entire receiver construction is open, providing good ventilation and easy access to any part. At the left of Fig. 285 may be seen the shielded assembly of a typical intermediate-frequency transformer of a superheterodyne receiver. The entire unit with its two small mica compression-type tuning condensers is enclosed in the aluminum shield can.

The construction in which separate shields are used for complete r-f stages, is usually more expensive than the individual unit-shielding just described, since much more shielding metal must be used and the entire structure of the receiver is more complicated. Testing and repair work are hampered, since the stage shields must be taken apart and removed in order to get at the wiring and parts for such work. The only real advantage it possesses is, that since all wiring in the r-f stages is enclosed within these shields the wires cannot be acted upon by any strong fields from powerful local broadcasting stations and have signal voltages induced in them. This, of course, would reduce the selectivity of the receiver. A metal cover-plate underneath the chassis of the unit-shielded receiver would eliminate this effect however.

413. How shielding affects a tuning coil: One effect accompanying the shielding of a coil by means of a metal enclosing shield is shown in Fig. 299. A shield for a screen-grid tube is shown at the left. Next to it is an r-f coil enclosed in a shield can, cut open at the front to show the interior. As shown at the right, the windings on the coil and the metal of the shield form the plates of a condenser. This is a constant capacity

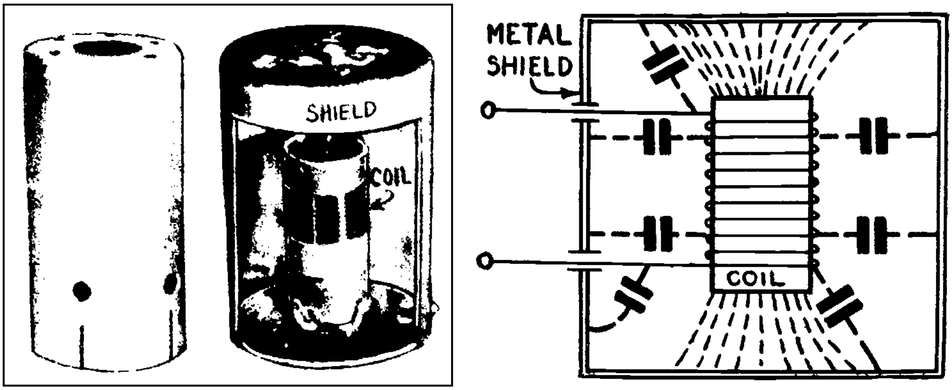


Fig. 299—Left: An aluminum shield for a screen-grid type r-f tube is shown at the left. Next to it is a shielded r-f coil with its shield cut open to show the interior. Right: How the shield around a coil adds to its distributed capacity and reduces effective tuning frequency or wavelength range of the coil.

and acts the same as the distributed capacity of the coil. It reduces the effective tuning range which may be obtained with any given tuning coil and condenser, acting like a small fixed capacity connected in parallel with the tuning condenser, so that even when the tuning condenser capacity is at minimum value, this capacity is still in the circuit. As a result of this capacity action, a shielded coil to be used with a tuning condenser of given size should have a few turns of wire *less* than if the shield were not used. This effect is partly counteracted by the fact that since part of the magnetic field of the coil is absorbed by the shields, a reduction of the self-inductance of the primary coil results. This makes it necessary to use a few turns more on the coil to compensate for this reduction. However, if the coil is of small diameter and the shield is of such size that a space equal to at least the diameter of the coil separates the coil from the shield all around, the latter effect will be smaller than the capacity effect, with the net result that a few turns less than the normal number must be used when the shield is employed. The shield around a coil should always be made as large as possible, especially along the length of the coil, consistent with the space available for it. If insufficient space is left between the coil and shield, the distributed capacity of the coil is increased very greatly, reducing the tuning range. Also, excessive eddy currents will be produced in the shield metal due to the magnetic field of the coil. This is a loss, and acts as an increase in the a-c coil resistance. When using a shielded coil, the coil itself should first be designed with proper proportion of length and diameter which will give a small external field. Then the shield should be designed to confine this field as much as is necessary, without seriously increasing the a-c resistance of the coil.

414. General shielding considerations: Shielding is rarely necessary in well-designed *audio* amplifiers, unless a large number of stages of high-gain amplification is used. Even in r-f amplifiers, shielding should not be used indiscriminately, since it not only adds to the cost of the receiver and complicates the construction, but if not employed properly, no practical advantage will be obtained from it,—in fact, it may cause harmful absorption of energy.

With ordinary tubes in receivers using one stage of amplification and regenerative detector, since most of the energy is confined in the detector circuit, with comparatively small r-f currents flowing in the r-f amplifier, shielding is usually unnecessary if the coils are kept at right angles and a fair distance apart. In exceptional cases, a grounded plate-shield placed between the coils will be all that is necessary for shielding. With two stages of tuned r-f, shielding is not usually required if small coils placed at right angles a reasonable distance apart are used, and if wiring is done carefully unless the receiver design is very compact and the parts must be mounted very close together. A small grounded plate-shield between the transformers will usually suffice in many cases. In sets employing three or more stages of r-f amplification, it is almost always necessary to completely shield the individual stages of the entire r-f amplifier, if high amplification per-stage is to be obtained. All "A" and "B" power supply leads should be properly choked and bypassed to prevent r-f currents from the various stages from passing into the power supply device and causing interstage coupling there due to the various impedances encountered.

Wiring in a shielded set should be laid out carefully. Plate and grid leads and connections to neutralizing coils and condensers must be removed as far as possible from the metal, in order to minimize their capacity to ground, and thus minimize detuning effects. Grid and plate neutralizing connections that must be run from one shielded compartment to another should be carefully insulated from, and not run parallel to, the shields.

REVIEW QUESTIONS

1. What must be the inductance of the secondary coil of an r-f transformer if it is tuned with a condenser having a maximum capacitance of .0005 mfd? The maximum wavelength is to be 600 meters.
2. The tuning condensers across the primary and secondary windings of the band-pass intermediate coils in a 175 kc superheterodyne receiver are of 200 mmf. capacitance. What is the inductance of each coil, in microhenries, neglecting the distributed capacitance?
3. An inductance of 150 microhenries is to be tuned to 200 meters. What is the capacitance of the tuning condenser required?
4. A tuning coil in a long-wave receiver is to tune to 1200 meters with a tuning condenser of .0005 mfd. What must be the inductance of the coil? What standard size of honeycomb coil would you use for this?
5. If the coil in problem 1, is wound with No. 30 enameled wire on a one-inch diameter form, find the total number of turns required and the length of the winding. (The coil design charts may be used for this.)
6. Draw the circuit diagram for, and explain the operation of two simple methods designed to produce uniform amplification in a simple tuned r-f amplifier over the broadcast frequency band. What are the advantages and disadvantages of each?
7. Show how the primary and secondary windings of an r-f transformer should be connected between two tubes for *normal phase* connection; (a) if both windings are in the same direction; (b) if the windings are in opposite directions.
8. What is meant by the distributed capacity of a coil? Illustrate your answer with a sketch. What is the objection to high distributed capacity in a tuning coil? How may it be kept low?
9. Describe several types of inductance coils and state the advantages and disadvantages of each.
10. How may the coupling between the primary and secondary of a coil be tightened, loosened?
11. What is the effect on the tuning characteristic if excessively tight coupling is employed between the primary and secondary of a t-r-f transformer?
12. How may 3 coils be placed to prevent inductive coupling between them?
13. What is the purpose of shielding in r-f amplifiers and how does shielding accomplish this purpose?
14. What materials are suitable for shielding? Which is used most? Why?

15. State three ways in which energy feedback from the plate circuit to the grid circuit can take place in an r-f amplifier stage. Illustrate your answers with sketches.
16. Name three losses which exist in tuning coils and explain how the coil should be constructed to make each as small as possible.
17. What is meant by "skin effect"? What causes it? Why does it increase greatly as the frequency is increased?
18. Why is it desirable to use more turns of wire for the primary winding of an r-f transformer used with screen-grid tubes than for one used with '27 type three-electrode tubes?
19. The secondary of an r-f transformer tunes from 200 meters to 600 meters with a certain tuning condenser. An aluminum shield is put around the coil to prevent interstage coupling. Now the coil and condenser tune from above 600 meters down to a minimum of 250 meters. Explain the reason for this.
20. What must be done to the coil in problem 19 in order to permit tuning down to 200 meters when this coil-shield is used?
21. A tuning coil is to be designed with a tap so that when it is used with a tuning condenser having a maximum capacitance of .00035 mfd., maximum wavelengths of 600 and 400 meters may be reached by using either the full coil or the part from one end to the tap. Design the coil if it is to be wound with No. 26 D. C. C. wire on a 2 inch diameter form. Locate the exact position of the tap, neglecting any interaction due to the unused portion of the winding when the tap is employed.
22. To what minimum wavelength will the arrangement in question 21 tune both when the full coil is used and when the tap is employed, if the total of the distributed capacity and the minimum capacitance of the tuning condenser is .00004 mf?

CHAPTER 24

AUDIO AMPLIFICATION

NEED FOR AUDIO AMPLIFICATION — R-F VS. A-F AMPLIFICATION — REQUIREMENTS OF THE A-F AMPLIFIER — FREQUENCY RANGE DESIRED — IMPORTANT CHARACTERISTICS OF THE HUMAN EAR — POWER IN SOUNDS OF VARIOUS FREQUENCIES — VARIATION IN INTELLIGIBILITY OF SPEECH SOUNDS — COMPENSATING FOR SIDE-BAND SUPPRESSION — THE TRANSMISSION UNIT—DECIBEL — FREQUENCY RESPONSE CURVES — COUPLING METHODS — TRANSFORMER COUPLED A-F AMPLIFIER — DESIGN OF THE A-F TRANSFORMER — TRANSFORMER RATIO — LARGE SIZE TRANSFORMERS AND CORE SATURATION — PARALLEL-FEED PLATE SUPPLY — CLOUGH SYSTEM WITH RESONATED PRIMARY — RESISTANCE COUPLING — SIZES OF RESISTORS AND CONDENSERS — MOTORBOATING — CHARACTERISTICS OF RESISTANCE-COUPLED AMPLIFIERS — IMPEDANCE COUPLED A-F AMPLIFIER — AUTOFORMER IMPEDANCE COUPLING — DUAL-IMPEDANCE COUPLING — DIRECT COUPLED AMPLIFIER — THE LAST AUDIO STAGE — POWER TUBES — PUSH PULL AMPLIFICATION — PARALLEL OUTPUT TUBES — DISTORTION TESTS — MAXIMUM UNDISTORTED OUTPUT — MATCHING INPUT AND OUTPUT IMPEDANCE — DUAL PUSH PULL — TONE CONTROL — REVIEW QUESTIONS.

415. Need for audio amplification: Thus far we have studied the construction and operation of the various r-f amplifier and detector systems employed in radio receivers. The function of the r-f amplifier is to increase or amplify the amplitude of the weak signal voltages before they reach the detector. The current in the plate circuit of the detector (Figs. 236 and 237) varies at the audio frequencies of the sounds being transmitted. These current variations are usually too weak to operate a loudspeaker, and can be amplified again before reaching the loud speaker, by means of one or more vacuum tubes connected up suitably as amplifiers. Since the currents and voltages appearing after the detector vary at the audio frequencies of the sounds in the program, this is known as *audio-frequency* (a-f) amplification, and the amplifier is called an *audio-frequency* (a-f) amplifier.

This presents then, three choices of amplification of the incoming signal voltages, (1) the r-f signal can be amplified before reaching the detector by successive stages of r-f amplification; (2) it can be amplified after leaving the detector by successive stages of a-f amplification; (3) it can be amplified both before and after by a combination of the two, as shown in Fig. 300. It should be understood that the r-f amplifier may be either of the t-r-f or superheterodyne type. A consideration of just what advantages and disadvantages can be secured by each of these methods is important at this time, as it will make clear the reasons for building radio receivers as we do, and the reasons for possible future changes. The question of the correct proportions of r-f and a-f amplification in a receiver is assuming great importance lately. A study of the advantages and practical limitations of each of these forms of amplification will help toward a clearer understanding of the receiver.

416. R-F vs. A-F amplification: Until recently, the use of detectors which operated on the square law principle was widespread. With

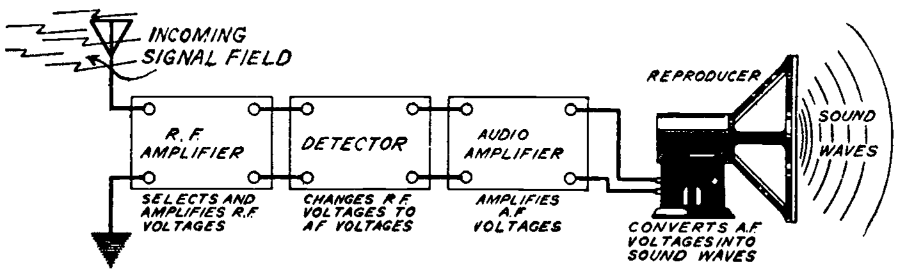


Fig. 300—Modern radio receiver system. The incoming radio-frequency signal voltages induced in the antenna, are tuned and amplified by the r-f amplifier, (which may be of the t-r-f or superheterodyne type); then they are detected or "demodulated", and the resulting a-f voltage variations are amplified further by the a-f amplifier, finally being converted into sound waves by the loud speaker.

a detector of this type, since the detector output is approximately proportional to the *square* of the strength of the voltage variations applied to its input, up to a certain limit, the advantage of doing the amplifying in the r-f amplifier ahead of the detector is self-evident, since amplifying the signal voltage a certain amount before the detector, makes the actual gain proportional to the square of this increase, when considered in the detector output. This advantage no longer holds when linear detectors of the types now becoming popular are employed, because with this type of detector the detector output always bears a certain fixed ratio to the input, regardless of the amplitude of the input signal voltages.

A real important advantage of r-f amplification is that the function of tuning or signal selection can be combined with that of amplification in the r-f amplifier, whereas no station tuning or selective effect is obtained in the audio amplifier. Therefore, even if we built a receiver simply with a detector and many stages of audio amplification, we would still need several tuning circuits ahead of the detector to obtain the necessary selectivity (ability to eliminate the signals of unwanted stations). The tuning circuits cannot be eliminated, with our present radio transmitting and receiving system. The increased number and power of transmitting stations on the air is daily making the selectivity problem more and more acute. On the contrary, if we build our receiver with many stages of r-f amplification and a detector (with no audio amplification) we have theoretically, all the requisites for a satisfactory, complete receiver, insofar as radio or television signals are concerned. The trouble with a system of this sort is that the detector tube must handle the full amplified signal voltage. There are no practical forms of detectors, (demodulators), available at the present time which are capable of handling signal voltages as large as would exist at the detector input of a receiver of this sort. Therefore a practical compromise is made in most commercial receivers by tuning and amplifying the incoming signal voltage in the r-f amplifier, to a value just below that which the detector can handle without overloading, then detecting or "demodulating" it by the detector tube and finally amplifying it further by one or two stages of audio amplification to the required strength necessary to satisfactorily operate the loud speaker. By using "power detectors", it is permissable to build up the signal voltage to quite some strength in the r-f amplifier before applying it to the detector, and therefore but one stage of audio amplification is required in most cases. This takes the form of a *power stage,* designed to deliver as much electrical "power" to the loud speaker for a given input signal voltage applied to its grid circuit, as possible.

Another disadvantage of employing much audio amplification lies in its ability to amplify all stray electrical disturbances which are of such frequency as to cause objectionable sounds in the loud speaker. Such circuit noises may be caused by low "A" or "B" batteries with consequent variation in supply voltage, hum due to incorrectly designed electric power supply units, loose connections, microphonic tubes, non-uniform emission along the length of the cathode, etc. These are all caused by electrical disturbances lying within the usual audio-frequency range and will of course be amplified by the audio amplifier because the a-f amplifier is actually designed to amplify voltage variations of such frequencies. This becomes especially important in a-c electrically-operated receivers, where slight 60 or 120 cycle voltages due to stray magnetic induction are amplified greatly, resulting in an objectionable low-pitched hum from the speaker. Such disturbances are not likely to cause as much trouble in an r-f amplifier because the r-f transformers do not efficiently transfer such low frequency variations from stage to stage.

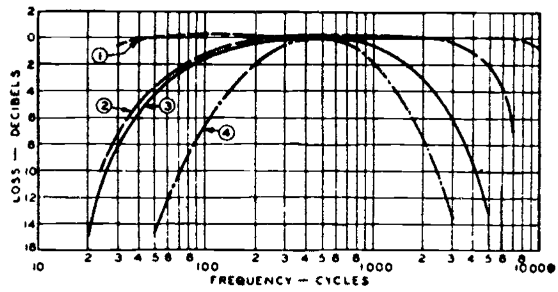
It is possible to build r-f amplifiers, using screen-grid type tubes, to produce any desired amount of amplification. The old troubles due to feedback and oscillation caused by the plate-grid capacity of the amplifier tube, have been practically eliminated with this form of tube. As a matter of fact, r-f amplifiers of both the tuned r-f and superheterodyne type may be designed and constructed to produce so much amplification, that they may actually be useless for use under average reception conditions, due to amplification of all stray electrical disturbances picked up by the antenna circuit to such an extent that extremely "noisy" operation results. In other words, they may receive below the "noise level". Of course, this is an undesirable extreme.

An advantage of a-f amplification lies in the fact that it is relatively easy to build a two-stage (and with care, a three-stage) a-f amplifier that is perfectly stable and gives high amplification. The amplifier noises mentioned are a disadvantage especially when more than two stages are used, but the production of better tubes and associated apparatus is reducing this objection. When a phonograph pickup is to be used in conjunction with the radio receiver, some audio amplification is necessary to strengthen the low output voltage of the pickup to a value sufficient to give satisfactory loud speaker operation. Since in such receivers, at least one stage of audio amplification must be provided for the phonograph pickup, it is also employed for amplifying the radio signal voltage, when radio programs are received.

A consideration of all these factors shows that the question of just how much r-f *or* a-f.; or r-f *and* a-f amplification it is best to employ must necessarily be decided by a compromise between all of the factors involved. In the old types of receivers employing 3-electrode tubes in the r-f amplifier it was almost standard practice to use at least two stages of a-f amplification following the detector. In modern receivers in which screen-grid tubes are employed in high-gain r-f amplifiers and a power detector is employed, the signal voltage is built up to such high values in the r-f amplifier that but a single stage of audio amplification is required and used. Of course audio amplifiers find many other uses outside of radio receivers. They make public address systems possible, are used in home recording of phonograph records, in photo-electric cell operated devices, in sound pictures, etc., so it is essential that the various systems employed be thoroughly understood. While the general audio amplifier systems are applicable in many of these fields, in this chapter we will consider them particularly from the viewpoint of the radio receiver. The special characteristics required for public address work, television signal reception, sound motion pictures, etc., will be discussed in conjunction with these subjects later.

417. Requirements of the a-f amplifier: It is desirable that an amplifier employed to amplify the audio-frequency signal voltage output from the detector tube of a radio receiver, be looked upon not as a separate device, but as part of the entire receiver consisting of the r-f amplifier, detector, a-f amplifier and loud speaker. It should be kept constantly in mind that the prime object of the radio receiving apparatus taken as a unit, *is to reproduce faithfully, without noticeable change or distortion of any kind, the music or speech produced by the performers in the studio of the broadcasting station.* Notice that "*noticeable change*" was mentioned, because due to certain characteristics of the human ear, it is possible to have some changes take place without being noticed or detected by the average ear; that is, absolute perfection is not necessary. It is not always desirable to have the audio amplifier, amplify all frequencies within the audio range equally, for in many cases deficiencies in loud speaker response, or even in the r-f amplifier or detector, can be equalized by an audio amplifier designed especially to over-amplify certain frequencies. It is desirable however, to have the amplifier amplify the incoming signal voltages without distortion of any kind in the wave-form.

418. Frequency-range desired: A detailed study of the characteristics of the various speech and musical sounds broadcast during radio programs was made in Chapter 2. We found that an audio-frequency range of from about 40 or 50 to 8,000 or 10,000 cycles is desirable for the transmission, reception and reproduction of speech and music. Radio



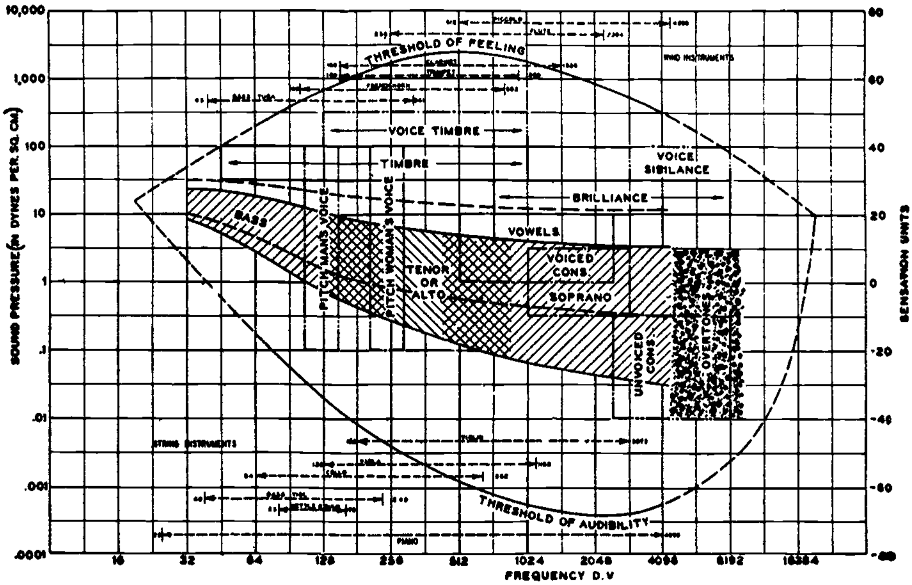
Courtesy Western Electric Co.

Fig. 301—Comparison of average sound frequency transmission characteristics of radio transmitters and receivers of a few years ago with those of recent date are shown by these curves. Curve (1) shows the audio frequency transmission characteristic of a modern broadcasting station.

transmitter development has reached a stage where the apparatus may be designed to transmit almost any required range of sound frequencies. The performance of recent broadcasting equipment in transmitting the range of audible frequencies is indicated in Fig. 301. In this figure, (1) is the characteristic of the present Western Electric 50 kw. transmitter, (2) is that of the Western Electric 500 watt transmitter of 1924, and (3) and (4) are characteristics of typical radio receivers of the present and 1926, respectively. It is evident that the faithfulness of reproduction still depends largely upon the performance of the receiver, since the modern transmitters are capable of almost perfect quality in this respect. Notice the almost flat transmission curve between 40 and 10,000 cycles for the modern 50 Kw. transmitter. Although these are designed with a sound frequency-range up to 10,000 cycles, they do not actually broadcast anything above 5,000 cycles. This is due to the fact that there is but a 10,000 cycle (10 kc) band between adjacent station carrier-frequency assignments, and since both sidebands are broadcast, frequencies above 5,000 cycles begin to overlap those of the station on the next assignment. It would appear that 5,000 cycles is the extreme limit of reproduction to be hoped for without a wider separation of transmitting station channels.

In order to obtain true reproduction of speech and music, the entire radio receiving equipment including the sound reproducer taken as a unit, should not introduce or suppress any of the audio frequencies present in the signal, nor should they be partial to certain frequencies and amplify them more than they do others. True reproduction requires that all the original frequencies, fundamentals and overtones be present in the same proportion as in the original sounds. Incidentally, the audio amplifier in a television receiver is called upon to amplify a much larger band of frequencies uniformly than that employed in a receiver for sound programs only.

419. Important characteristics of the human ear: When considering audio systems, some important characteristics of the human ear must also be considered. There is a minimum sound intensity below which the human ear cannot detect sounds and a maximum intensity above which sound becomes painful. These values vary with the frequency. At low levels of sound intensity, a change of about 25 per cent in loudness must



Courtesy Bell Telephone Laboratories

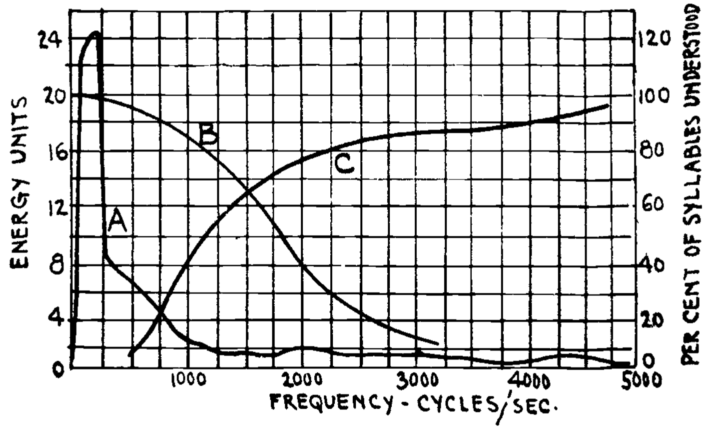
Fig. 302—Any sound wave that can be heard, lies within the field outlined here. Areas covered by the most prominent speech sounds are indicated both as to their frequency, range and sound pressure by the center shaded region. The threshold of audibility curve indicates the actual value of sound pressure required to just produce an audible sound at the various frequencies. The threshold of feeling curve indicates the sound pressures which produce the sensation of feeling or pain rather than of sound—at various frequencies.

occur before it will be detected by the human ear. At greater intensities, the change must be at least 10 per cent before it will be noticed.

The range of pressure and frequency that the ear will respond to, is shown in Fig. 302, in which the scale of absicissas is frequencies in cycles per second, and the ordinate scale is sound pressure in dynes. Frequencies above about 20,000 cycles are not perceived as sound, nor are those below about 20. Any frequency between these limits, however, is recognized as sound if its pressure is above the lower boundary curve marked "Threshold of Audibility." The upper boundary, marked "Threshold of Feeling" indicates the pressure at which feeling begins. Above this line the sounds are felt, actually causing pain by their excessivc pressure.

Frequency and pressure are only the physical characteristics of a sound; our mental responses are called pitch and loudness. Both of these vary logarithmically with their stimulas, difference in pitch between two sounds corresponding to the logarithm of the ratio of their frequencies, and similarly, differences in loudness are proportional to the logarithm of the difference in pressure, but with loudness the proportionality is not quite constant so that constant loudness lines are not truly horizontal. Because of this logarithmic law the illustration is plotted with logarithmic scales, and in addition an arbitrary loudness scale is shown on the right, the units of which, called "sensation units", are defined as twenty times the logarithm of the pressure.

420. Power in sounds of various frequencies: Although sounds of different frequencies can be adjusted so they sound equally loud to the average human ear, the power required to produce these sounds differs widely. It has been determined experimentally by Dr. Harvey Fletcher and his associates at the Bell Telephone Laboratories, that the energy



Courtesy Bell Telephone Laboratories

Fig. 303—Curve A shows how the *power* necessary to produce sounds of different frequencies but equal loudness, varies. Curve B shows how the intelligibility of speech sounds varies as all the frequnecies *below* the certain value are eliminated. Curve C shows how this varies as all the frequencies *above* the certain value are eliminated. The scale at the right applies to these two curves.

necessary to produce speech sounds of the same intensity but of different frequencies, varies according to the curve A in Fig. 303 for the average human ear. It is evident that a very large increase in power is required to produce the sounds below about 500 cycles. Since the ear is very sensitive to tones around 1,000 cycles, very little energy is required to produce tones of this frequency for the same degree of loudness as shown by the sharp drop of curve A around 1,000 cycles. This curve is very important in the study of the "power" or "output stage" of audio amplifiers, for it shows that the loud speaker will require a much larger amount of power from the power tube for these frequencies than for the higher ones—provided it is capable of producing the lower-frequency sounds. An amplifier that can amplify the low frequencies requires a power tube and power supply system of larger rating, and more amplification, than another amplifier that does not amplify these low-frequency notes.

421. Variation in intelligibility of speech sounds: We have seen that the ear is able to perceive a large number of tones of different intensity and frequency. We have also seen that the voice and various musical instruments produce tones which cover a large portion of the auditory sensation area. In order to obtain information as to the relative importance of various parts of this area to the sensory characteristics of speech and music, experiments have been performed in which the tones falling in various parts have been eliminated from the sounds by means of high-pass, low-pass and band-pass filters.

It has been found that if all of the frequencies below 100, 200, 300 or on up to 1,000 cycles are progressively eliminated from speech, it is still 85 per cent intelligible, though a greater part of the energy of the sounds has been removed as shown by curve A. Curve B of Fig. 303 shows the relation between the intelligibility of speech (per cent of words understood) and the elimination of all frequencies *below* a given frequency. The vertical scale for this is at the right.

However, although the sounds can be understood, the character or "tone quality" of the speech changes markedly. Due to this relative insensitivity of the ear, an average audio amplifier and loud speaker can be built with a rather poor audio characteristic and still sound reasonably good to the average ear. Although the ear can understand those sounds which lack the lower tones, listening to an amplifier and reproducer of this kind is very tiring and irritating.

When frequencies above 8000, 7000, or on down to 3000 cycles are eliminated, the character of the speech again changes markedly. The term "sibilance", appearing to describe best the characteristic lost, refers to the prominence of the hissing or frictional character of speech. If attention is directed to such sounds as s, f, th, and z, the elimination of frequencies above 6000 or 7000 cycles is readily detectable, but it requires rather close attention to detect the elimination of frequencies above 8000 cycles. Curve C of Fig. 303 shows the relation between intelligibility and the elimination of all frequencies *above* a given value. As will be seen from this curve, if the frequencies above 1,000 cycles are omitted, only 40 per cent of the speech sounds will be understood. Although the sounds may be easily understood if the frequencies above 3,000 cycles are eliminated, they sound very unnatural, and again tire the ear, causing irritation. The higher frequencies are really necessary to give clearness, definition, and depth to the sounds, and since they consist mostly of the harmonics, they are the means of recognizing different instruments which produce the same notes, and different voices (see Article 6).

It is evident from a consideration of these facts, that the average ear is a rather poor measuring instrument and should not be trusted too much in judging either frequency or intensity of sound outputs. It is also evident that the sound output from an audio amplifier and loud speaker combination can be quite far from an exact reproduction of the original sound and still appear satisfactory to the ear. At medium frequencies, a change in frequency of about 0.3 per cent can be detected, at low frequencies a change of about 1 per cent is necessary for detection by the ear. Another phenomenon of hearing which enters into the sensation of sound, is called *masking*. Lower pitched tones in a sound deafen the hearer to the higher tones, and this masking effect becomes marked when the loudness of the low tones is great. Masking of the higher notes makes the combined sound appear to be lower in pitch. For true reproduction then, the sounds should be reproduced with about the same loudness as the original sounds in the broadcast studio. Intense high-frequency notes do not appear to mask low-frequency notes to any degree.

422. Compensating for side-band suppression: In this discussion it has been assumed that the audio amplifier is to follow an r-f amplifier and detector in which no side-band frequencies are suppressed (see Article 358) and in which no other distortion takes place. If this is not the case, the problem becomes further complicated, as the amount of side-band suppression is rarely known. If it is known, it can be corrected in the audio-frequency amplifier system by increasing the amplification of the high frequencies which have been suppressed in the r-f amplifier. This is beyond the scope of the home constructor but is feasible for manufacturers who sell sets complete with built-in loud speakers.

It must be remembered that the cutting off of some of the lower frequencies does not prevent the listener from hearing these notes, for the second (and possibly the third) harmonics of these are amplified and passed on. The ear partly adds the fundamental pitch of a note, of which only the harmonics are being produced, so that these notes are heard, although the "quality," "timbre," or "tone color" of the tone is changed. If it were not for this fact, some of our older sets and speakers would sound terrible, as they do not reproduce any of the fundamentals below 200 or 300 cycles. Timbre is probably more important in music than in speech, as it is one of the things that distinguishes the tones of the various instruments. In general, the fundamental and first two or three overtones are necessary in order to distinguish clearly the tones of the various instruments.

It can be seen that an a-f amplifying and reproducing system may fall considerably short of the ideal without giving really objectionable reception, due to the peculiarities of hearing of the average person. A trained ear could possibly detect the elimination of frequencies above 8,000 cycles per second from the ordinary run of music, but the average individual would have difficulty in detecting the elimination of frequencies above 6,000 or 7,000 cycles, unless he paid particularly close attention to each of the instruments in an orchestral selection. The factor which really guides the design, is how good the system will be when apparatus which is not prohibitive in cost is used under practical working conditions.

423. The transmission unit—decibel: Before proceeding with the study of audio amplifiers, it is necessary that we learn something of the common methods used to express and compare their operating characteristics. Then we will be prepared to pass judgment on the worth of any amplifier system.

It has been determined experimentally that the response of the human ear is such that the impression it gives of *loudness* of a single note is not linearly proportional to the sound energy acting upon it but is *approximately* proportional to the *logarithm* of sound energy. For example, a full orchestra playing a passage of music at its full volume creates sound energy about 1,000,000 times as great as when it plays this same passage at its softest volume. However, to the average normal ear the loud passage does not scund 1,000,000 times as loud as the soft passage. It sounds only about *60* times as loud. The *energy* ratio in this case is 1,000,000 to 1. The *loudness* ratio (as perceived by the ear) produced by it is only about 60 to 1.

(This fortunate provision of nature is really a blessing in a way, for it protects our delicate ear mechanism against injury from sound waves of great energy.)

It is evident then, that in any electrical system having to do with the transmission, amplification, or reduction, of electrical energy which is finally to be changed into sound energy it is convenient to have a unit of transmission efficiency that bears some close relationship to the logarithmic loudness response characteristic of the average human ear and also that can be treated by the ordinary processes of addition and subtraction in order to obtain the total *gains* or *losses* in a circuit. In order to do this it is necessary that the unit be an exponential one, and it was for this reason that the *decibel* was chosen as the unit of transmission efficiency.

In communication work *the common logarithm* of the ratio of the power P_2 which exists in the termination or receiver when the device or circuit under consideration is inserted, to the power P_1 which exists in the* *termination or receiver when the device or circuit is removed is a measure of the transmission "loss" or "gain", in "bels" which the device or circuit introduces.* That is, bels=$\log_{10} \frac{P_2}{P_1}$.

The bel was named in honor of Alexander Bell the inventor of the telephone. Since for the ordinary power ratios encountered in practice the bel is too large a unit for convenient expression, the *decibel*† (one-tenth of a bel) is the unit more commonly used. Therefore, since 1 decibel=0.1 bel and, conversely, 1 bel equals 10 decibels, the number of *decibels* difference in level between P_2 watts and P_1 watts is

$$\text{Decibels} = 10 \log_{10} \frac{P_2}{P_1}$$

(In telephone work) the decibel (abbreviated DB, or db) has also been called the *transmission unit* (abbreviated TU).

The two power values P_2 and P_1 in the equation for decibels must both be expressed in the same unit (kilowatts, watts, milliwatts, microwatts, etc.). If the ratio of the *output* power (P_2) is greater than the *input* power (P_1), there is a "positive" *gain.* If the output power (P_2) is less than the input power (P_1) there is *loss* (indicated by a *negative* sign for the logarithm value).

It happens that only a trained musical person could notice any difference in loudness produced by a 1-DB change in the sound energy intensity of a single note. Changes of less than 1DB cannot be noticed by the human ear. In fact, to most persons, even a 2DB change is only slightly noticeable. Thus, an increase from 3 watts to 4.75 watts is only a slightly audible increment, since it is an increase of 2DB in sound energy.

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*The common logarithm of a number is the power to which 10 must be raised to equal the number. Thus, log 10=1; log 100=2 (because 10^2=100); log 1000=3 (because 10^3=1000). Similarly, log 45=1.653 because $10^{1.653}$=45. This common system of logarithms uses 10 for the base. The values of the logartihms of numbers may be obtained from tables published in books on Algebra, Trigonometry, etc., but this is rather tedious work. The chart of Fig. 304 makes the work of solving decibel equations simple, for no logarithms need be looked up. First locate the point corresponding to the given *loss* (or *gain*) ratio on the left, or right hand, vertical scale respectively. From this point project across horizontally to the heavy diagonal "loss (or "gain") line. Then project downward from this point of intersection to the decibel scale at the bottom. If the given ratio involves *power* values, the decibel value is read on the upper horizontal scale marked "power Scale." If the given ratio involves *currents* or *voltages*, the decibel value is read on the lower horizontal scale marked "voltage or current scale."

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†It must always be remembered that the *loudness* response of the human ear for the wide range of frequencies in music is not *exactly* in accordance with the logarithmic unit of transmission efficiency (the decibel), for the ear is not equally responsive to all sound frequencies (see Art. 420 and Fig. 303). Hence confusion between the Decibel which is not a loudness unit but a unit of *change of power*, and the Phon which is a true *loudness* unit should be avoided If the ear were equally responsive to all frequencies, the Phon and the decibel would be identical.

It should be remembered that the basis of the decibel as a unit of loss or gain is founded on *power* ratios. However, voltage or current ratios can also be used. In such cases since $P=I^2 \times R$ or E^2/R, substituting these values for P in the equation for decibels, we obtain:

$$\text{decibels}=10 \log_{10} \frac{(I_2)^2 R_2}{(I_1)^2 R_1} = 20 \log_{10} \frac{I_2 \sqrt{R_2}}{I_1 \sqrt{R_1}}$$

$$\text{likewise, decibels}=20 \log_{10} \frac{E_2/\sqrt{R_2}}{E_1/\sqrt{R_1}}$$

(The factor 20 appears in the above expression since the right hand expression appeared as a number "squared." Since the logarithm of the power of a number is equal to the logarithm of the number multiplied by the exponent of the power, this gives 10×2, or 20, in front of the logarithm expression.)

If the resistances into which the two currents I_2 and I_1 flow are equal, or across which the two voltages E_2 and E_1 appear are equal, then R_2 and R_2 cancel, and these expressions reduce to the simple forms:

$$DB=20 \log_{10} \frac{E_2}{E_1}, \qquad \text{and } DB=20 \log_{10} \frac{I_2}{I_1}$$

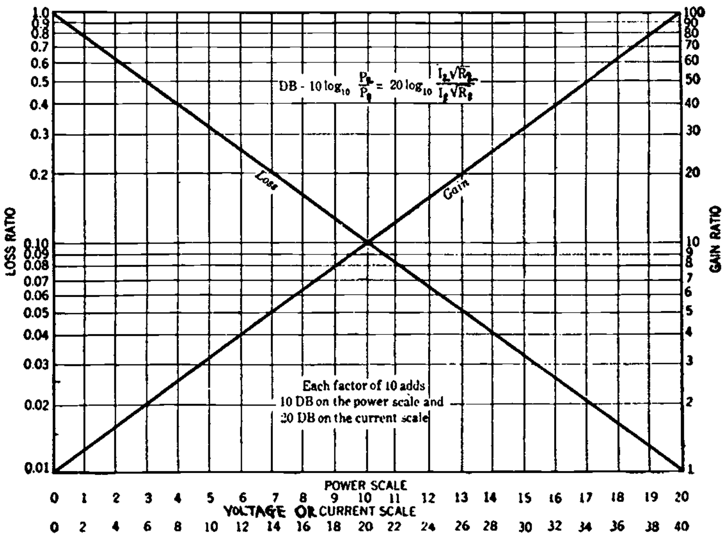


Fig. 304—Chart for quickly obtaining decibel values for various gain or loss ratios of power, current, or voltage.

The same holds true in the case of a-c circuits, provided that the impedances Z_2 and Z_1 across which E_2 and E_1 are measured are equal. When the impedances are not equal, the gain in decibels is

$$DB=20 \log_{10} \frac{E_2}{E_1} + 10 \log_{10} \frac{Z_1}{Z_1} + 10 \log_{10} \frac{k_2}{k_1}$$

$$\text{also, } DB=20 \log_{10} \frac{I_2}{I_1} + 10 \log_{10} \frac{Z_2}{Z_1} + 10 \log_{10} \frac{k_2}{k_1}$$

where, Z_1 and Z_2 are the corresponding impedances, and k_1 and k_2 are the corresponding power factors of these impedances.

To illustrate the use of the decibel formula for calculating *gains* and *losses* in circuits involving a **change of power at one point**, suppose that an amplifier driving a loudspeaker is delivering 1 watt to it and that subsequently this is *increased* to 2 watts, i.e., the power is doubled. The *gain* in decibels is then

$$\text{gain} = 10 \log_{10} \frac{2}{1} = 10 \log_{10} 2 = 10 \times 0.301 = +3.01 \text{ DB}$$

In a similar manner suppose the original power was 2 watts and it was then decreased to 1 watt. This represents a *loss* in power, and the ratio is 1 to 2. The *loss* is therefore

$$\text{loss} = 10 \log_{10} \frac{1}{2} = 10 \log_{10} 0.5 = 10 \times \bar{1}.699 = -3.01 \text{ DB}$$

To illustrate the use of the decibel formula to calculate a **difference in power existing between two points**, consider an amplifier having an input of 0.002 watts into 500 ohms and an output of 0.2 watts. The power *gain* due to the amplifier is then

$$\text{gain} = 10 \log_{10} \frac{0.2}{0.002} = 10 \log_{10} 100 = 10 \times 2 = +20 \text{ DB}$$

This amplifier may therefore be described as having a *gain* of 20 DB (this neglects any consideration of the input or output impedance)

Reference Levels: What has been said thus far refers to the application of the "decibel" to increases or decreases in power.

The next important use of the decibel is for "power level" considerations, that is, for expressing the power existing at any point in a circuit as so many DB *above*, or *below*, a standard amount of power. Since decibels refer to *ratios*, they may only be used in this way (as a measure of *absolute magnitude*) when referred to a definite *reference level.* The very term "power level" implies that we have established a standard "zero reference level" by which to gauge all others.

Unfortunately, there is no one power reference level standard which has been universally adopted, and until such standardization has been accomplished it is always important to clearly specify what reference level is being used. Several levels have been in common use. Thus, 6 milliwatts (O DB=0.006 watts) is widely used in sound picture and public address system work; RCA rates its equipment on a 12.5 milliwatt "zero level" basis; the U. S. Navy has used 1 milliwatt as the zero level in its specifications, etc.

If 0.006 watts is considered as the zero reference level, then since the number of DB equals $10 \log \frac{P_2}{P_1}$

$$\text{Power level}_{(DB)} = 10 \log_{10} \frac{\text{power (watts)}}{0.006}$$

For example, if an amplifier delivers 0.06 watts to its output circuit, its power output level is

$$\text{DB} = 10 \log_{10} \frac{0.06}{0.006} = 10 \log_{10} 10 = +10$$

This could be written: Power level=10DB/0.006 watts

to indicate definitely that the amplifier under consideration delivers a power level which is 10DB above the arbitrary reference level of 0.006 watts.

Overall Gain or Loss: Because of the logarithmic character of the decibel, successive gains and losses expressed in db are added algebraically (when two numbers are to be multiplied, their **logarithms are added**), provided they are all expressed with reference to the same reference **power** level. For instance, suppose we have a system containing successively an amplifier giving a positive *gain* of 40 db, a line having a negative gain (*loss*) of 5 db, an impedance-matching network giving a negative gain (*loss*) of 30 db, and ending up with an amplifier contributing a positive *gain* of 10 db—(all gains and losses referred to the same reference power level). The overall *gain* of the system, from the input of the first amplifier to the output of the terminating amplifier, would be +40db—5db—30db+10db=+15db. This feature itself contributes considerably to the simplification of power level calculations where there are a number of pieces of equipment between the input and output terminals of a system. Once the gain (or *loss*) for each piece of equipment is known (providing the couplings have proper characteristics) it is necessary only to perform a simple algebraic addition to determine the overall gain (or *loss*) for the entire system.

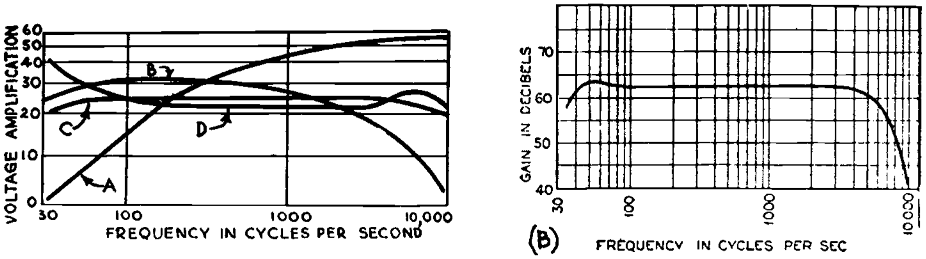


Fig. 305—Left: Audio amplifier response curves plotted with "voltage amplification" along the vertical scale.
Right: Audio amplifier response curves plotted with "gain in decibels" along the vertical scale.

424. Frequency-response curves: One important thing to know about an audio amplifier, is how much it amplifies equal input voltages of different frequencies in the audio range. This data is obtained by applying equal signal voltages of the various known frequencies to the input, and measuring the output voltage in each case with a vacuum tube voltmeter or other suitable device. The results of such a test may be plotted in the form of a graph, with frequency along the horizontal scale and voltage amplification along the vertical scale as shown in Fig. 305. This is called the *frequency-response* curve of the amplifier.

The frequency-response curves should *not* be plotted with the frequency laid off uniformly along the horizontal axis. Since the ear hears logarithmically, the response curves are usually plotted so that distances along the horizontal frequency scale are made proportional to the logarithm of the frequency. The vertical scale is drawn proportional to the logarithm of the voltage amplification, as shown in the curves at the left of Fig. 305. In some curves the gain in decibels is plotted along the vertical scale as shown in the curve at (B). In this case, equal gains in decibels are represented by equal divisions on the scale. This is all due to the fact that we hear logarithmically. The difference in pitch between two sounds as heard by the human ear, corresponds to the logarithm of the ratio of their frequencies. Similarly, the ear's response to differences in loudness are nearly proportional to the logarithm of the difference in pressure. Therefore, the audio-frequency response curves should be plotted this way in order to show the variations in their relative intensities just as they would actually affect the ear.

It is essential that the frequency-response curve of any audio coupling unit should show the performance of the unit when in actual use, that is, with its associated vacuum tubes and under operating conditions. A curve of a transformer, impedance coupling unit, resistance coupling unit, etc., when used with the testing device only, and not in actual practice with the correct vacuum tubes and plate and grid voltages, is useless, since the performance will be different in actual practice, due to added tube capacities, etc. The plate resistance of the tube (which depends among other things, on the plate voltage and filament current) will affect the operation of the coupling unit. If this is a transformer, the load applied will produce marked changes. Considering all these factors, frequency response curves are without real value unless made under actual operating conditions.

425. Coupling methods: In most a-f amplifiers, the greater portion of the amplification is produced by vacuum tubes, and the usual problem of coupling each two successive tubes together so that plate current changes in one will cause corresponding grid potential changes on the next, arises. Fig. 306 shows a simplified diagram of a two stage amp-

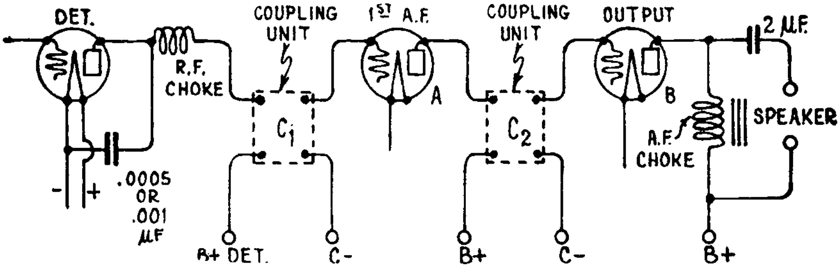


Fig. 306—How the coupling units are connected between the successive amplifier tubes of an a-f amplifier. These transform the plate current changes existing in one tube, to grid voltage changes applied to the following tube.

lifier in which amplification is secured by first-stage tube A and output-tube B. The coupling units C1 and C2 serve to couple the grid and plate circuits of successive tubes together. The output or varying plate current of one tube must be made to flow through an impedance, (see Art. 336), producing a varying voltage drop which is applied to the grid circuit of the next tube. This impedance, or coupling unit between, may take the form of an inductance or a resistance. This leads to three popular main forms of coupling for a-f amplifiers.

(1) Transformer Coupling.
(2) Resistance Coupling.
(3) Impedance Coupling.

Each system has its own peculiar limitations and advantages. They can all be made to work surprisingly well under certain conditions. The operation of each will be studied separately.

426. Transformer-coupled a-f amplifier: Fig. 307 shows a circuit diagram of a conventional two-stage transformer-coupled a-f amplifier. In Fig. 308 a single stage of this amplifier has been drawn separately for purposes of analysis of the actions taking place. We will study the design and construction of the coupling transformers in detail presently. For our purpose at the present time, suffice it to say that the transformer T, is constructed with a primary and secondary winding on a steel core, usually with the secondary having more turns than the primary so that a step-up in the voltage occurs in the transformer itself. One stage of amplification comprises tube A and transformer T. Varying signal voltages applied to the grid circuit of tube A, cause corresponding varying plate current changes. This varying plate current flows through the primary winding. If the current is increasing, the e. m. f. induced in the secondary will be in a certain direction; if the current through the primary is decreasing, the induced e. m. f. in the secondary will be in the reverse direction. Thus, with a pulsating or varying direct current through the primary winding, an alternating e. m. f. is induced in the secondary. No voltage, however, is induced in the secondary when the current through the primary is steady. The output voltage of one stage can be fed to the input of another stage, etc., so that the signal may be amplified again and again, and built up to the desired strength.

Now, referring to (A) of Fig. 308, we can see that the primary winding of the transformer is connected in the plate circuit of the previous tube and the secondary is connected across the grid input circuit of the following tube. Let E_1 be the a-f signal voltage applied to the input of the stage. This is equivalent to an a-f voltage of μE_1 (μ is the amplification constant of the tube) introduced in the plate circuit of the first tube A, tending to cause the a-f component of the plate current to flow. The plate-to-filament path in the tube acts like a variable resistance equal in value to the plate impedance of the tube. The primary of the audio transformer, consisting of thousands of turns of wire wound on an iron core, has appreciable inductance, so that it presents an impedance to the varying a-f plate current. These facts can be used to draw the simplified equivalent circuit diagram (B), where μE_1 is a source of a-f voltage tending to send current around the circuit through the plate resistance

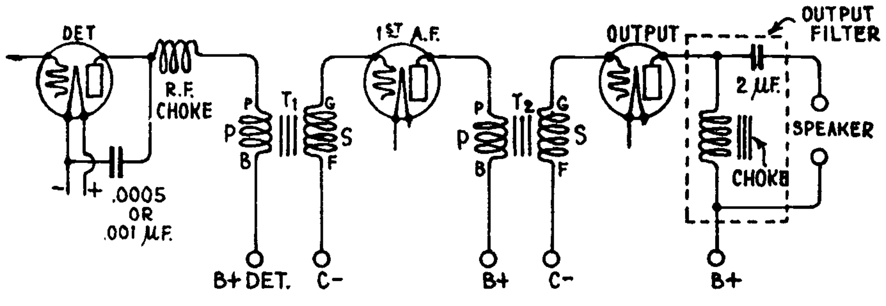


Fig. 307—Transformer coupling units between successive tubes of an a-f amplifier.

R_p, and the transformer primary impedance Z. This current, flowing through R_p and Z, produces a fall of potential across each, the sum of the two being equal to μE_1. The varying voltage or fall of potential appearing across the primary of the transformer is stepped up by an amount equal to the turns ratio. This secondary voltage E_2 is impressed on the grid circuit of the following tube. As the vacuum tube is a voltage-operated device (changes in grid *voltage* producing changes in plate current) we are interested in getting as large a voltage E_2 across the input of the second tube as possible. This means that as large a voltage drop as possible must be developed across the primary (see article 337). Therefore, its impedance must be made high compared to the plate impedance of the tube. If N is the turns-ratio of the transformer, the amplification of a complete transformer-coupled *stage* for each frequency then is:

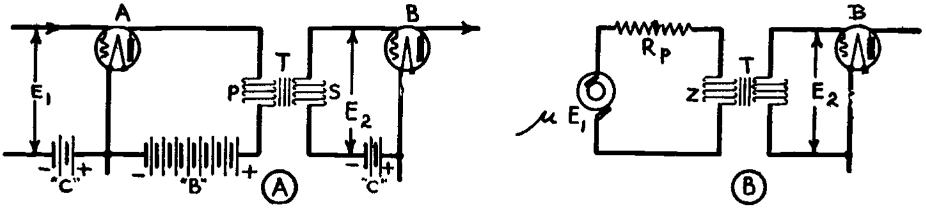


Fig. 308—The typical transformer-coupled a-f amplifier stage at (A) may be considered as shown at (B) for purposes of analysis of the actions.

$$\text{Amplification} = \mu \frac{Z}{Z+R_p} N.$$

If the transformer primary impedance Z is very high compared to R_p, so that the relation $\frac{Z}{Z+R_p}$ is nearly equal to 1, the amplification of the stage can be reasonably assumed to be equal to the amplification factor of the tube times the turns-ratio of the transformer. Of course this is true only when a transformer having a high-impedance primary is used, and as we shall see, this value is not exactly constant at all frequencies. Actually, if the transformer primary impedance is about 3 times the plate impedance of the tube, an amplification equal to 75 per cent of the mu of the tube multiplied by the turns-ratio of the transformer is obtained. It should be remembered that in a transformer-coupled a-f amplifier the transformers contribute to the step-up in voltage. For this reason, if the same type of tubes are employed, a transformer-coupled a-f amplifier requires less stages for a given total amplification than either the resistance or the impedance coupled types do. This is one of its advantages.

427. Design of the a-f transformer: An audio transformer consists of a primary and secondary winding placed on a laminated magnetic core (usually shell-type as shown in Fig. 72), of silicon-steel, nickel-steel, or other special alloys. As shown in Fig. 309, the primary is wound inside around the center core leg and insulated from the core. Around this, and insulated from it is the secondary winding.

A steel core can be used in a-f transformers because since the frequencies of the currents in them will never be above 5,000 to 8,000 cycles or so, the losses due to the eddy currents and hysteresis can be kept small by proper design. It will be remembered that ordinary steel cores could not be used satisfactorily in r-f transformers on account of the excessive losses at the high radio frequencies.

The secondary usually has more turns than the primary, in order to step-up the voltage. The usual turns-ratios employed are between 2 to 1, and 4 to 1. However, it is evident that not only the turns-ratio but also the impedance of the primary winding is important in determining the total voltage amplification of each stage. The turns-ratio determines how much the signal-voltage variations applied to the primary will be stepped up in the transformer, but the primary impedance determines just how strong these signal-voltage variations appearing across the primary, will be.

The windings consist of many thousands of turns of about No. 40 or 44 enameled copper wire. Small wire is used so that a large number of turns can be wound in a small space. No. 40 wire will safely carry about 1.85 amperes. The cores are laminated to reduce eddy current effects due to the constantly changing magnetic field. The shell type or "closed" core shown in Fig. 309 is used most, because of the small amount of magnetic leakage between the primary and secondary. The primary is usually placed inside of the secondary, and if both coils are wound in the same direction the connecting leads are usually taken off in the order shown. The inside end of the primary (P) goes to the plate of the vacuum tube, the outside end (B+) goes to the B+ terminal of the "B" voltage supply. The inside end (F−) of the secondary goes to the negative terminal of the grid-bias voltage source, and the outside end (G) goes to the grid. This keeps the grid and plate terminals as far apart as possible, thus lowering the effective capacity across the coils. Fig. 310 shows a typical high grade transformer removed from its soft iron protective case. The markings which appear on the terminals a-f transformers are such as to assist in connecting them up. Thus the terminal of the primary which goes to the *plate* of the tube is marked "P". The other end, which goes to the B+ source is marked "B+". The end of the secondary which goes to the *grid* of the following tube is marked "G", and the end which goes to the negative terminal of the grid-bias source is marked F−. The connections of the transformer in the actual circuit are shown in Fig. 307.

Since the primary of an a-f transformer consists of a great many turns of wire wound on an iron core, it has inductance, and presents an

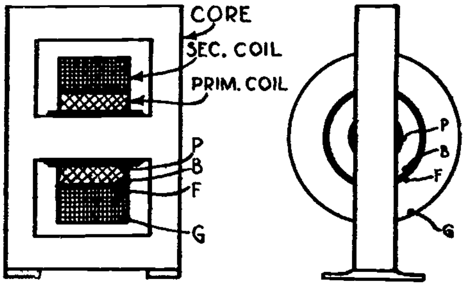


Fig. 309—Cross-section and side view, of an a-f transformer, showing the relative positions of the primary, secondary, core, and terminals. The terminals of the windings are arranged so that the minimum capacitance exists between the P and G terminals.

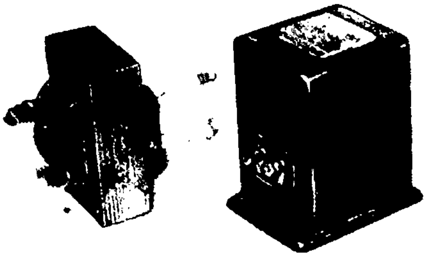


Photo Courtesy Pilot Radio & Tube Corp.

Fig. 310—A typical a-f transformer and its metal enclosing case. Notice the substantial core and windings. This transformer contains about 16,000 turns of No. 40 enameled wire, which, if stretched out straight, would be nearly a mile in length.

impedance or opposition to any variation of the plate current flowing through it. Its impedance varies with the frequency of the plate current variations, being much greater when the higher frequency audio signal voltages are being received than when those of lower frequency are coming through. The signal voltage E_1 impressed on the tube may be of any frequency between 40 and about 5000 cycles, depending on the range of frequencies concerned in the reproduction of the speech and music being received. Practically, the result is that at the low frequencies at which the transformer impedance is low, very little of the total applied plate circuit voltage is effective across the transformer; most of it is across the tube. At the higher frequencies a greater proportion of it is applied to the transformer, because the transformer primary impedance is higher. As a result of this, the low notes do not receive as much amplification as

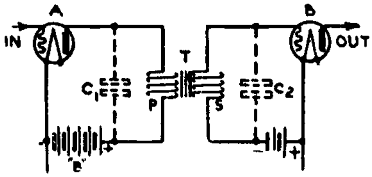


Fig. 311—The distributed capacity of the primary and secondary windings on an a-f transformer may be represented by the condensers C, and C2 across these windings.

do the moderate and high frequencies, resulting in distortion of the program. Actually, the high frequencies are reduced somewhat by the decrease of amplification due to the distributed capacity of the windings.

The frequency response of an a-f transformer having a characteristic like this is shown by curve A in Fig. 305. In order to keep the amplification up at the low frequencies, the primary impedance must be designed to be large at these frequencies, compared with the plate impedance of the tube. Since the impedance increases with the frequency, there is no difficulty in obtaining the necessary high impedance at the upper audio frequencies. The impedance at low frequencies depends upon the inductance. The larger the inductance the greater the impedance. To get a large inductance a large number of turns of wire are required on the primary coil, and a core material of high permeability must be used. This makes the transformer more expensive of course.

If the voltage step-up property of the transformer is to be made available, the secondary must have more turns than the primary (in a 3 to 1 transformer the secondary has 3 times as many turns as the primary). Let us assume a 3 to 1 transformer. If the primary contains enough turns to have the proper impedance necessary to match that of the tube, the secondary will have 3 times as many turns and be very large and expensive. Also, the large number of turns of wire on both the primary and secondary coils will have a large distributed capacity. These will act as shunt condensers C_1 and C_2, across the coils, as shown in Fig. 311. Since the reactance of a condenser decreases as the frequency is increased, the effect of C_1 is to shunt the high-frequency plate current variations away from the primary of the transformer. One effect of this is to partially reduce the high-note response, since these shunted current variations do not produce any varying magnetic field or secondary voltage in the transformer. Condenser C_2 also has the effect of putting a load on the secondary coil, since currents flow back and forth in the circuit consisting of this capacity and the winding. The magnetic fields set up by these currents as they flow back and forth through the winding, oppose the magnetic field due to the primary, and so reduce the primary inductance, and the voltage transferred to tube B. The result is that the high distributed capacity in either of the windings cuts down the amplification of the high frequencies, and since the high-frequency notes are therefore not reproduced, distortion results. Curve B (Fig. 305) shows the frequency response of a stage of a-f amplification using a transformer of this kind. Notice that the response at the low notes has been improved greatly, at the expense of the high notes. (One manufacturer reduces the distributed capacity by winding the coils in helical fashion.) The size of the secondary coil could be kept down by making a 1 to 1 transformer, but then the amplification would be reduced.

It can be seen that a compromise must be made between primary inductance, turn-ratio, and cost. The turn-ratios of modern high grade transformers vary from about 2 to 1 to 4 to 1, 3½ to 1 being a common value. The primary inductance is made large enough to reproduce the low notes well, without serious decrease in high-frequency response due to distributed capacity. Curve C shows the frequency response of an a-f amplifier stage using a high-grade transformer. Notice the compromise between curves A and B. An idea of the characteristics of this transformer can be obtained from its specifications: turn-ratio 3 to 1, primary inductance 100 henrys, primary resistance 3,700 ohms, primary impedance 19,000 ohms at 32 cycles, 626,000 ohms at 1000 cycles under operating conditions. Secondary inductance 900 henrys, secondary resistance 10,000 ohms. Referring to Fig. 214, we find that the a-c plate resistance of a '27 type tube operated as an amplifier is 9,000 ohms. Therefore, the impedance of this transformer is about twice as great as that of the tube at 32 cycles, so that about 0.7 of the mu of the tube would be obtained, (mu=9) at the lower frequencies. The amplification *per stage*, at this frequency would be $.7 \times 9 \times 3 = 19$ approximately.

428. Transformer ratio: The effect of the transformer ratio on the total amplification of an a-f stage (tube and transformer) is usually very misleading. We know from the foregoing discussion that a high-ratio transformer is more desirable from the standpoint of transformer voltage step-up than one of lower ratio. But the advantage gained by the use of the higher ratio transformer depends upon how the higher ratio is obtained. Some manufacturers put out a line of transformers of various ratios in which the number of secondary turns is the same for all transformers. Various ratios are obtained by changing the number of primary turns. Thus, their 1 to 1 transformer has equal primary and secondary turns. Their 3 to 1 transformer has the same number of secondary turns but only one third as many primary turns. Obviously the 3 to 1 transformer has a higher step-up voltage in itself, but the impedance of its primary is so low compared to the plate impedance of the tube that the amplification of the low-frequency signal voltages is greatly reduced and the low notes are slighted. The amount of amplification lost through this poor match is usually greater than the amount gained in the transformer by the higher ratio. With such transformers, it is sometimes found that an amplifier using 2 to 1 transformers produces more amplification and better quality of reproduction (due to the higher primary impedance) than one using 5 or 6 to 1 transformers of the same make.

A transformer following a detector tube should necessarily have a high impedance primary if high amplification is to be obtained, because a vacuum tube has a high plate resistance when connected as a detector. If transformers of different ratios are to be used in a two stage amplifier, the transformer having the higher primary impedance should *always* follow the detector tube in order to match its plate resistance better—no matter what the turns-ratio is.

429. Large size transformers and core saturation: The primary of each audio transformer has flowing in it, the direct plate current of the preceeding tube, varying at audio frequency. It is only the *variations* in the current that are effective in producing voltages in the secondary, the steady direct component of the plate current (see (C) of Fig. 275) produces absolutely no voltage in the secondary. It merely produces magnetic lines of force which tend to magnetically saturate the core of the transformer and cause distortion due to the decreased inductance of the coils. The subject of transformer and choke-coil core saturation was studied in Article 123. If the plate current is large enough so that the increases of the plate current when the grid becomes *less* negative, cause the iron to operate over the "knee" of the magnetization curve, then the flux change and the secondary induced e. m. f. due to the positive half of each signal impulse will be less than those due to each negative half, and consequently, distortion of the wave-form of the signal voltage will result. The result will be a reduction of the upper half of each plate current ripple. Also the inductance of the primary is decreased due to the decreased flux changes, and less voltage therefore appears across the secondary. Since the voltage appearing across the secondary coil is proportional at any instant to the change in magnetism in the core at that instant, it is evident that the secondary voltage wave-form will be distorted by the non-linear characteristics of the iron. This is sometimes called *hysteretic distortion,* because it is caused by the hysteresis in iron (Art. 99). Hysteretic distortion, which may cause serious distortion of the wave-form of the signal, is not shown by the ordinary frequency-response curves of Fig. 305. Thus, while an audio amplifier may have a perfect frequency-response characteristic, excessive hysteretic distortion may make it a very poor amplifier when operated for the amplification of speech and musical frequency voltages.

Saturation can be avoided by the use of rather large amounts of steel in the cores. The increased amount of copper and steel used in modern high-grade audio transformers is the result of a study of these factors. Of course, the cost has also increased. Some manufacturers use special nickel-steel alloys of very high permeability for the transformer cores, in order to obtain a high primary inductance. However, the danger of core saturation is greater with these materials on account of the increased magnetic field produced by a given steady plate current and the parallel-plate feed circuit is usually employed with them to avoid this. The steady flux is decreased by some manufacturers by inserting a small air-gap in the magnetic circuit. This also decreases the primary inductance slightly, but helps solve the problem of saturation. A solution to this problem is the use of the parallel or shunt-feed plate supply, connection described in Article 356.

430. Parallel-feed plate supply: The trouble arising from the effects of the steady direct plate current flowing through the primary of the audio transformer can be eliminated by keeping this current out of the winding and allowing only the varying a-f signal component of the current to flow through. One way of doing this is by connecting a blocking condenser C in series with the transformer primary and supplying the steady plate potential to the plate of the tube either through a resistance

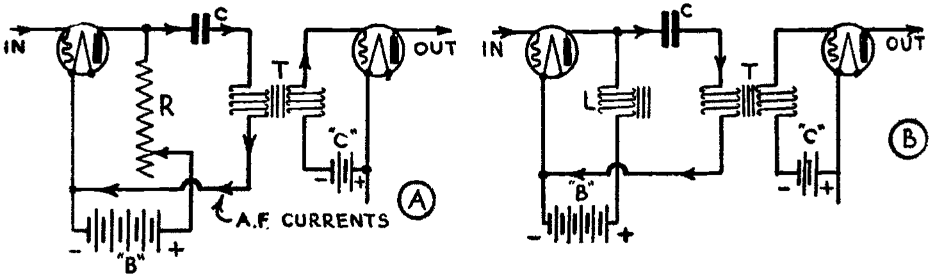


Fig. 312—Two arrangements for parallel feed of the plate voltage supply.

R, as in (A) of Fig. 312, or an audio choke coil L, as in (B). Condenser C blocks the passage of steady direct current, but is made of large enough capacity (2 to 4 mfd.) so its impedance to the passage of the a-f currents flowing through the primary winding of the transformer is very low. The resistance R (about 30,000 ohms), or the choke coil L (100 henries), block the a-f currents (since they offer a high impedance to these currents), but allow the easy passage of the direct plate current. The path of the a-f currents is shown by the arrows. This system gives slightly lower amplification and increases the cost of the amplifier, but presents a means for eliminating the distortion caused by the direct plate current.

431. Clough system with resonated primary: An improvement in the parallel-feed method of transformer coupling, known as the Clough system, is shown in Fig. 313. The d-c component of the plate current flows through a resistance R of about 30,000 ohms (100,000 ohms for detector unit) which is connected as shown. The path of the a-c component is in the condenser C and lower portion (primary) of an auto-transformer through the grid-bias voltage supply, to the cathode circuit of tube B, and back to tube A, as shown by the arrows. Since the secondary of the auto-transformer includes the whole winding, there is a step-up in voltage, depending on the position of the tap. This ratio is usually made about 4.5 to 1. The system is so arranged that when a "B" potential of 180 volts is used, the voltage drop through the 100,000 ohm detector plate resistor is just sufficient to leave about 45 volts available for the detector plate, and the voltage drop through the 30,000 ohm plate resistor is just sufficient to leave about 135 volts available for the plate of the first audio tube. For tubes drawing different plate currents, different values of plate resistors can be used. This system gives a greater effective inductance for a given expenditure of copper and iron, due to the absence of the steady d-c current in the primary. Therefore, for a given low-frequency response, the primary and secondary turns can be made less in number than in an ordinary transformer connected in the ordinary way, thus reducing the distributed capacity and improving the high-frequency response. The

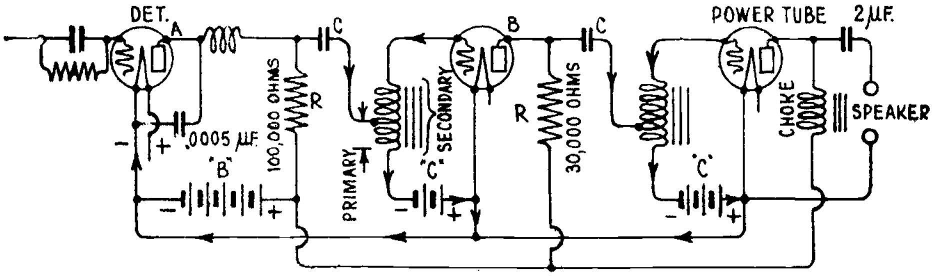


Fig. 313—Typical 2 stage a-f amplifier arrangement using the Clough resonated primary system. This system can be used both in battery-operated and electrically-operated receivers.

low-frequency response can be altered at will by using condensers of various sizes for C.

As the reactance of C and that of the primary portion of the auto-transformer are opposite in sign, there is some frequency at which these reactances will be equal and they will be in resonance. At that resonant frequency, large voltages will exist across this condenser and primary. At this frequency there will be increased amplification, due to this large voltage developed across the primary by the resonance currents. It is possible to so select the coupling condenser C, that it resonates with the primary at a low frequency which normally is not amplified well, and so increase the gain at this frequency to any reasonable desired value, equal to, or greater than the gain of the stage at the other frequencies. It is even possible to resonate each stage at a different frequency to give almost any desired shape to the low-frequency part of the amplification curve of the amplifier. Curve D in Fig. 305 shows the response curve for a system of this kind in which the proper size of coupling condenser C was employed to produce resonance at about 30 cycles, to boost the low-frequency amplification. For instance, a transformer primary having an inductance of 125 henries will resonate at about 60 cycles with a condenser C, of about .05 mfd. The resistance, coupling condenser and auto-transformer are available in commercial units, enclosed in a case with proper terminals. Different units are used for the first and second stages.

As we shall see later, a very good form of adjustable low-frequency tone control can be included in this system by connecting a variable resistor in the resonant circuit. This system can also be employed with an ordinary audio-frequency transformer which has a separate primary and secondary winding.

432. Resistance coupling: The plate and grid circuits of succeeding audio amplifier tubes may also be connected together by means of a resistor in the plate circuit and one in the grid circuit,—with the grid isolated from the plate circuit insofar as the direct plate voltage is concerned, by a blocking condenser, as shown in the typical three-stage resistance-coupled amplifier of Fig. 314. The action in the first stage is typical of all the rest. The varying plate current I_p of the detector tube, flowing through plate resistor R_1 (about 100,000 ohms) produces a varying voltage drop across it equal to $I_p \times R_1$. Since the voltage of the plate battery is constant, this makes the *potential* of point A vary in exact accordance with the plate current variations. Now point A cannot be connected directly to the grid of the second tube, as a large positive grid bias due to the "B" battery would thereby be put on it. This would cause a grid current to flow and cause distortion, and also probably damage the tube due to the heavy plate current set up. It is removed by placing a blocking condenser C_1 between point A and the grid. If this condenser has good insulation, it presents practically infinite impedance to the continuous (or direct) voltage, but allows the alternating a-f signal voltages to act around its circuit. The presence of this blocking condenser necessitates that the grid be connected to the filament through a high resistance R_2 in order to provide a leakage path for the negative charges which would otherwise accumulate on the grid and block the operation of the tube. A negative grid bias potential for the grid is secured by connecting the lower terminal of R_2 to the negative terminal of the grid bias voltage source. This may be a "C" battery or a voltage-drop through a cathode resistor. The varying voltage across R_1 is thus impressed between the grid and cathode (through the grid return circuit) of the second tube. The following stages are similar, except that different resistor values may be used.

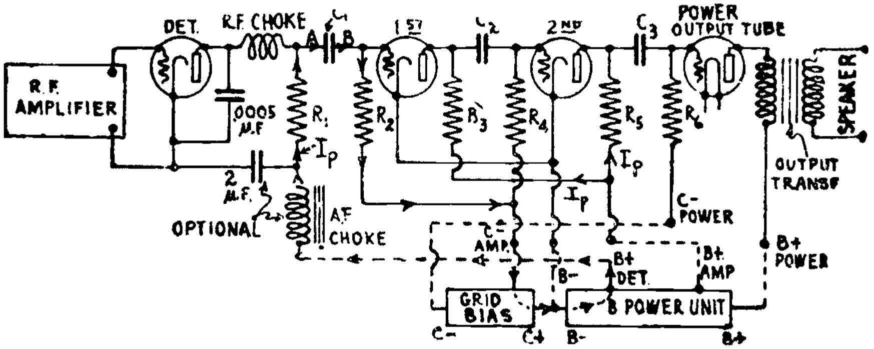


Fig. 314—Typical 3-stage resistance-coupled audio amplifier system.

As there is no voltage step-up in the coupling resistors, all of the amplification is produced by the vacuum tubes. This makes it necessary to use more stages for a given amount of amplification than when transformer coupling is employed.

Theoretically, the plate resistors should be as large as possible, for the amplification per stage is proportional to the ratio of this resistance to the total plate circuit resistance. However, this resistance cannot be increased beyond certain practical limits, for the voltage effective at the plate of the tube is less than the "B" supply voltage by an amount equal to the $I_p R$ drop through the resistor. If the resistor is made too large, abnormally high "B" supply voltages are necessary in order to apply enough voltage to the plate of the tubes to operate them at the proper points on their characteristic curves to prevent distortion. Since the plate resistance of a vacuum tube operating as a detector is much higher than when acting as an amplifier, in general the plate resistor in the detector circuit should be of higher value than those used in the following amplifier stages, in order to effectively match the detector tube a-c plate resistance.

Each plate resistor is a pure resistance, but it has shunted across it, the plate-cathode capacitance of the tube (see (A) of Fig. 249). This tends to shunt the plate current variations at the high audio frequencies and so reduce the amplification at these frequencies. As the plate resistor is increased in value in order to obtain higher amplification, the plate-cathode capacity of the tube becomes more and more effective as a shunt across it and so tends to reduce the amplification at the higher frequencies. So a compromise must be made between "gain" and good high-frequency response.

The blocking condensers can also be a source of serious frequency-distortion due to the fact that their impedance varies with the frequency. Thus the impedance of a .01 mfd. condenser is about 530,000 ohms at 30 cycles and 5,300 ohms at 3,000 cycles. This varying impedance prevents the low-frequency currents from getting through as easily to the grid circuit, and being amplified as much as the high-frequency currents. Also, the blocking condenser and grid resistor form a circuit which requires a definite time for discharge of the negative charge accumulated on the grid. Unless this time constant is sufficiently short, the grid will usually block on strong signals resulting in a gurgling sound in the amplifier. This can be corrected in most cases by careful choice of the proper plate and "C" bias voltages. The amplification of a resistance-coupled amplifier can be made substantially uniform for all audio frequencies, provided the handling capacity is reduced somewhat. The amplifier is cheap to construct and the plate current drain is light, but the plate voltage supply must be high.

Resistance coupling is especially valuable in receivers using screen-grid tubes as detectors, or using power detectors. In these, the plate impedance is too high to permit of proper matching by the primary of a transformer of reasonable cost. By using a resistance-coupled audio stage following the detector, very good amplification and frequency-response may be obtained. The same is true when screen-grid tubes are to be used in the audio amplifier.

433. Sizes of resistors and condensers: The plate circuit resistors should preferably be at least three times the value of the a-c plate resistance of the tube. With this value, an amplification of .75 times the amplification factor of the tube is obtained for each stage. Larger values will increase this gain but the increased voltage drop in them necessitates the use of high "B" supply voltages, if normal values of effective plate voltage are to be applied to the tubes. Also, the plate-cathode capacity becomes more effective in reducing the high-frequency response. The resistors must be of high grade and of permanent resistance value, able to carry the plate current flowing through them without any undue heating or change in value. The actual values of these resistors used in practical amplifiers, will be shown in the diagrams of such amplifiers later when considering the complete battery-operated and a-c electric-operated receivers for sound-program and television reception.

The size of the coupling condenser and the grid leak largely affects the operation of the resistance-coupled amplifier and its stability and frequency-response. The condenser should be large to avoid loss of low-frequency voltage across it, and the leak resistor should be large to cause the voltage drop to be as large as possible. However, the condenser will take an appreciable time to discharge through a large leak when it is charged up by a strong signal. This will cause the amplifier to block by reducing the plate current to zero. The size of both is then limited to a value such as will allow the *strongest* signal to leak off in the time between the *highest* frequency to be received. This means that the size is a compromise, but it is best to keep the leak resistors as high as possible in order to reduce the loss of signal voltage. Since the last tubes in the amplifier handle more signal voltage than those up ahead, it is common to employ leaks of lower resistance value for the last tube to avoid "blocking". A .01 mfd. condenser is usually employed in receivers for broadcast reception and leaks from .05 to 5 megohms are used, depending on the conditions of signal strength, etc. Resistance-coupled audio amplifiers are used exclusively in television receivers. As their requirements for this service are somewhat specialized, they will be studied in detail in the chapter on television.

The blocking condensers should have high insulation resistance, for faulty insulation will allow some of the plate potential to leak through it to the grid of the next tube, causing distortion or complete inoperation.

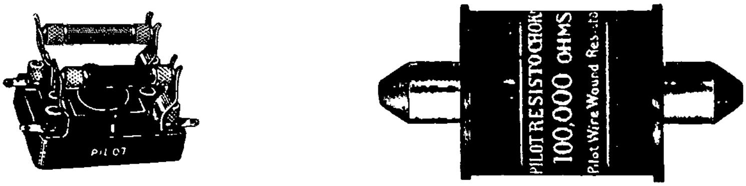


Fig. 315—Left: Resistance-coupling unit containing the plate and grid circuit resistors and the blocking condenser for a single amplifier stage.
Right: Wire-wound form of plate resistor with special end terminals to snap in place in the unit at the left.

Fig. 315 shows a commercial form of resistance-coupling unit consisting of a Bakelite base which contains the coupling condenser. The plate and grid resistors are of the cartridge type held in metal clips which also serve as connections. Several units of this kind can be wired up to form a complete amplifier. At the right is a wire-wound plate resistor unit designed especially to carry the plate current when high plate voltages are employed. All "B" and "C" circuits should be properly by-passed by condensers of at least 1 mfd. capacity to prevent interstage coupling in them.

434. Motorboating: When resistance or impedance-coupled amplifiers are operated with weak dry batteries or with socket-power operated "B" battery eliminators, trouble may arise due to coupling between the stages, because of the high internal resistance of these devices. This makes itself evident by the setting up of low-frequency audio-oscillations which sound like a motorboat engine, when reproduced by the loud speaker. This action is popularly known as *motorboating*.

Motorboating can sometimes be eliminated by reducing the internal coupling impedance by by-passing all coupling resistances in the "B" power supply with condensers of from 2 to 10 mfd. An audio-frequency choke and large by-pass condenser in the detector plate lead, as shown in Fig. 314 usually helps by keeping the detector audio currents out of the plate supply unit. Coupling between the detector plate circuit and the plate circuits of the audio amplifier tubes is the cause of most motor-boating. This coupling takes place due to the internal resistance or impedances in the "B" batteries or "B" eliminator, common to the various stages, (see Art. 377).

Thus in Fig. 316 let the resistance D-E-F-G represent the internal resistance of the "B" batteries or "B" eliminator operating the 3-stage resistance-coupled amplifier. The taps at E and F are for securing intermediate voltages. An alternating voltage impressed between points 1 and 2 is amplified by the audio amplifier and is then impressed on the grid of the last tube. This voltage will cause a pulsating audio fre-

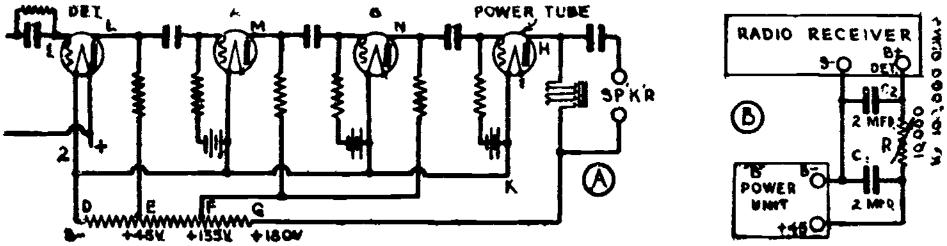


Fig. 316—Left: How interstage coupling may occur due to the impedance of the B supply unit in a multi-stage amplifier.
Right: How "motorboating" may be eliminated by means of a resistor and condensers connected between the B power unit and the radio receiver.

quency current to flow in the plate circuit of the last tube. This current will flow in the path D-E-F-G-H-K. This varying audio-frequency current flowing through the resistances D-E and D-F will cause varying falls of potential across them. This will cause these varying audio-frequency voltages to be impressed back on the plate circuits D-E-L (detector-tube) D-E-F-M (tube A), and D-E-F-N (tube B). These audio-frequency voltages will depend on the currents and the impedances between the points DE and EF. This small voltage is again amplified and fed back, and if the phase relation of the fed-back voltages E_{ED} and E_{FD} is such that the original signal is increased by the feedback, the audio voltage will keep on increasing until the amplifier breaks into low-frequency oscillation and gives the characteristic motorboat sound.

If motorboating occurs in a transformer-coupled amplifier, it can usually be stopped by changing the phase angles of the voltages E_{ED} or E_{FD} by reversing the connections to the primary of one of the audio transformers.

A simple cure for most cases of motorboating is also shown in the circuit of (B) in Fig. 316, which was developed by the E. T. Cunningham Co. It eliminates coupling effects at the low frequencies. It can be built right in the receiver or can be added to any existing receiver installation by connecting the resistance R in series with the lead connecting the B+ detector terminal on the receiver to the B+ detector terminal on the power unit. Condensers C_1 and C_2 of 2 mfd. each are then connected as shown between the B— terminal and the two B+ terminals. It is preferable to locate the resistor R at a point close to the receiver, rather than at the power unit. The value of the resistance may be anywhere from 10,000 ohms to 100,000 ohms for best results, depending upon the characteristics of the receiver and power unit. A variable resistor is suitable. Since the resistor is in series with the B+ detector lead, a slightly higher plate voltage will have to be used to compensate for the IR voltage drop in the resistor.

435. Characteristics of resistance-coupled amplifiers: One of the advantages of the resistance-coupled audio amplifier is that it is compact and cheap to build and that, for low signal voltages at least, the amplification can be made very uniform over quite a wide frequency range. This characteristic makes it especially valuable in television work. Of course the gain per stage is quite low unless screen-grid tubes are employed (since all the amplification is due to the tubes alone). The "B" supply voltage must be increased above the normal value for the tube used, in order to compensate for the voltage drop in the plate resistor. The grid is always kept negative by the proper grid-bias voltage, as in the case of all other types of amplifiers.

436. Impedance-coupled a-f amplifiers: The impedance-coupled amplifier is similar to the resistance-coupled type just described, excepting that the plate resistors are replaced by inductance or impedance coils as shown in Fig. 317. Each coil consists of thousands of turns of wire wound on a laminated steel core. A unit of this type is shown at the left of Fig. 318.

The resistance of these coils to direct current is comparatively low, but the opposition or impedance offered to currents of audio frequency is very much greater on account of the inductive effect. Thus the direct current component of the plate current is not opposed very much by the low d-c resistance of the choke coil windings, so comparatively low "B" supply voltages can be used. The impedance offered to the a-c component however is very much higher, so that an effective match with the plate resistance of the tube is secured if chokes of sufficiently high inductance are used. The impedance varies with the frequency just as in the case of the transformer primary, so that large impedances must be used if the low frequencies are to be amplified. The effect of the blocking condenser and grid leak are the same as for the resistance coupled amplifier.

As no voltage step-up is secured in the impedances, the amplification per stage is lower than that of transformer coupling—all the amplification

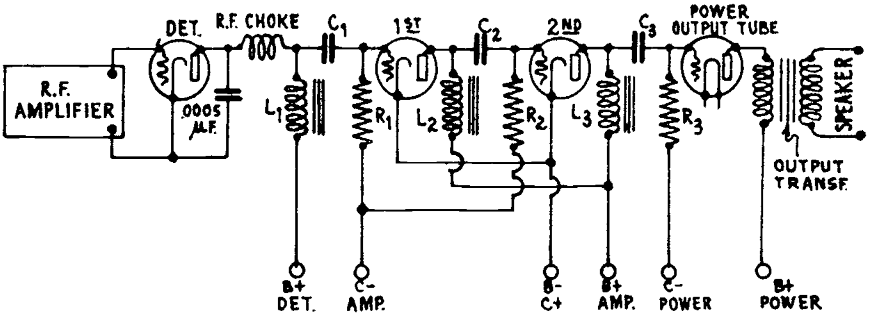


Fig. 317—Typical 3-stage impedance-coupled amplifier arrangement.

being due to the tubes themselves. For this reason, where two stages of transformer coupling would provide sufficient amplification, it is common to use at least three stages if either resistance or impedance coupling are employed. Any tendency toward motorboating can be removed by the same method shown in Fig. 316. The same design considerations as regards size of blocking condenser, leak resistor, etc., apply for this amplifier as were mentioned in Article 433.

437. Autoformer impedance coupling: Some voltage step-up in the impedance coil can be obtained if it is connected up as an auto-transformer (Fig. 319), so that the plate current flows through only part of the winding (usually 2/3). The varying current induces a voltage in the remaining part of the winding, and the total voltage is applied to the grid circuit of the following tube. The circuit now possesses the voltage step-up features of a circuit employing a two-winding transformer, except that the blocking condenser and grid leak with their disadvantages are

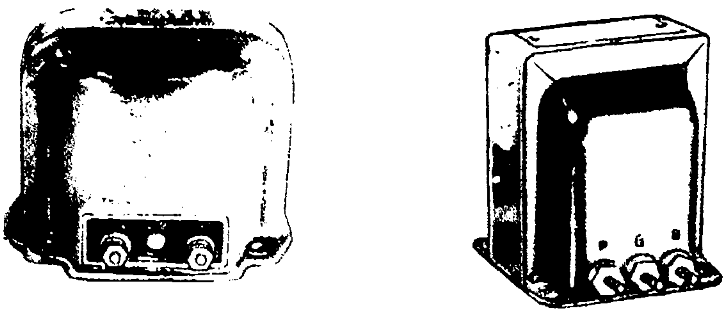


Fig. 318—Left: Typical iron-core impedance unit for use in impedance-coupled a-f amplifiers. Right: Typical auto-transformer for use in auto-transformer coupling.

still required. Auto-transformers can be built with much less wire and a smaller core to handle the same power and to have the same ratios as 2-winding transformers. By using well designed auto-transformers, proper blocking condensers and grid leaks, and a high mu tube, a two stage auto-transformer coupled amplifier may be built, having excellent frequency characteristics and about the same volume as the ordinary transformer coupled amplifier. It must be remembered that the position of the plate tap P is determined by the fact that the portion of the winding between P and B must have sufficient inductance to match the plate impedance of the tube at the low audio frequencies. A commercial autoformer unit manufactured especially for amplifiers of this type is shown at the right of Fig. 318. Notice the three terminals. Here again, the same design considerations as regards size of blocking condensers, leak resistors, etc., apply for this amplifier as were mentioned in Article 433.

438. Dual-impedance coupling: Another arrangement which has many of the advantages of the ordinary impedance-coupled amplifiers, with the additional advantage of giving higher voltage amplification, is known as *dual-impedance* coupling. As shown by a single stage of Fig. 320, two windings L_1 and L_2, having a 1 to 1 turns-ratio, are arranged *on a single core* with a blocking condenser connected between them. Thus instead of the usual leak resistor we have an impedance-coil leak. An e. m. f. is introduced into the leak impedance by the mutual inductance between the plate coil and the impedance coil. At the same time they are arranged so the capacity between them is very small. The extra voltage

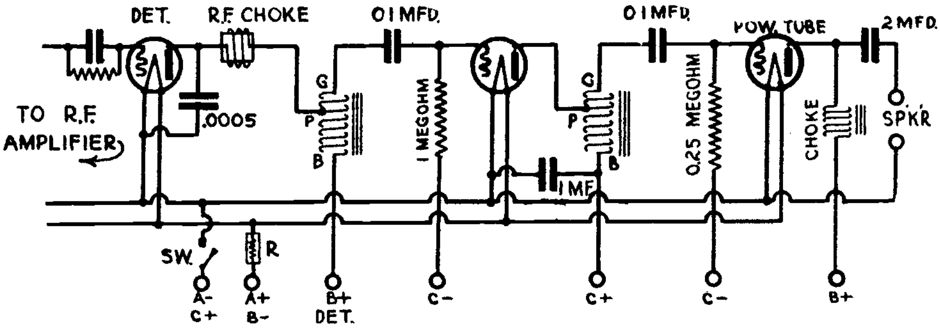


Fig. 319—Typical 2-stage auto-transformer coupled amplifier circuit arrangement

introduced into the grid circuit makes the total amplification greater than for straight impedance coupling, with the advantage that strong signals do not block the grid. Very good reproduction is secured if the plate coil has an inductance of at least 100 henries, and a blocking condenser of about 0.1 mfd. is employed. In some dual-impedance coupling units, very good low-note amplification is secured without using very large coils and cores, by so determining the inductance of the plate and grid coils and the capacity of the coupling condenser that the entire combination tunes or

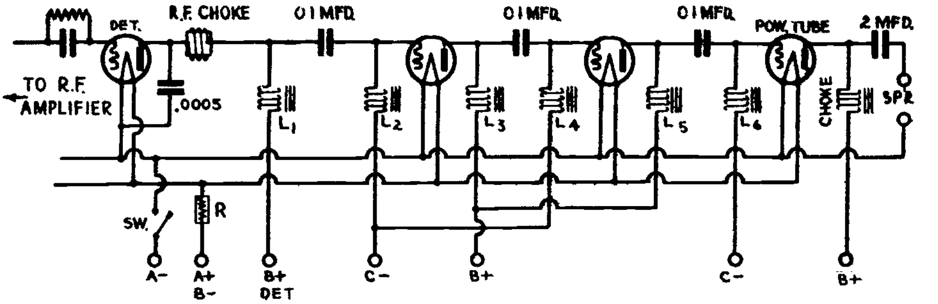


Fig. 320—Typical dual-impedance coupled amplifier circuit.

resonates at about 30 cycles. The result is that the amplification of these low frequencies is unusually good. High-mu tubes are usually employed in a dual-impedance amplifier.

439. Combination couplings: Amplifiers are often built with combinations of the coupling devices described, in order to secure certain desirable characteristics, such as a compromise between the well known high "step-up" of one, with the high "quality" and "power handling capacity" of another. One popular combination has been that of one stage of transformer-coupling and two stages of resistance-coupling. Care should be exercised in the use of such combinations, in order to secure desirable results. The proper relative order of the stages should be considered, to prevent overloading. In a combination of transformer-coupling with any other type of audio-frequency amplification, the transformers should be in the last stages, and the transformer with the highest ratio should be the last one. This tends to prevent overloading of the next to the last tube. Combination amplifiers also show a decreased tendency to motor-boat, since the phase of the transformer stage can be reversed by reversing the connections going to either the primary or secondary winding.

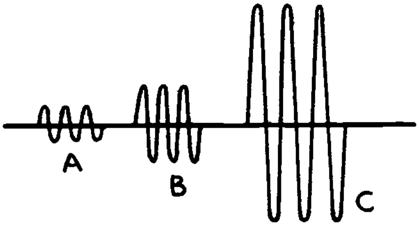


Fig. 321—The signal voltage variations are amplified by the successive amplifier stages as shown by the succeedingly larger amplitudes of curves A, B, and C.

440. The direct-coupled Loftin-White amplifier: In the direct-coupled amplifier system the plate of one tube and the grid of the next are coupled directly through a common resistor—no blocking condenser and leak resistor being employed. By eliminating these, grid blocking due to strong signals is avoided and the frequency response is improved. The problem of coupling the successive tubes in vacuum tube amplifiers is largely the problem of causing the plate current variations in the circuit of one tube to cause grid potential variations which are as large as possible and unaffected by the frequency, in the following tube. Of course the proper plate and grid bias voltages must be applied. The so-called "resistance-coupled amplifier" discussed in Article 432, a single stage of which is shown in simplified form at (A) of Fig. 322, really resolves itself into a resistance-capacity coupling by reason of the coupling condenser C_1. The reactance of this condenser varies with the frequency, and on low frequencies this reactance is sufficiently large to cut down the frequency response. In this type of coupling also, the effective input capacity $C_{g\text{-}c}$ between the grid and cathode of the second tube will operate substantially as a shunt across the leak resistance R_g at high frequencies, and will cut the response in the upper range. The plate-cathode capacity $C_{p\text{-}c}$ of the first tube acting across the plate resistor R_o also acts the same way. This is larger as the amplification of the tube and associated circuit is increased.

The third fault lies in the fact that there is no voltage step-up in the coupling itself, and thus additional stages are required to secure a desired gain. Also, on strong signals there is a tendency for the grid circuit of the last audio tube to block due to the accumulation of electrons on the grid, and the resulting reduction in the plate current. Direct-coupling schemes have been developed to eliminate the coupling condenser and grid resistor in order to do away with these objectionable frequency-characteristics. This means that a *direct coupling* between the plate and grid circuits must be employed. Arnold proposed a scheme shown in simple form at (B) in which the coupling condenser and grid resistor were eliminated. The plate of the first tube is conductively or direct-coupled to the grid circuit of the next, through the plate circuit resistor R.

Now let us see what the objections to such a system are. It is seen that a common resistance is used in the plate circuit of one tube and the grid circuit of the succeeding tube. In such a case, the entire positive plate potential, less the drop in the resistance, would be applied to the grid of the next tube. Of course the tube cannot be operated satisfactorily as a distortionless amplifier with a high *positive* grid potential, so the "bucking" or "C" battery is used in the grid circuit. This battery must of necessity have voltage enough to cancel the plate battery voltage plus whatever grid bias is required. This would all be very well were it not for the fact that in such a circuit the drop across the resistance R, which is common to both these circuits, is not constant. When a signal is applied to the grid of the first tube, its plate current rises, and consequently the drop across the resistance is greater. This upsets the bias on the grid of the next tube, usually sufficiently to throw the second tube off its operating curve. Should the signal get past the second tube, the effect would be even greater in the next stage. Also, in a system of this nature, there is a "drift effect". That is, if for any reason the current through any tube should change, there is no provision made to restore the state of equilibrium. Consequently, after it has been in operation for a moment or so, the various circuit conditions will drift until the entire system is blocked and no signal can find its way through. Also the battery requirements for such a system are impractical.

E. H. Loftin and S. Y. White reduced the direct-coupled circuit to a practical form, eliminating the necessity for the separate "C" battery and adapting the entire amplifier for practical a-c electric operation. A simplified diagram of the essential arrangement in their system is shown at (C). The sources of filament voltages are omitted for simplicity in this diagram. A single source of voltage is used in the plate circuit (shown by the box), and a single coupling resistance R_c is employed. The "B" current flows from terminal Y through the plate circuit of the second tube to point T and to N. At point N, the plate current of this tube divides, part flowing through the resistor from N to M, and back to B— and the B· power supply unit. The other part flows up through coupling resistor R_c to S, and across the plate-cathode path of the first tube to W, then down through resistor R to M—where it joins the other part which came through the resistor from N to M—and back through the "B" power unit. Point M is the most negative point in the entire circuit. The plate current taken by the first tube flowing through the coupling resistor R_c from N to S causes a voltage drop in it, and point S is therefore negative with respect to points N and T by an amount equal to this voltage drop. Hence the grid of the second tube has a negative grid bias voltage with respect to the center point T of its filament circuit, due to this ingenious voltage distribution arrangement. Resistor R_c is constant in value, but the plate-cathode impedance of the first tube will vary when the signal voltage is applied to its grid circuit. There is, therefore, a continually varying change in the voltage distribution between the plate-cathode path of the tube and the coupling resistor R_c when a signal is acting on the amplifier. If the plate impedance is large, the drop across R_c will be com-

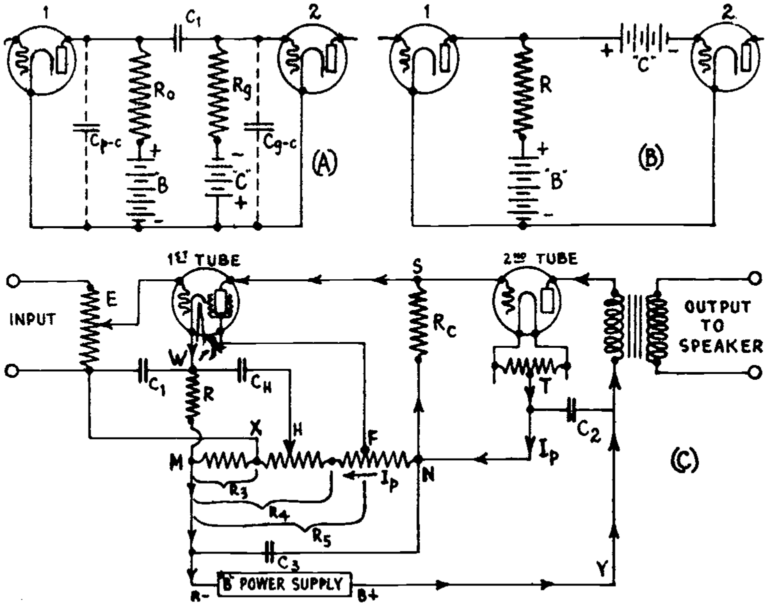


Fig. 322—Development of the Loftin-White direct-coupled amplifier system.

paratively small and vice-versa. When a varying signal voltage is applied to the grid circuit of the first tube, it causes variations in the plate current of this tube. This varying plate current flowing through R_c causes instantaneous variations of the voltage drop across it, which are impressed between the grid and filament of the second tube, and amplified by it. It is evident that the total voltage which must be supplied by the B power unit, is equal to the *sum* of the effective plate voltages actually on the tubes, plus the grid bias voltage (voltage drop in R_c) of the second tube. This means that for given type of tubes employed, the B power unit in this type of amplifier must be capable of supplying a higher voltage than when ordinary forms of coupling are employed.

The voltage drop from N to M through the total resistor is of course the same as the total voltage drop through R_c plus that from the plate to cathode of the first tube plus that in R, since these are two parallel circuits. Furthermore, each is equal to the entire B voltage, minus the voltage drop in the second tube. A screen grid tube is usually employed as the first tube, on account of its high amplification factor. Since current flows from N to M, by tapping the resistor at a suitable point F, a suitable positive potential, (with respect to the cathode at W), for the particular plate voltage employed, exists across total resistance R_5 and may be applied to the screen grid of this first tube. Resistor R in the cathode-return circuit of the first tube is used as a bias resistor for this. Any tube will have a tendency to increase its plate current when a signal is applied to the grid circuit. As the plate current of the first tube flows through R, the voltage drop across this resistor will tend to increase with the input of the signal. Grid bias resistor R (50,000 ohms for a '24 type tube) for the first tube, is considerably larger than is commonly employed for tubes of this type. There is a definite reason for this. The grid return circuit of this tube is brought back to point X as shown. Point X is at a higher potential than point M by an amount equal to the IR drop in resistance R_3. Also point W is at a higher potential than point M, by an amount equal to the IR drop in resistor R; or, stating this another way, M is negative with respect to W. Now by using suitable values of resistance for R_3 and R, it is possible to make point M more negative with respect to W, than point X is positive with respect to M. Then, point X will be negative with respect to W and therefore the net bias voltage applied to the grid (which is equal to the difference between these two voltage drops) will be negative with respect to the cathode point W.

Perhaps this may be understood more easily by considering points M, X and W, as three men on three different floors of a building, and considering that lower level is negative and higher level is positive. Man M is on the ground floor. Say man W is on the 10th floor. Then he is positive with respect to M by 10 units. X is on the sixth floor. Therefore he also is positive with respect to M, but only by 6 units. But at the same time he is 10 minus 6, or 4 floors under W, so he is negative with respect to W by 4 units.

In this way, a negative grid bias voltage is applied to the first tube and the grid is kept at practically a constant negative value irrespective of the signal input. Any drift effect is also compensated for by this method. The action taking place is very important.

Referring to the diagram at (C), it will be seen that when, for any reason, an increase occurs in the plate current of the first tube, the bias voltage on the second tube increases automatically due to the greater voltage drop in R_c. This causes a decrease in the plate current of the second tube. This latter plate current constitutes the major portion of the current through the resistor from N to M, so that when it decreases, the voltage drop in the resistor R_3 *decreases*. Therefore the net grid bias voltage applied to the first tube *increases*, tending to keep the plate current of this tube constant. This is the important regulation feature of this circuit.

A condenser C_H, is connected between the cathode of the screen grid tube and a point H on the voltage divider resistance. The object of this is to introduce a varying hum component voltage into the grid circuit of the tube, of just equal value and opposite phase to that introduced by the varying voltage drop across R caused by any ripple in the plate current, so as to neutralize it and prevent hum. The amount of neutralizating hum-frequency voltage thus introduced, is varied by an adjustable slider H, arranged to be moved along the resistor until no hum appears in the signal output. Under this condition, the varying voltage drop across R due to the ripples in the plate current, are just equal at every instant to the hum-frequency variation in the voltage drop from H to M. Connecting the condenser as shown, makes these hum voltages oppose and neutralize each other in the circuit between the terminals, at every instant. This hum-bucking arrangement is very effective and important and may be applied in any form of amplifier circuit. It enables satisfactory hum-free operation to be obtained even when rather poor filtration exists in the "B" power supply unit, thereby reducing the size and cost of the filter necessary in this unit. By-pass condensers C_1, C_2 and C_3 are connected across the various resistors to prevent undesirable coupling which might take place.

The advantages of the use of this system are cheapness, low weight, low bulk, high gain and the fact that any frequency can be handled with practically no frequency discrimination or wave-form distortion. The amplifying possibilities are limited only by the amplification constant of the tubes. Of course it is advantageous to use a screen grid tube with its high amplification. Due to the high amplification produced, the output tube chosen must have sufficient capacity to handle, without distortion, what the system will apply to it. The output tube is merely a coupling tube between the amplifier and the loud speaker. It must be built to handle *power*. Even with a single screen-grid tube ahead of it, a large size power tube such as the '50 type should be used in the last stage if the large amplification of the screen-grid tube is to be used. Otherwise the input or the amplification of the first tube must be materially decreased in order to prevent overloading of the last tube. Usually, lower voltages must be employed on the screen grid tube than are specified in the table of Fig. 214, simply because of the limited grid-swing which the following tube can handle. Thus, when a '24 type tube is followed by a '45 type, since the '45 type can only handle a signal voltage of about 40 volts on its grid, the plate, grid and screen voltages used on the preceeding '24 type tube must be less than if, say, a '50 type tube followed. The plate current of the '24 tube under the conditions of operation existing in the usual amplifier of this type is only a few microamperes.

Heater types of amplifier tubes are more convenient in the utilization of the voltage distribution existing in the direct-coupled amplifier because the cathodes of the various tubes are independent of each other. With filament types of tubes, the filaments of all the tubes are connected together in the "A" supply, and so it is difficult to apply the voltage distribution system outlined herein. When applying this system to a practical amplifier operated from the a-c electric light circuit, several precautions are necessary in the design.

For instance, even though the filaments of the tubes employed are all designed to operate at the same voltage, say 2.5 volts, it is necessary to operate the filament of the power tube from a separate 2½-volt winding of the power transformer. Any attempt to run this filament from the same 2½-volt winding that operates the heaters of the other tubes will result in trouble. The cathodes of the rest of the tubes are practically at ground potential, or at best, at only a small bias above ground. If, then, we proceed to connect their respective heaters on to the power filament winding, we will be placing the same high-voltage-to-ground on to the heaters of these other tubes as we have on the filament of the power tube. This high voltage to ground on the heater is liable to break down the insulation between it and cathode, which is practically grounded since it is only at a small potential above the ground point M. Such breakdowns will ruin reception and the tube. This point is important. Even if this insulation were perfect, there is still another trouble which necessitates the separation precaution. The heater, though only used for its heat, can also be a plate circuit for the electrons given off from the heated cathode. The number of these electrons reaches a real value when the heater becomes positive with respect to the cathode, the condition is excessive when this heater is allowed to reach any such value as say 180 volts positive with respect to the cathode, which it might reach in an actual amplifier. This current would result in fictitious bias voltages in both the power tube and the cathode circuit of the first tube. Consequently in all amplifiers of this type, the filament voltages for the individual tubes are supplied by separate windings on the power transformer.

The direct-coupled amplifier has perhaps found its greatest application in public-address work for amplifying the output of microphones, phonograph pickups, or talking moving picture equipment. Commercial units for this purpose are described in Arts. 547 and 548 in the chapter on Sound Amplifier Systems. By proper design, it is possible to build a two-stage amplifier having a voltage gain of 450 or more. The frequency response may be made flat from 30 to about 7,000 cycles. At higher frequencies, it begins to droop due to the plate-cathode capacity of the input tube and the grid-cathode capacity of the output tube acting across the coupling resistor, but the response can be made uniform to about 10,000 cycles by employing special forms of neutralization. The output stage may be made of the push-pull type for greater signal-handling capacity as we shall see later when discussing power amplifiers.

441. The last audio stage: Every vacuum tube has a certain definite operating range over which its E_g - I_p characteristic is fairly straight, and over which changes produced in the plate current are proportional to the changes in voltage applied to the grid circuit. If the signal voltage is small enough so it produces grid potential swings which cause the tube to operate wholly over this part of its characteristic, and which do not make the grid positive at any time, the amplifier tube itself will not cause noticeable distortion. Now in an audio amplifier, or a radio receiver as a whole, the signal voltage is being amplified in each stage, somewhat as shown in Fig. 321. Assume that the signal e. m. f. input to the first amplifier tube is represented by curve A. After passing through the first amplifier stage the amplified voltage applied to the second stage is as shown in curve B. If it passes through still another stage it becomes stronger, as shown in curve C. Since each stage amplifies the voltages more, the amplitude of the signal e. m. f. may become so great by the time it is impressed on the grid of the last audio tube that it may either swing the grid potential beyond the linear portion of the characteristic curve—see curve E at (B) of Fig. 244—and therefore introduce distortion of the wave-form, or it may exceed the grid bias and cause distorting grid currents to flow while the grid is positive. This may take place even though the correct plate and grid bias voltages are being applied to the tube. It is simply a case of *overloading* of the tube, resulting in distortion of the wave-form of the signal. Overloading of the radio-frequency amplifier tubes rarely occurs, as the input signal voltages existing in it are small. Overloading of the tubes in audio amplifiers is common—especially in the last or "output stage", and has led to the development of special tubes known as *power tubes,* designed to have a characteristic curve which is sensibly straight for comparatively wide swings of grid potential (when proper load impedances are used). They are therefore able to handle larger signal voltages without overloading and distortion. (Note: The student is advised to review Arts. 340 to 344 at this point.)

It will be instructive at this point to study the characteristics of the various power tubes listed under the heading *power amplifiers,* in Fig. 214. By referring to the grid-bias voltage column, an idea of the signal voltage amplitude, which each tube can handle without driving the grid positive, may be seen. (The maximum permissable grid voltage swing in either direction is equal to the negative grid bias voltage.) Notice that the large '50 type power tube can handle an 80-volt grid voltage swing, a '45 type can handle 48.5 volts and the '47 type power pentode tube can handle 16.5 volts. However, for a given output the pentode does not need as large an input signal voltage as the others, since it has a greater "power sensitivity". Referring now to the column marked "maximum undistorted output in milliwatts," the relative output powers which these tubes can handle without distortion, is seen. For ordinary home use, the '45 and '47 type tubes are popular for the last audio stage. For powerful amplifiers and other special purposes the '50 type tube is employed, since it is capable of handling a greater signal voltage and can supply a greater amount of undistorted power to the loud speaker. Where more handling capacity than a single tube can provide, is required, it is common to connect two output stage tubes in *push-pull* in order to divide the load. This is often an advantage instead of using a tube having a larger watts rating, for as will be seen from Fig. 214, the higher the rating of a power tube, the higher the plate voltages and currents it requires. This greatly increases the cost of the B power supply unit required, so it is usually much cheaper to use two of the smaller tubes in push-pull instead. This connection will be studied later in Art. 447.

442. Power tubes: Since the function of the last audio tube or tubes in a radio receiver is not only to amplify the signal voltages applied to the grid circuit, but also to supply as much undistorted electrical *power* to the loud speaker as possible with a given input signal, *power tubes* are designed with special characteristics suitable for this purpose. It is the electrical power which the power tube supplies to the loud speaker that is converted into sound by the speaker. In this respect, the requirements for tubes used in the output stages of radio receivers differ from those used in the other amplifier stages, since the latter are not called upon to supply power, but merely to amplify signal *voltages* applied to their grid circuits. It will be seen from Fig. 214, that tubes having various output power ratings are available. Those used in battery-operated receivers employ rather low plate voltages and pass low plate currents, so their power handling capacity is in general much less than the tubes designed for use in a-c operated receivers where higher plate voltages are more economically available. Since the large power tubes such as the '45, '47 and '50 type must handle quite large plate currents, they are constructed larger than the others in order to dissipate the heat developed in them. A summary of the undistorted power outputs of some popular power tubes is given in Fig. 336.

In the case of the three-electrode tubes, the larger power handling capacity is obtained at the expense of amplification factor, since in order to design a tube of this type with low plate resistance, the relative spacing between plate and filament, and grid and filament, is reduced so the amplification factor is less, as explained in Article 314. Thus, it will be noticed from Fig. 214, that while an ordinary general-purpose amplifier tube of the '27 type has a mu of 9 and a plate resistance of 9,000 ohms, a small power tube like the '71 type has a mu of only 3 and a plate resistance of only 1850 ohms. The larger '50 type tube has an amplification factor of 3.5 and a plate resistance of 1850 ohms. By means of the five-electrode pentode tube construction, (see Articles 317 to 320), whereby the secondary emission is effectively reduced, a much higher amplification factor is obtained, but the plate resistance is also high. Thus, the '47 type pentode tube has a mu of 90 and a nominal plate resistance of 35,000 ohms.

443. Maximum power output: The power output of a power tube is measured in watts or *milliwatts*, whereas the voltage output is measured in *volts*. The voltage output might be very high, but if the plate current were small, the power output of the tube in watts (volts× amperes) would still be small. Let us consider the circuit of a tube supplying power to a load of some kind connected in its plate circuit. This might be the winding of a loud speaker as at (A) of Fig. 323, or the pri-

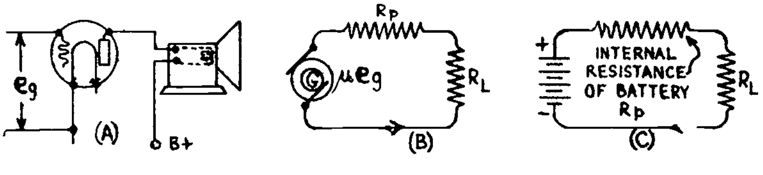


Fig. 323—Arrangement of the plate circuit of a power tube supplying power to a device connected in its plate circuit. The essential parts of the circuit are shown in schematic form at (B).

mary of a speaker-coupling transformer as at (B) of Fig. 325, etc. A signal voltage having an "effective" or r. m. s. value of e_g is applied to its grid circuit. At (B) of Fig. 323, the plate circuit of the tube is drawn in the simple schematic form which we found helpful in previous tube discussions. The r. m. s. signal voltage acting on the grid is replaced by the a-c generator whose voltage is μe_g, acting directly in the plate circuit, where μ is the amplification constant of the tube. The internal a-c plate resistance of the tube is represented by R_p and the impedance of the plate circuit load is R_L.

We must remember, that it is the current *changes* or *variations* due to the signal which supply the motivating power to the loud speaker and cause motion of its diaphragm. A steady direct current sent through the speaker coils would produce no motion or sound, no matter how large it was. The amplitude of the current changes in the plate circuit will be equal to the amplified voltage changes (μe_g) acting in the plate circuit, divided by the total resistance and impedance in the plate circuit, thus:

$$\text{Varying plate current} = \frac{\mu\, e_g}{R_p + R_L}$$

The varying voltage acting across the load is equal to the load impedance multiplied by the varying current through it, that is,

$$e_L = \frac{\mu\, e_g\, R_L}{R_p + R_L}$$

The power in watts ($W = E \times I$) expended in the load impedance is therefore equal to the product of the r.m.s. values of current and voltage. Therefore the power output is:

$$\text{Power output} = \frac{\mu\, e_g\, R_L}{R_p + R_L} \times \frac{\mu\, e_g}{R_p + R_L} = \frac{R_L\, \mu^2\, e_g^2}{(R_p + R_L)^2}$$

This equation is fundamental for all vacuum tubes, assuming the tube to be operating on the straight portion of its characteristic, i.e., that the plate and grid voltages are properly adjusted. It can be shown, both mathematically and experimentally, that the *power output* for any given signal input voltage is a *maximum* when the a-c plate resistance R_p and the load impedance R_L are equal. Under this special condition, the equation for *maximum power output* reduces to:

$$P = \frac{\mu^2 e_g^2}{4R_p}.$$

Note: The dissipation of maximum power in one of two resistors or impedances connected across a source of voltage may be illustrated by the simple case of a battery of internal resistance R_p, with external resistance R_L connected across its terminals as shown at (C) in Fig. 323. If the external resistance were made equal to zero, the battery would be short-circuited. The available potential difference at its terminals would be zero under these conditions and all the power would be dissipated in its internal resistance, producing heat there. Under this condition, the useful output power is zero. If the external resistance is made very large, the current is small, and consequently the useful power in the resistance is small. If the resistance is now decreased in value in steps, a point will be found where the power of the battery is equally divided between the external resistance and its own internal resistance. This takes place when the external resistance and its own internal resistance are equal. This same condition holds true in a vacuum tube or in any circuit in which a source of e. m. f. supplies power to a load.

If the above equation is to be expressed in terms of maximum or *peak* signal voltages, then remembering that the effective value of a voltage or current equals .707 times the maximum value, or equals the maximum value divided by the square root of 2, this expression becomes:

$$P=\frac{\mu^2 E_g^2}{8R_p}$$

Where P is the maximum power output obtainable when a signal voltage having a peak value of E_g is applied to the grid circuit of the tube.

The power which is fed into the load resistance must come from the B-voltage source, because the tube itself does not generate power. It merely acts as a sort of valve in which the variations in signal voltage applied to the grid circuit allow more or less power to be drawn from the "B" voltage source and expended in the plate circuit. Working on the above basis, we can conclude that a '45 type tube for instance, which has an a-c plate resistance of 1750 ohms, will supply maximum output for any given input signal voltage, when the load resistance is 1750 ohms. A '50 type tube having an a-c plate resistance of 1800 ohms will supply maximum power to a load resistance of 1800 ohms, and so forth.

444. Maximum undistorted power output: In radio circuits we cannot consider merely the *power output of a tube*, for the problem of distortion is of equal importance. Numerous tests have shown that a limit of about 5 per cent may be set upon the distortion permissible in a power tube circuit. Distortion under this value will not be noticeable by the average human ear. Now we found at (A) of Fig. 210 that the behavior of a vacuum tube is such that the operating characteristics are somewhat affected by the load impedance, a low impedance shortening the straight portion of the characteristic by causing it to curve more. This occurs, and distortion is introduced, if a load impedance as low as the plate resistance of the tube is used. It has been experimentally determined that the *maximum undistorted* power output of the tube is obtained for any given input signal voltage, when the load impedance is equal to about twice the plate resistance of the tube when the plate current is at its peak value. The power output when $R_L=2R_p$ becomes $P=\frac{\mu^2 E_g^2}{9R_p}$. This is very little less than the maximum power of the previous equation. The result is in watts if E_g is the peak value of the signal voltage in volts applied to the grid. This voltage is limited to a value approximately equal to the grid bias voltage, if tube overloading is to be avoided. Even with the load impedance equal to twice the tube resistance, there is considerable curvature at the bottom of the characteristic. Therefore, input voltages high enough to make the plate current too low must not be applied, for the lower bend may be reached at signal voltages which are not even nearly strong enough to drive the grid positive. In the case of pentode power tubes, since the plate voltage-plate current curves are not parallel throughout the operating range of the tube, it should be remembered that the a-c resistance of the tube should be considered when the plate current is at its *peak value.* Thus a pentode tube whose a-c plate resistance at its normal operating point is say 40,000 ohms, may have an a-c resistance of only 5,000 ohms at the peak value of a grid swing so that the load impedance for maximum undistorted power output is 5,000 × 2, or 10,000 ohms and not 80,000 ohms as might be supposed.

The '47 type pentode tube has, compared with a 3-electrode power tube, quite a high a-c plate resistance at normal grid potential, yet for maximum undistorted power output it should work into a load impedance of about one-fifth this normal rated a-c plate resistance. Since no usable load such as a speaker circuit can have a constant output impedance, and as speaker impedances actually rise with frequency, the output of the pentode will increase with frequency. This is a particularly desirable characteristic in a very selective radio circuit, such as a superheterodyne, where considerable high-frequency suppression, in the form of sideband cutting, may exist if a

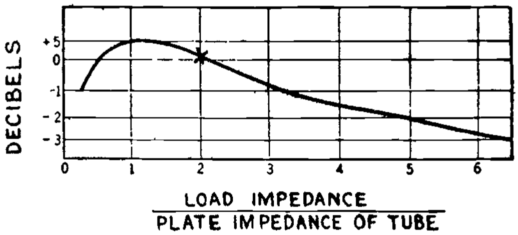


Fig. 324—Curve showing how the *ratio* of the load impedance to the plate impedance (or a-c plate resistance) of the tube affects the *total power output* of the tube, for a given input

high order of selectivity is to be realized. The output rising as frequency increases, with the pentode, provides excellent compensation in such a circuit—not enough in itself it is true, but sufficient to simplify considerably the problem of complete equalization when coupled with an audio amplifier and speaker of corrected design. It actually permits an extremely selective and well designed superheterodyne to be built to show a flatter audio response curve up to over 4,000 cycles than has in the past been possible even with the best of t-r-f receivers. Quite some mismatching of the load impedance with the a-c plate resistance is permissable, provided the former is greater than the latter. The curve in Fig. 324 indicates relatively in decibels, (according to the way the ear would be affected), how the total power in the load, (not undistorted power), varies as the ratio of the load impedance to the tube's a-c plate resistance is changed. The "X" on the curve indicates where a tube is normally operated, the load impedance at this point being twice the a-c plate resistance. Statements are frequently made to the effect that the loud speaker used must be matched to the tube to get the largest amount of undistorted power into the loud speaker. Such is the case, but the curve indicates that there can be considerable mismatching without serious loss of power. For example, even when the load resistance is about five times greater than the tube's resistance, there is only a 2 DB loss—a loss which would hardly be noticeable to the ear.

It is unwise, however, to work a tube into a load resistance less than its own a-c plate resistance, because under such conditions the tube's characteristic is curved and this curved characteristic introduces distortion due to harmonic frequencies generated by the tube.

Now it is evident that since the conditions for *maximum power output* and *maximum undistorted power output* are different. If the tube is actually operated with a load whose impedance is equal to twice its plate resistance in order to obtain maximum undistorted output, the maximum amount of power it is capable of putting into the load for any given signal voltage, will not be obtained. Actually the power is reduced about 11 per cent.

Actually a decrease in power output of 25 per cent would be just noticeable to the ear and therefore a decrease of 11 per cent will not cause trouble. Circuits using power tubes are therefore designed on the basis that the load resistance will be equal to twice the a-c plate resistance of the tube. This condition is always assumed in plotting tube characteristics and in all tables of tube characteristics will be found a column headed, "Maximum Undistorted Power Output" which indicates the power output of the various tubes when they are worked into a load resistance equal to $2R_p$ (two times the plate resistance).

Power tube distortion is more prevalent at the low frequencies than at the higher ones. One reason for this is that since there is greater energy in the low notes, the grid potential is swung further when a low note is being received than when a high one comes in, causing overloading. Also, the loud speaker winding has impedance which varies with the frequency, becoming low at low frequencies. In some cases this may become lower than the tube resistance, with resulting distortion due to curvature of the characteristic. The solution of course is to use a power tube which is able to handle the greatest input signal voltages which will be encountered. Preferably, it should also have a low internal a-c plate resistance so that the load impedance will, at the lowest audio frequency received, be larger than the a-c plate resistance of the tube.

445. Impedance-adjusting methods: The fact that the actuating winding of the usual loud speaker is not a pure resistance, but is really an inductive reactance (capacitive reactance in the case of the condenser-type speaker), complicates the problem of efficiently connecting a loud speaker to a tube. Since the impedance of a loud speaker varies with the frequency, what we do in practice is to pick some impedance which gives a good characteristic and work out the necessary design of the remainder of the circuit using this value of impedance. In working with most magnetic type speakers for example, we assume that the effective impedance is about 4,000 ohms, although actually the impedance varies from about 2,000 ohms up to 30,000 ohms, or so. Since the a-c plate resistance of most power tubes (see Fig. 214) is in the neighborhood of 2,000 ohms, the speaker impedance of 4,000 ohms is just suitable for the condition of maximum undistorted output. However, as we shall see, an output filter device is sometimes used between such a speaker and the tube to keep the direct plate current of the tube out of the speaker winding.

The moving-coil system of the modern electro-dynamic loud speaker has a very low impedance, usually around 10 or 20 ohms. This raises the problem of how we can work such a loud speaker out of ordinary power tubes which usually have an a-c plate resistance of about 2000 ohms, and still get a large amount of undistorted power output for any given input signal voltage. This difficulty is solved by the use of a transformer which has the very useful characteristic of permitting us to make a 10-ohm moving-coil act as though its impedance was 1000 or 5000 ohms, or any other impedance we might choose. How this is accomplished will now be shown.

A general expression may be derived for the turns-ratio of an "impedance adjusting" or "matching" transformer for coupling a source of power and a load in the most efficient manner, for any circuit conditions.

Thus in (A) of Fig. 325, let E_p be the voltage applied to the primary of the impedance adjusting transformer T by the source of power G, whose internal impedance is R_G. Let the load, whose impedance is R_s, be connected to the secondary winding as shown. Let N_p be the number of turns on the primary winding and N_s the number of turns on the secondary. Now to obtain maximum power transfer from the generator G to the primary of the transformer, R_G must equal R_p. This then determines the design of the primary winding. The power which the primary takes from G is converted by means of the magnetic field into power in the secondary winding, so that the secondary really becomes the source of power for the load. For maximum

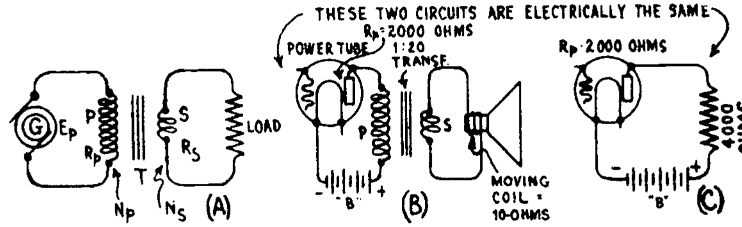


Fig. 325—Use of a transformer with proper primary impedance and impedance ratio as an impedance adjusting transformer.

power transfer from the secondary to the load, the impedance of the secondary must equal that of the load, that is, R_s equals R_L. Let I_p and I_s be the primary and secondary currents respectively. Then, by simple transformer action we have,

$$\frac{N_s}{N_p}=\frac{E_s}{E_p} \qquad (1)$$

and,

$$\frac{N_s}{N_p}=\frac{I_p}{I_s} \qquad (2)$$

multiplying the left hand parts of the two equations together, and doing the same with the right hand side will not change the equality. Doing this we obtain,

$$\frac{N_s}{N_p}\times\frac{N_s}{N_p}=\frac{E_s}{E_p}\times\frac{I_p}{I_s}=\frac{E_s}{I_s}\times\frac{I_p}{E_p}$$

Now in each case, $E/I=R$. Therefore this reduces to:

$$\left(\frac{N_s}{N_p}\right)^2=\frac{R_s}{R_p} \qquad (3)$$

That is, the ratio of the two impedances equals the square of the ratio of the turns. This relation greatly simplifies the problem of determining the turns ratio required to adjust the impedances of any two circuits for satisfactory operating conditions.

Let us now apply this to a practical tube problem. Suppose a '45 type tube has a plate resistance of 2,000 ohms and is to supply power to a moving-coil loud speaker, the effective impedance of the moving-coil being 10 ohms. The circuit arrangement is shown at (B), of Fig. 325. For maximum undistorted power output for any given signal voltage, the load impedance should be twice that of the tube, or 4,000 ohms in this case, since the source is the amplifying tube. In this case, the primary of the impedance-adjusting transformer forms the load for the tube, so its impedance is to be 4,000 ohms. We want to work into a loud speaker whose impedance is 10 ohms. For maximum power transfer from the secondary to the loudspeaker, their impedances should be equal. Therefore the impedance of the transformer secondary should be 10 ohms. Hence, from equation (3) we obtain:

$$\text{turns ratio}^2 = \frac{R_s}{R_p} = \frac{10}{4{,}000} = \frac{1}{400}$$

from which, the turns-ratio equals 1/20 or .05. This means that, if we take our 10 ohm loud speaker winding, and connect it to the secondary of a 1 to 20 ratio transformer, which has enough turns on the primary so its impedance is 4,000 ohms, then the primary may be connected in the plate circuit of the 2,000 ohm power tube and the entire circuit will operate just as though the loud speaker had an impedance of 4,000 ohms, (the correct load impedance for a 2,000 ohm tube) and was connected directly in the plate circuit, as shown at (C). It will be noticed that the "impedance adjusting" or coupling transformer ratio has been referred to in the same way as for ordinary transformers, i.e., the ratio of the *secondary* to the *primary* turns. The source of power fed to the impedance-adjusting transformer is called the "source". The device into which the secondary feeds the power is called the "sink". It is evident then that the impedance-adjusting transformer is simply a device designed so its primary absorbs power most efficiently from the source, and its secondary delivers this power (which is transferred to it by electromagnetic induction from the primary) most efficiently to the sink. The primary of the coupling transformer for loud speakers should be wound with sufficient primary turns so its primary impedance is equal to 2 times that of the a-c plate resistance of the power tube at the lowest frequencies to be received, provided this value of the impedance is practical from the point of view of cost and distributed capacity of the winding. The value is really not critical. In the case of the push-pull connection of audio output tubes, the plate resistance of the two tubes combined is equal to twice that of one tube alone, (see Art. 447). Therefore, the load impedance should be made equal to twice this, i.e., equal to 4 times the a-c plate resistance of one tube.

Impedance "adjusting" transformers are used extensively in radio and telephone work for coupling power tubes to loud speakers, for coupling phonograph pickups to inputs of amplifiers, for coupling power tube outputs to low-impedance lines and then coupling the low impedance lines to higher-impedance lines or loud speakers, etc. We will study some of these applications in our later work. In any case, the design of the coupling transformer is arrived at in the same way as has been explained here.

446. Output coupling systems: There are in general, three main types of loud speakers in common use. These are, the electrostatic or *condenser* type; the *coil* type; and the *permanent magnet* movable-armature or diaphragm type. The coupling of the condenser type to the power output tubes of a radio receiver presents a special problem which will be considered when that type of speaker is studied. The moving coil type commonly known as the electro-dynamic speaker employs a moving coil of such low impedance (10 ohms or so) that an impedance adjusting transformer must always be employed to couple it to the plate circuit of the power tube for satisfactory power transfer. This is true for both the electro-dynamic and permanent magnet dynamic types of speakers. As this system has already been discussed in Article 445, and shown in Fig. 325, it will not be considered again here. In speakers which employ permanent magnets for producing the steady magnetic field, there are usually one or more coils of wire through which the signal current flows. These produce variations in the main magnetic field of the permanent magnet and the construction is arranged so that this varying field moves an iron armature or reed, whose motion is transmitted to the diaphragm or cone which produces the sound waves. This type of speaker is commonly referred to as the "magnetic speaker" although a moving coil speaker is also a "magnetic speaker", properly speaking. The problem of coupling this type of speaker to the output power tubes of a radio receiver presents several problems which we will now consider.

The coils on these magnetic type speakers must have a large number of turns of wire, (two or three thousand turns), in order to provide a field which will be effective in causing motion of the armature or reed. Since the variations in the plate current of the last audio tube are not very great, when considered in terms of *amperes*, these coils must have a large number of turns of wire in order to have an effective number of *ampere turns*. In order to use the large number of turns required for proper operation and sensitivity, it is necessary to use very small, enamel-covered copper wire, since only a very limited space is available for the windings. The very fine wire employed is usually unable to continuously carry the *direct* plate current of the larger sizes of power tubes without undue heating and eventual burn-out. Therefore some means must be provided to keep the total direct plate current out of the speaker windings if it is more than about 10 milliamperes, and allow only the variations or a-c signal component to act on them. The steady direct component of the plate current does not produce any motion of the diaphragm anyway, so it can be kept out of the speaker. It is only the audio-frequency variations in the plate current which produce the motion. Another reason for keeping out the direct plate current, is that this current may be made to flow through the speaker windings in either one of the two directions depending on how the speaker terminals are connected in the plate circuit. With one arrangement the direct plate current flowing through the coils produces a steady field in such a direction as to aid the magnetism of the permanent magnet. However, if the speaker terminals are connected in the opposite order, the field will buck that of the permanent magnet continuously and weaken it. The possibility of connecting it in the latter way is another reason for keeping this current out of the speaker winding.

Another reason is that this current flowing through the winding produces a field which deflects the armature or reed from its neutral position and thereby makes it much more liable to strike the pole pieces of the magnet when strong signals are being received, resulting in "rattling". This condition is neither necessary nor desirable.

There are in general two common methods of keeping the direct com-

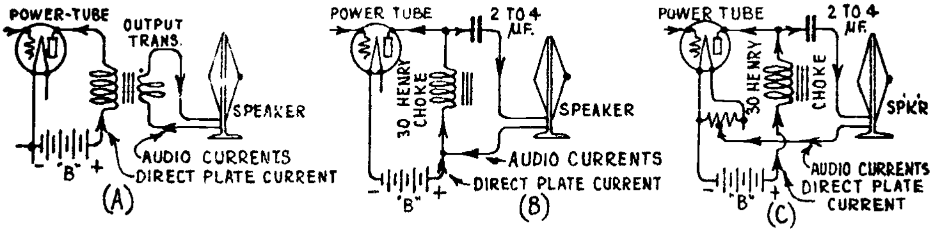


Fig. 326—Three loudspeaker coupling systems for keeping the steady direct component of the plate current of the tube, out of the fine-wire loud speaker winding.

ponent of the plate current out of the speaker winding. In the first, a coupling transformer is employed; in the second a form of choke coil-condenser coupling is used. The first method is shown at (A) of Fig. 326. Here a coupling transformer commonly called an *output transformer* is employed with its primary connected in the plate circuit of the output tube and the loud speaker connected across its secondary. Since the induced voltages in the secondary are produced only by the *variations* in the plate current, the output in the secondary is an alternating voltage and current and is not affected by the direct component of the current through the primary. The objectionable operating conditions described above are thereby eliminated by its use.

Accurate data on the impedance characteristics of all types of magnetic and dynamic speakers is not available, but the usual type of magnetic speaker has a coil winding having a d-c resistance of from 1,000 to 2,000 ohms with an impedance which varies from that value at zero frequency (d-c current flowing through the windings), to a value of about 2,500 ohms at 100 cycles, 5,000 ohms at 300 cycles, 10,000 ohms at 750 cycles, 20,000 ohms at 1750 cycles and up to 30,000 or 40,000 ohms at the higher frequencies up to 5,000 cycles per second. These high values of impedance for this type of loud speaker unit are due to the comparatively high inductance of the winding which is made up of a large number of turns. Now we found in Article 444 that for minimum undistorted power output from a 3-electrode vacuum tube the load impedance should be equal to about twice the a-c plate resistance of the tube. If a power amplifier tube having an a-c plate resistance in the neighborhood of 2,000 ohms is employed, the impedance of a speaker of this type will be fairly well matched to the plate resistance of the tube to fulfill this condition for maximum undistorted output, and the coupling transformer may have a 1 to 1 impedance ratio, i.e., it has a turns-ratio of 1 to 1. As we are not limited by space considerations in the size of wire used in the primary of such a transformer, it can be designed to have sufficient carrying capacity to eliminate danger of burnout due to the flow of the plate current of the power tube. However, since this direct plate current tends to produce saturation of the core, the cores of such transformers are usually provided with a suitable air-gap. If a speaker of this type is to be fed from a power amplifier tube having a plate resistance in the neighborhood of 4,000 ohms or more, it is evident that in order to secure the proper 2 to 1 impedance relation at the low frequencies, the output transformer must be designed to adjust the impedances as explained in Article 445. In this case, its turns-ratio will be something other than 1 to 1, and the coupling transformer acts as an impedance-adjusting device as well as to keep the direct plate current component out of the speaker windings.

Another popular coupling system for magnetic speakers is shown at (B) of Fig. 326. In this, an a-f choke coil is connected directly in the plate circuit of the power amplifier tube and the speaker winding is connected across it through the series blocking-condenser as shown. The varying plate current flowing through the choke coil produces varying voltage drops across it, (assisted by the self induction of the choke), so that due to the signal, the potential of the plate varies up and down from its steady normal no-signal value. This voltage variation is applied in the circuit consisting of the speaker winding and the condenser in series, so that a transfer of electrons takes place from one condenser plate to the other through the speaker winding, the B power supply unit and the plate-cathode path in the tube. This flow of electrons of course constitutes a flow of electric current varying at the audio frequencies at which the plate current of the tube varies, i.e., at the frequencies of the audio signals, so the speaker produces sounds corresponding to these. The paths of the direct plate current and the audio current are shown in (B). It should be remembered that while the choke and condenser coupling system does serve the purpose of keeping the direct component of the plate current out of the speaker winding, it does not act as an impedance adjuster, unless a tapped choke is used. Where impedance adjustment is necessary, it is cheaper and more advantageous to use a coupling transformer of proper design.

The arrangement of (B) sometimes leads to trouble due to coupling in the "B" power supply unit, because the varying audio currents flowing through it may cause variations of potential across impedances common to the circuit of the output stage and those of the other amplifying stages. This often causes "howling" or "singing". There are several variations of this circuit arrangement, but the one shown at (C) is probably the most satisfactory. In this, the series combination of condenser and choke is returned directly to the filament or cathode circuit of the tube. In this way, a direct path is provided for the varying audio current so it does not flow through the B-power supply, thus preventing the undesirable common coupling which often results with the schemes of (B). If the filament of the power amplifier tube is heated with d-c, the speaker-return lead can be brought directly to the negative filament terminal. If the filament is operated by raw alternating current from a transformer, the speaker return should be brought to the electrical center of the filament. This can be done by either returning it to a center tap on the transformer filament winding, or to the center tap of a fixed resistance connected across the filament as shown. Another advantage of the connection at (C) is that since one end of the speaker connects to the filament, (or B minus), and the other end is isolated from the plate—so far as direct potential is concerned—the speaker terminals have no high voltage on them at all and are perfectly safe to handle. It must be noted, however, that the full "B" potential is placed directly across the speaker circuit to the negative return. This means that the condenser must be of the high-voltage type. A shorted condenser would put the full "B" voltage through the speaker, by way of the choke, with the result that the speaker windings would probably burn out in time.

The capacity of the condenser should be as high as possible (it should not be less than 2 mfd.), to avoid resonance peaks in the loud speaker response and should have a breakdown voltage rating safely above the plate voltage to be applied to the tube. The choke coil inductance should be as high as possible so as to offer a very high impedance to the passage of the signal current through the choke. An iron-core choke coil of 30 henries inductance is commonly used for this purpose. This is wound with many turns of wire on a "core" or "shell" type laminated silicon steel core. The higher the ratio of impedance of the choke to the combined impedance of the condenser and loudspeaker, the greater will be the proportion of signal current in the loudspeaker circuit and consequently the greater the volume produced by the loud speaker for a given signal input to the amplifier. The values are not critical, however. In some cases, two condensers are connected in series with the speaker, one on each side. The special coupling arrangements used when a push-pull output stage is employed will be studied in connection with push-pull amplification.

447. Push-pull amplification and wave-form distortion: We have found in our study of audio amplification and the action of the vacuum tube as an amplifier, that distortion of the wave-form of the a-f input signal voltage can take place due to the tube itself. As a result of this distortion, the wave-form of the plate current variations is not exactly similar to the wave-form of the signal voltage variations impressed on the grid circuit. Therefore, the sound waves created by the movement of the diaphragm of the loud speaker to which these plate current variations are fed, will not be a true reproduction of the wave-form of the original signal voltage variations, and the sound output is said to be *distorted.* The four ways in which wave-form distortion may take place in an amplifier tube have already been discussed in Arts. 339 to 344, but they will be reviewed here briefly, as they are very important in the consideration of the push-pull amplifier connection. As already explained, frequency distortion may take place in tube-coupling devices, but it does not occur in the tubes.

Let us consider a typical "static" grid voltage—plate current characteristic of a vacuum tube operated with a high impedance in the plate circuit, as shown at (A) of Fig. 327. It curves over at the upper region C, curves under at the lower region A, and is sensibly straight at the middle portion B. If the plate voltage, grid bias and filament voltage are adjusted properly, so that the "no-signal" operation point is at the center, B, of the straight portion, (which is the proper operating point for an amplifier tube), then a signal voltage 0-1-2-3-4 of medium value applied to its grid circuit will produce plate current variations 0-1-2-3-4 having exactly the same wave-form as shown. Since this plate current wave-form is exactly the same as that of the applied signal voltage, no distortion is produced by the *tube* under these condi-

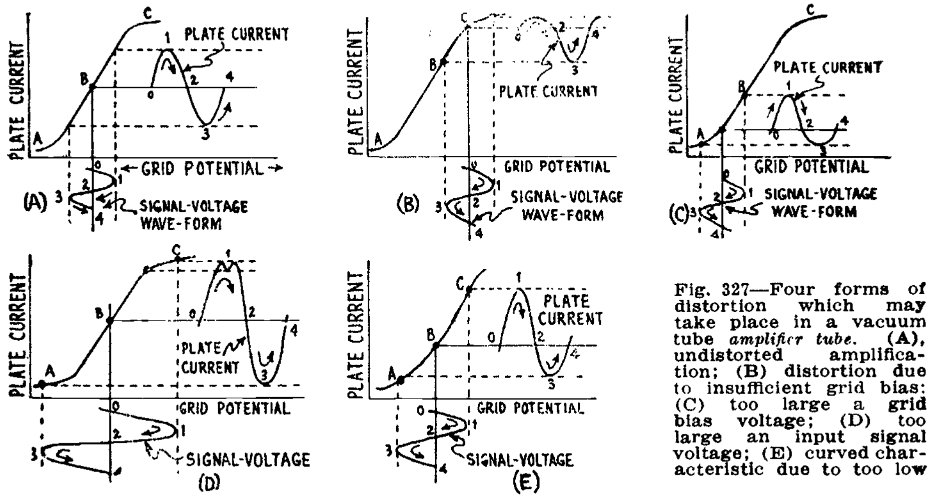


Fig. 327—Four forms of distortion which may take place in a vacuum tube *amplifier tube.* (A), undistorted amplification; (B) distortion due to insufficient grid bias: (C) too large a grid bias voltage; (D) too large an input signal voltage; (E) curved characteristic due to too low a plate load impedance. These are forms of distortion which may take place in the tube itself.

tions. For simplicity in our discussion, we will assume that the signal voltage applied to the grid circuit is of simple sine-wave form. Actually of course, the signal voltages existing in the a-f amplifier of a radio receiver are varying in frequency, intensity, and wave-form at each instant, depending entirely upon the pitch, loudness and timbre respectively of the sound acting on the microphone in the transmitting station. The considerations for distortion and action of amplifiers however, are no different for these complicated wave-forms than they are for a simple sine-wave sound or current. The actions of the latter are easier to follow and understand.

If the plate and grid voltages are such that the signal voltage applied to the grid circuit causes it to become positive during each positive half cycle of the signal voltage, or causes it to operate over the upper bend C, of the curve, distortion will be produced as shown at (B). In the former case, current flows in the grid circuit each time the grid is made positive by a positive half cycle of the signal voltage. This results in a voltage drop in the apparatus connected in the grid circuit and so reduces the signal voltage actually affective at the grid. The result is not only a flattening of the upper loop of the plate current variation, but a dip may actually be caused at the peak as shown at (D) of Fig. 328. In the latter case, even if the grid does not go positive, the mere fact that the tube is operating on the upper bend of the characteristic curve, causes distortion. In either case, the variations of the plate current changes during the positive half cycles of the signal voltage are *less* than those produced by the *equal* negative half cycles. The wave-form of the plate current variations is now different than that of the applied signal voltage variations, so distortion has resulted. As shown at (B), the increases produced in the plate current are smaller than the decreases.

If the tube is operated at the lower bend A, of the characteristic, as shown at (C), the reverse action takes place. As shown in the diagram, even though the positive and negative half cycles of the signal voltage are equal, the corresponding plate current variations are not equal. The decreases in the plate current are smaller than the increases. (This is exactly what happens in a grid bias detector, by the way.) Therefore distortion takes place.

If the tube is now operated at the center of the straight portion as shown at (D), and a large signal voltage is applied to the grid circuit so that the grid potential varies over both the upper and lower bends of the characteristic, then the form of the plate current variations is flattened both at the top and bottom of each half cycle, as shown. Due to the grid current flowing when the grid becomes positive, the upper peak of the plate current dips as shown. This of course, also represents distortion of the wave-form.

Up to this point we have assumed that the E_g - I_p characteristic of the tube is straight over the center region B. Now this is the "static" characteristic curve and really does not represent the situation under which the tube actually operates. When some form of *impedance* consisting of a loud speaker winding, the primary of a transformer, etc., is connected in the plate circuit, the conditions are somewhat different, as we found in Article 293 and showed in Figs. 209 and 210. Under these operating conditions, the voltage drop in the load impedance at each instant, causes variations in the plate voltage which is actually effective on the tube, and causes the plate current changes to lag the grid potential changes, so that the characteristic becomes curved over a large part and is not as straight as we have supposed.

Now considering the output power tube of the receiver, we know that for a given signal voltage, maximum power is transferred to the load in the plate circuit if the impedance of the load is equal to the plate resistance of the tube. However, for the straight amplifier connection, if the plate load is made of this value, the characteristic of the tube becomes very much curved, as shown at (E) and distortion of the wave-form of the plate current results, as shown. If the load impedance is made smaller than the plate resistance, the curvature of the characteristic becomes more and more pronounced, and severe distortion takes place. Actually, in practice the output load is made equal to about twice the tube resistance in order to reduce this curvature of the characteristic to a point which does not cause objectionable distortion due to this cause. This means of course, that the full power output which the tube is capable of delivering for any given signal voltage applied, is not obtained, but a value less than this, which is commonly called the "undistorted output" is obtained. The push-pull amplifier circuit eliminates the distortion effects of the curved characteristic and therefore enables us to use a lower load impedance in the plate circuit—one which is nearer to the value of the plate resistance of the tube. This means that with the push-pull circuit, for a given signal input voltage applied to the grid, an *undistorted power output* more nearly equal to the *maximum output* available for that signal voltage can be obtained for each tube. This is one big advantage of push-pull. It helps toward enabling smaller size power tubes to be employed in the last audio stage for a given output. The use of the smaller power tubes means that lower "B" voltages are employed and a saving in the cost of the "B" power supply unit is effected. Its other advantages such as larger signal-voltage-swing handling capacity, elimination of hum caused by a-c current ripple, elimination of necessity for a by-pass condenser across the grid-bias resistor, and cheaper construction of the output transformer will be pointed out as we proceed.

Before proceeding with the detailed study of the push-pull action, let us see just how "harmonics" enter into the wave-form distortions shown in Fig. 327. During our study of sound waves in Article 6, we found that "harmonic", or "multiple", frequencies are very common in speech and musical sound waves and are really the cause of the different quality or timbre which enables us to distinguish one musical instrument from another when a note of the same frequency is played. We found that the "second harmonic" is a sound wave of double the frequency of the fundamental wave. Now when dealing with sound, since the device which produces the sound introduces the harmonic frequencies which determine its wave-form, the harmonics are not looked upon as forms of distortion for they really are part of the distinguishing character of the sound. We speak of such sound waves as are shown in Fig. 14, as being "complex",

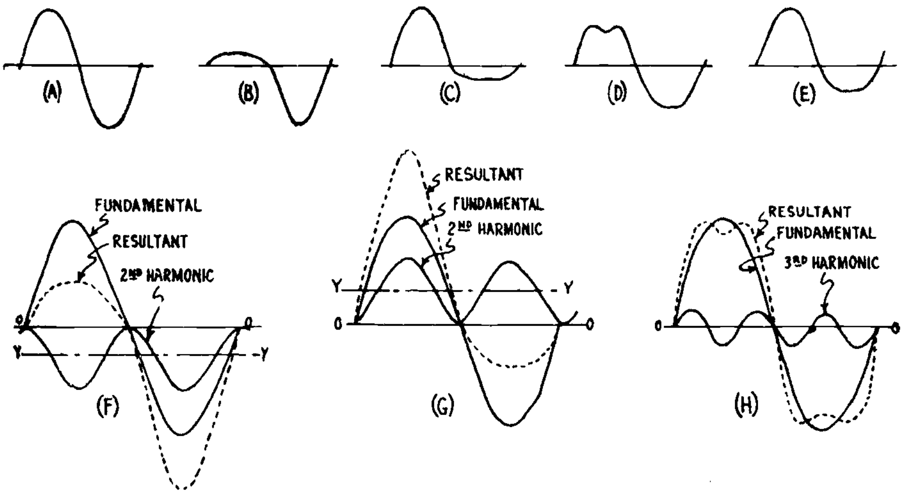


Fig. 328—How the distorted wave-forms in Fig. 327 may be duplicated by considering them to be equivalent to the sum of a fundamental sine wave, and second or third harmonic sine waves.

due to the harmonics, but we do not consider them as distortions. However, when harmonic frequencies which are introduced into electrical circuits or sound waves by a vacuum tube or any other device, are of an undesirable nature and were not present in the original sound itself, the waves resulting from the combination of the harmonics with the original waves are said to be *distorted.* We found that distortion of the plate current variations in a vacuum tube amplifier could be produced by operating the tube improperly, and by its curved characteristic. Let us see how harmonic frequencies enter into this.

If we consider the simple sine-wave input signal voltage again with a symmetrical wave-form as shown at (A) of Fig. 328, we find from Fig. 327 that if the grid bias of the tube is insufficient, the curve representing the variations in the flow of the output plate current is distorted to the form shown at (B) of Fig. 328. If the grid bias is too large, the distorted plate current wave is as at (C). If the grid bias is correct, but the input signal voltage is too great, the wave is distorted as at (D). If the characteristic is curved due to a plate circuit load of too low an impedance, the wave is distorted as at (E). Now the distortion of the plate current waves at (B), (C) and (E) is of the same character. Our study of distorted wave shapes of this sort may be greatly simplified by considering that instead of having in the circuit, a single current or voltage which varies in value as shown by the wave-form, we have a pure sine-wave of the same frequency as the distorted wave, (this sine-wave is known as the *fundamental*), plus pure sine-waves of frequencies which are multiples of the fundamental frequency. The latter are of the *harmonic* frequencies. Let us fix this matter firmly in our minds before we proceed any further. Even though we speak of a distorted wave voltage or current, as containing harmonics, it does not necessarily mean that these harmonics exist as separate waves, voltages, or currents distinct from the distorted one, but rather the effect or action of the distorted one upon the circuit is exactly the same as if it were replaced by one of the fundamental frequency and associated harmonics all of simple sine-wave form. This should always be kept in mind. Now referring to the distorted wave-forms at (A) and (B), we can consider them to be equivalent to a sine-wave fundamental plus a sine-wave second harmonic which is entirely above or below the zero axis. The axis of the second harmonic is Y - Y. The three wave-forms drawn together, are shown at (F). At every point along the "O-O" axis, the amplitude of the fundamental plus the height of the second harmonic (with due regard to direction above or below the axis), is equal to the height of the resultant wave-form. Therefore, the fundamental plus the second harmonic of these relative strengths are equivalent to the resultant distorted wave-form, and this wave-form is exactly as shown at (B). Consequently, since the resultant distorted wave-form is obtained by combining a pure sine-wave of the same frequency with a second harmonic wave, we usually say that the distortion is due to the second harmonic present, and that if the second harmonic were eliminated, the pure undistorted wave-form would result. At (G), the combinations to produce the distorted wave-form of (C) and (E) are shown. Notice that (F) and (G) are similar in shape excepting that they are 180 degrees out of phase. At (H) we have the combination of a fundamental sine-wave with a third harmonic sine-wave of smaller amplitude, to produce the resulting symmetrical distorted wave-form which has a dip at each peak. This will be seen to be similar to the wave-form distortion produced by the condition of (D) in which the grid going positive causes a flow of current in the grid circuit. The distortions represented by (B) and (C) will never occur in a well designed amplifier, in which the proper grid bias voltage is applied to the grid. That at (D) may occur if signals which are stronger than the permissible grid swing of the tube used will allow, are applied. That at (E) is very likely to occur unless we are satisfied to use a very costly, high impedance load in the plate circuit of the output tube and be satisfied with the reduced power output which will result. We can consider that these wave-form distortions of (B), (C) and (E) are caused by parasitic second harmonic current variations set up in the plate circuit of the tube, since they are similar to the conditions shown at (G) and (F). The condition of (D) is a combination of second harmonic and a weak third harmonic distortion. Consequently, our problem is one of eliminating the effects of the second harmonics.

If a certain distorted wave-form can be conveniently considered as the sum of a fundamental and say even number (2, 4, 6, etc.) harmonics, it must not be supposed that absolutely no odd number harmonics (3, 5, 7, etc.) exist, but rather that the maximum amplitude of any odd harmonics that must be added to give exactly the original distorted wave form is so small compared to the maximum amplitude of these

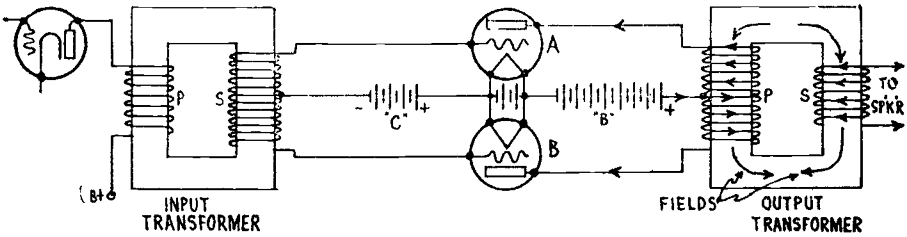


Fig. 329—Typical push-pull amplifier stage showing instantaneous directions of currents and voltages.

even harmonics necessary, that the odd harmonics may be neglected. The reverse is true regarding a distorted wave-form containing a predominance of odd harmonics.

Now assuming that the objectionable wave-form distortions which we have found to exist in a vacuum tube operated as an amplifier—especially in the last audio stage—are caused mainly by second harmonics, let us see how the push-pull tube connection eliminates them. A typical circuit diagram of a simple-push-pull connection of amplifier tubes is shown in Fig. 329. This connection is usually employed in the last audio stage of the receiver, but it may also be used in the r-f amplifier, or in any of the other audio stages.

For convenience, the diagram is drawn for battery operation, and the usual input and output transformers are shown with rectangular iron cores so that the instantaneous directions of the voltages, and currents may be more clearly shown. The input transformer consists of a primary wound to have a satisfactory impedance to work out of the plate circuit of the preceeding tube. The secondary S, wound in the same core with the primary, has a tap at the *electrical center* of the winding, i.e., at the center point considered from the "induced voltage" standpoint. Each end of the secondary connects to the grid of a tube, the center tap connects through the grid bias voltage source to the cathode. The primary of the output transformer is also tapped at its electrical center, the midpoint connecting to B+ and the two ends connecting to the plates of the tubes. It is wound to have the proper impedance for efficient transfer of power from the plate circuit of the tube. The secondary is usually a single winding as shown, wound on the same core. Now let us see how this combination operates. The C battery places a certain definite value of negative bias voltage on the grid of each tube. This is the proper value to set the operating point at the middle of the straight portion of the characteristic. Since the plate voltage source is also common to both tubes, if they are matched, i.e., have similar operating characteristics, the same plate current will flow through both. Now when no signal is applied, since the equal plate currents flow through the equal halves of the primary of the output transformer in opposite directions as shown, they produce equal and opposite magnetomotive forces which neutralize each other. Therefore there is no magnetic field in the core due to the steady direct component of the plate currents. This is one important inherent advantage of the push-pull circuit which we shall consider again later.

Now let us see what happens when a signal voltage is applied to the amplifier. A varying current flowing in the primary of the input transformer produces a varying magnetic field which induces a corresponding varying voltage in the entire secondary. As each half of the secondary is connected across the input circuit of a separate tube, the total induced signal voltage in the secondary of the input transformer is divided, each tube receiving an input grid voltage equal to only half this signal voltage. This point is important for it means that any two tubes in push-pull can handle twice as much *total* input signal voltage, without operating on the bends of the characteristic curve, as one of these tubes alone can.

Let us now see what happens during each half cycle of the signal voltage applied to the grids. Suppose that at a certain instant the voltage induced in the secondary of the input transformer is such that the grid of the top tube "A" becomes positive with reference to the center-tap of the transformer secondary, and the center tap is equally positive with reference to the grid of the lower tube "B". (This does not mean that the grid is "positive" with reference to its filament, for in this event distortion would be produced due to the flow of grid current. The "C" battery voltage is greater than any signal voltage that may be applied, so the grids are always *negative* with respect to the *filament* or cathode. It merely means that due to the signal voltage, the grid of tube A, becomes less negative than it was before and the grid of tube B becomes more negative.) This will cause the plate current of tube A, which flows

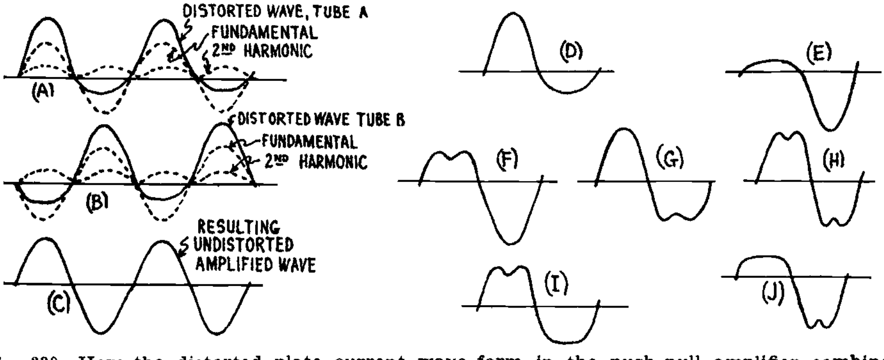


Fig. 330—How the distorted plate current wave-form in the push-pull amplifier combines in the output or choke to eliminate second harmonic distortion.

through the upper half of the output transformer primary, in the direction shown by the arrows in Fig. 329, to increase. At the same time, the plate current of tube B, decreases an equal amount. Since these currents both flow in opposite directions in the output transformer primary, as shown, the effect of changes of opposite nature in the plate current or of the two tubes is *additive* both as regards change of "magnetism" in the core, and "voltage" induced in the secondary winding. That is, if at one instant the current in the upper half of the primary winding (plate current of tube A) *increases*, the magnetic field produced by it *increases* correspondingly. If *at the same instant*, the current in the lower half of the primary (plate current of tube B) *decreases*, the magnetic field produced by it *decreases*. Under these conditions, the fields produced by the two halves of the primary winding no longer equal and neutralize each other, but there is a resultant field in the direction determined by the direction of flow of the larger current. For the particular conditions and instant mentioned above, this is downward in the left leg of the core as shown by the arrows on the core. This resultant field therefore induces a voltage in the secondary in such a direction as to tend to oppose this increase (Lenz's law of electromagnetic induction). The direction of the secondary voltage and the field produced by the secondary current are shown in Fig. 329. Therefore, the effects of the varying signal voltage, on the plate currents of the two tubes, are *additive in the output transformer*.

On the next half cycle of the signal voltage, the induced voltage in the secondary of the input transformer reverses, the lower end now becoming more positive and the top end more negative. Therefore, the plate current of the tube B, increases and that of A decreases. The net magnetic field is now in the opposite direction and so a voltage is induced in the secondary in the opposite direction to that induced before. This appears across the terminals of the secondary. This action is repeated during each cycle, first the plate current of one tube increasing, and that of the other tube decreasing and vice-versa—hence the name "push-pull".

Now let us first suppose that the correct grid bias voltage is being applied to the tubes and a value of sine-wave signal voltage is applied, such that it does not overload the tubes. Then due to the curvature of the characteristic (caused by the plate load impedance), the plate current changes of tube A, will vary according to the distorted wave-form shown at (C) of Fig. 328 and at the same instant that of tube (B) varies in accordance with the wave-form of (B). These wave-forms for two cycles have been drawn again, directly under each other in Fig. 330 for convenience, the top one being for the tube A, and the next one for tube B. Now as shown previously, each of these distorted wave-forms can be considered to be replaced by a fundamental and second harmonic as shown by the dotted curves. It will be noticed that the fundamentals in the two *tubes* are 180 degrees out of phase and the second harmonics are in phase. It will be evident by referring to these current directions at any instant that the fundamentals, which are 180 degrees out of phase with each other in the plate circuit (one increases while the other decreases), add together in the output unit (whether it be a choke coil or a transformer), since an increasing current through the upper half of the winding produces the same induction effect as a decreasing current in the lower half. For the same reason, the harmonics (which are in phase with each other) in the plate circuit neutralize each other in the output unit and the resultant output to the loud speaker is an amplified reproduction of the fundamental wave only. This is an undistorted sine wave-form in this case, similar to that of the input voltage. It is shown at (C).

Thus the effect of the push-pull connection is to balance out in the output transformer or choke coil, the second harmonic distortion produced by the tubes. Any second harmonic distortion which may exist in the wave-form of the signal voltage which is applied to the amplifier is not balanced out by the push-pull stage however, since the secondary of the input transformer applies this distorted wave-form and the second harmonics to the inputs of the tubes 180 degrees apart. Therefore they add together in the output transformer and are still present in the output and are passed on to the loud speaker. Consequently, while a push-pull amplifier stage will correct the second harmonic distortion produced by its own tubes, it will not correct any which might have been caused by a previous amplifier stage, or which may be caused by apparatus which follows it. For the same reasons, any second harmonics existing in the input signal voltage due to the sound program itself, are not eliminated.

If the two tubes were operated with too large a value of negative grid bias voltage, the plate current wave-forms of the two tubes at any instant would be as shown at (D) and (E) of Fig. 330. Since this is a case of second harmonic distortion only, it would be corrected in the output transformer. However, if too low a value of grid bias were applied, each grid would swing positive during each half cycle on loud signals, and the grid current flowing would produce the dips in the plate current wave-forms as shown by curves (F) and (G) of Fig. 330. The push-pull system does not eliminate the third harmonic, as the reader will readily see by following through the actions of the system for third harmonics. Therefore the second harmonic distortion only is removed in this case and the resulting current delivered to the loud speaker is of the distorted form shown at (H) of Fig. 330. The dip in the peaks indicates third harmonic distortion. The magnitude of the third harmonic that is usually present is small enough to be neglected.

If a large signal voltage be applied to the grids of both tubes such that the grid potentials swing over the upper and lower bends of the characteristic, the plate current variations of each tube are as shown at (I) and (J) of Fig. 330. The resulting current (as at H) contains a large third harmonic distortion, which is passed on to the loud speaker.

It is evident that with balance conditions, no fluctuating audio signal current flows down through the "B" power supply line, since the increase in the plate current of one tube just equals the decrease in the plate current of the other at each instant. Therefore, the total plate current supplied by the "B" circuit remains constant. Therefore, no audio coupling can take place in the impedance of the B power supply, so far as the push-pull stage is concerned. This reduces the possibility of instability due to feed-back voltage variations from the power tube plate circuit to that of the detector or first audio tube, and also greatly reduces the possibility of "motorboating".

A complete circuit diagram for a two-stage audio amplifier arranged for a-c electric operation and employing a push-pull output stage is shown in Fig. 331. This may be employed either as the audio amplifier in a radio receiver, or as a "phonograph" or small "public-address" amplifier. It will be noticed that the automatic grid bias method is used for the push-pull stage, grid bias being obtained by connecting the grid bias resistor R, in the plate return circuit between the center tap of the filament resistor and the negative terminal of the B power supply unit. If both tubes have the same mutual conductance and output resistance no condenser is necessary across this automatic grid bias resistance, for the reason that the plate current variations will always be equal and 180° out of phase. The sum of both currents will then always be a constant. Since there is no a-c component in the plate current, no by-pass condenser is necessary.

If both tubes of a push-pull amplifier are not matched, so that the mutual conductances are not the same, then the plate current variations of the two tubes flowing through this grid bias resistance will be unequal

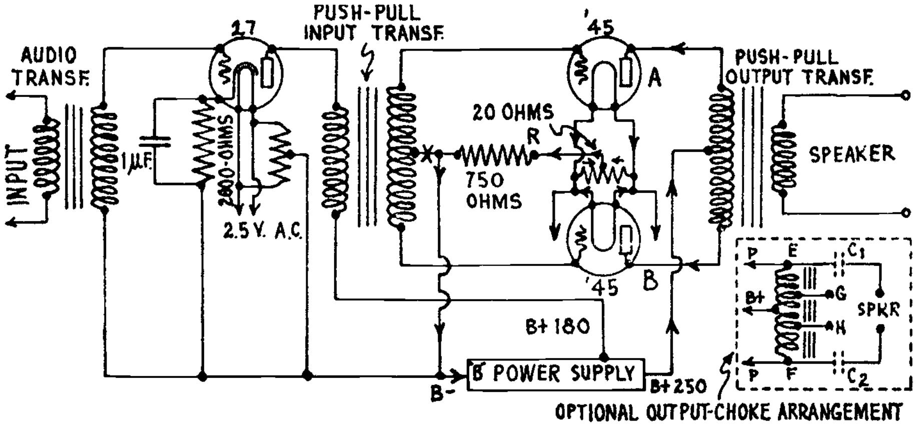


Fig. 331—Typical 2-stage transformer-coupled audio amplifier circuit with push-pull output stage. The amplifier is arranged for a-c electric operation. The actual amplifier is shown in Fig. 333.

and 180° out of phase. The result will be an a-c component which can be by-passed with a condenser in the usual way if desired, but it is really not necessary. If this by-pass condenser is omitted, the voltage across the grid bias resistance will vary. This variation will be 180° out of phase with the grid voltage of the tube having the greater variation of plate current (greater mutual conductance) and in phase with the grid voltage of the other tube. In other words, the tube having the greater mutual conductance will receive *degenerative* action while the other tube will receive *regenerative* action, the tubes tending to divide the load equally. Thus the effect of the mis-matching of the tubes is not so serious.

This will be understood by referring to Fig. 331. Suppose the mutual conductance of tube A, is greater than that of tube B. Also suppose that at one instant the signal voltage applied to A is increasing in a positive direction while that of B is increasing in a negative direction. The increase of plate current of A would be greater than the decrease in plate current of B, resulting in an average increase of voltage drop across R. The grid bias then becomes more negative. The increasing bias is in phase with the increasing negative signal voltage of B, producing *regenerative* action and at the same time being 180 degrees out of phase with the signal voltage of A producing *degenerative* action. Thus one tends to equalize the other. Regenerative action means an action which helps the applied signal voltage. Degenerative action opposes the signal voltage. The circuit connections for a push-pull output stage employing pentode tubes is shown in the circuit diagram of Fig. 283.

Inspection of Fig. 331 shows that any plate current ripple caused by incomplete filtration in the B power supply unit will affect the plate currents of both tubes equally and in phase. Therefore the effect automatically cancels out in the primary winding of the output transformer. This means that since not so much filtration is required, the filter in the B supply unit can be made more simple and cheaper.

Push-pull amplifiers are apt to oscillate in some cases, due to energy feedback by some path. To prevent this condition, a high resistor of from 10,000 to 50,000 ohms should be connected in the input transformer center-tap grid-return lead, at the point marked "X" in Fig. 331. This should *not* be by-passed with a condenser. The amplifier can be tested for oscillation either by listening for the howl or whistle which accompanies it, or by connecting a low reading milliammeter in the "C"— leg at point "X" in order to determine whether any current is flowing in the grid circuit. Under normal conditions there should be no deflection of the needle. However, if the circuit is oscillating, several milliamperes of current may be found to flow in the grid circuit. Then the remedy described above should be applied.

The center tap on the secondary of the input transformer need not be located exactly at the electrical center, for any slight unequality in the voltages applied to the grids, due to a slightly off-center tap will automatically be taken care of by the degenerative action of the plate current of the tube obtaining the larger signal voltages, somewhat in the same manner as already described for the grid bias resistor case. The center tap on the output transformer should be accurately located at the electrical center of the winding however, for any inequality here will not only cause a magnetic flux in the core due to the direct component of the plate currents, but will also result in incomplete balancing of the second harmonics, with resulting distortion of the output current. So far as the current from the "B" power supply unit is concerned, the plate circuits of the two tubes are in *parallel*, and the total current it must supply is equal to the sum of the plate current taken by each tube. So far as the *variations* in plate current are concerned, the path consists of the primary of the output transformer in *series* with the plate-to-filament circuits of the two tubes, for the plate current variations due to the signal exist only in this path. Therefore the impedance of the primary of the output transformer must be designed with this fact in mind. The plate impedance of the push-pull combination is taken as equal to the sum of the plate impedances of the two tubes, due to this series path condition. In the push-pull circuit, since the two d-c plate currents in the two halves of the primary flow in opposite directions; the resultant magnetization of the core is very small. Since the two halves of the windings are connected "series aiding" so far as a-c currents are concerned, the total inductance is increased. This means that not only less iron, but less copper as well, can be used for a given inductance value in a push-pull output transformer or choke than would be used for a single tube output device. The air gap in the core should not be dispensed with altogether;

it should simply be reduced. An air gap should be used in order that the original high value of inductance effective at small values of a-f may be maintained at high signal levels.

The output unit in a push-pull amplifier may be either a choke coil, as at the lower right of Fig. 331 or a transformer, as in the main diagram.

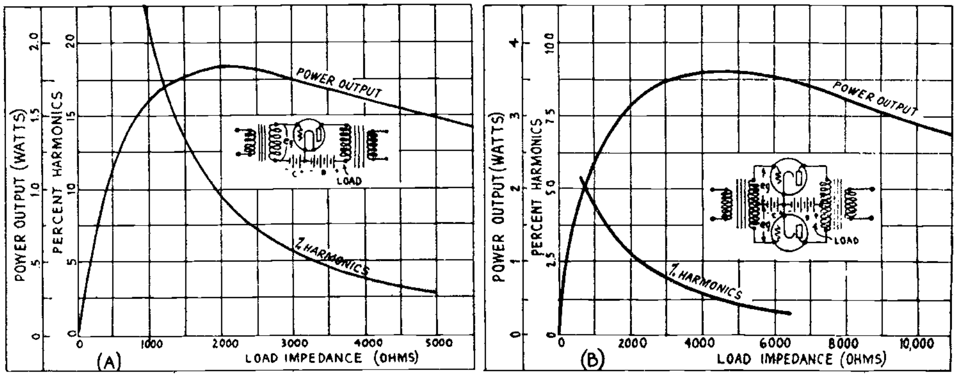
When a choke coil is used, with well matched tubes, (passing the same plate current) the ends of the winding E and F are at substantially the same D. C. potential, for there will be the same potential drop from the common center tap to E and F. For this reason the speaker can be connected across these points without danger of any damaging direct current flowing through the windings. This eliminates the necessity for any blocking condensers between the choke and the speaker. However, fixed condensers C_1 and C_2 of 2 to 4 mf. capacity are sometimes connected in the speaker circuit in order to insulate the speaker terminals from the high plate voltage to prevent severe shock if they are touched by a person whose body is grounded. This is especially advisable when the larger power tubes such as the 210 or 250 types are employed, as the voltages then are above 300 volts.

Some push-pull output impedances are made with two taps. Points G and H are at the same d-c potential when placed equally distant from the center tap. They may be used for speaker connection when a step-down impedance ratio is required for the best operation of low-impedance speakers, such as for feeding directly into the 10 or 15-ohm voice-coil of an electro-dynamic type loud speaker. The use of an output transformer is perhaps more popular than the choke for push-pull circuits. In most cases the secondary is designed to work directly into the 10 or 15-ohm voice-coil of the electro-dynamic speaker employed.

Maximum power output is obtained from a tube when the load impedance equals the a-c plate resistance of the tube. If the load impedance is made equal to the tube resistance in a straight amplifier, maximum output will be obtained, but the percentage of the second harmonic present due to the curvature of the characteristic prohibits the use of this one-to-one ratio. The ratio of load impedance to tube resistance is usually made about 2 to 1, in order to minimize the second harmonic distortion. This is shown very clearly by the graph at (A) of Fig. 332 (reprinted here by courtesy of *Electronics Magazine*) in which the power output and per cent second harmonics are plotted for various values of plate load impedance (or a-c plate resistance), for a typical three-electrode power amplifier tube having an a-c plate resistance of about 2,000 ohms and having a signal voltage as large as it is permissible to apply without working over the bends in the characteristic, applied to its grid circuit.

The power output curve shows that greatest power output (about 1.8 watts) occurs when the load impedance is made equal to 2,000 ohms, which is the same as that of the tube. Since a harmonic distortion up to about 5 per cent is not considered objectionable in practice, it is seen that the 9 per cent distortion which results if this optimum value of load impedance is used, is very high. If the load impedance is made equal to 4,000 ohms (twice the plate resistance of the tube), about 1.6 watts or 90% of the maximum power output possible is obtained, and the harmonic distortion is reduced to the low value of about 3.5 per cent—which is permissable.

Now contrast this with the curves at (B) which are drawn for the push-pull output stage using the same type of tubes and operated at the same voltages. The same signal voltage is applied between the grid and filament of *each* tube in this case, as was applied to the single tube just discussed. It is seen that the maximum power output of 3.6 watts is obtained when the plate load of 4,000 ohms (equal to the plate resistance of the tubes in push-pull) is used. Since the distortion due to harmonics is only 1.3% for this operating condition, the conditions for undistorted output are being satisfied and this may be considered as the *maximum* undistorted output also. Notice that this power output is 3.6 watts as against 1.8 watts for the similar case with the single tube, i.e., just twice as much. Therefore for a given signal input voltage applied to the grid of *each* tube, and a given allowable distortion, the push-pull connection puts twice as much *undistorted output power* into the load, as the single tube does. This demonstrates forcibly the advantage of the push-pull connection over the single output tube connection in the matter of wave-form distortion due to harmonics. It also illustrates the fact that since the harmonic distortion is so low with the push-pull connection, the load impedance may be made equal to the effective plate resistance of the tubes in push-pull (twice the plate resistance of one tube), without introducing objectionable distortion. This enables the maximum power output of the tubes to be obtained without distortion. That is, for a push-pull amplifier the terms *maximum power output* and *maximum undistorted power output* (distortion below 5 per cent) mean one and the same thing, whereas for the single tube connection the maximum undistorted power output which can be obtained, is *less* than the *maximum* power output, due to the necessity of using a higher impedance plate load to reduce the har-



Courtesy Electronics Magazine.

Fig. 332—(A) Graph showing how the power output and per cent harmonics in a single tube output stage varies for different values of load impedance (or a-c plate resistance) for a tube having an a-c plate resistance of 2000 ohms.
(B) Same for a push-pull stage with similar tubes.

monic distortion to the traditional "5 per cent maximum" value. If the load resistance is double the total plate resistance of one of the push-pull tubes, then the maximum undistorted power output of a push-pull stage is obtained for a given signal input applied to it. The maximum undistorted power output of *each* tube in watts is then given by the general formula for maximum power output, for the reasons stated above. This is:

$$P = \frac{\mu^2 e_g^2}{4R_p} \text{ or } \frac{\mu^2 E_g^2}{8R_p}$$

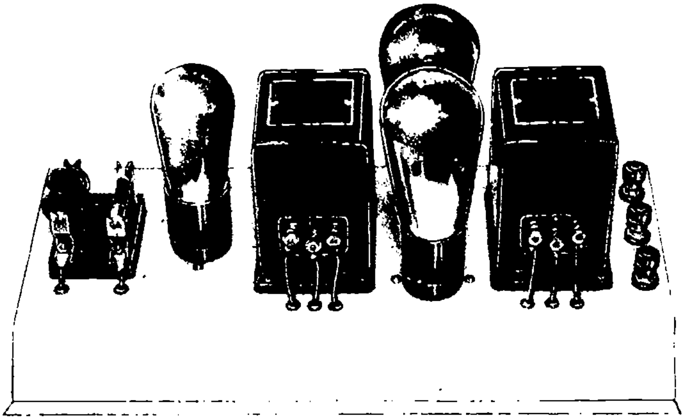
Since the total power output of the two tubes in push-pull is equal to the sum of the power delivered to the load by each tube, the maximum undistorted power output for the entire push-pull stage is,

$$P = \frac{\mu^2 e_g^2}{2R_p} \text{ or } \frac{\mu^2 E_g^2}{4R_p}$$

where e_g is the *r. m. s. value* of the signal voltage applied between the grid and filament of each tube (equals one-half the total signal voltage developed across the secondary of the input transformer), and E_g is the *peak* value of this voltage. R_p is the a-c plate resistance of a *single* tube.

When speaking of the turns ratio of a push-pull input transformer, the ratio between the turns included between the center tap and one end of the secondary, to those on the primary is meant. Thus a 3 to 1 input transfer has 6 times as many turns on its entire secondary winding as it has on the primary, or 3 times as many turns between the center tap and either end as it has on the primary. The reason for this is that we are interested in the actual ratio between the voltage applied to the primary of the transformer by the preceeding tube and that applied to the grid circuit of *each* tube considered separately, by half of the secondary winding.

Because of the greater freedom from objectionable harmonics when a push-pull amplifier is overloaded, it is permissable in practice, to apply somewhat greater input signal voltages voltage per tube without serious distortion, than when a single-tube stage is used. Hence the maximum



Courtesy Pilot Radio & Tube Corp.

Fig. 333—The 2-stage amplifier with push-pull output stage whose circuit diagram is shown in Fig. 331. Resistance input coupling is also used. The push-pull tubes and transformers are at the right.

undistorted power output obtainable from two tubes in push-pull is us ually considered as being equal to about 2.25 times that obtainable from a single tube of the same type, (see Fig. 336). The advantages of the push-pull amplifier circuit may now be summarized as follows:

(A) Elimination of second harmonic distortion originating in the tube circuit. (It does not eliminate second harmonic distortion originating in preceeding or following equipment.)

(B) Twice the permissable grid-swing voltage allowable for a single tube stage may be applied to the push-pull using the same type of tubes. This means that smaller size power amplifier tubes can be used to handle a given total signal voltage. This results in decrease in cost of the "B"-power supply unit.

(C) Reduction of hum when a-c operated. Less filtering is necessary in the "B"—power supply unit. Also, hum-voltages originating in the filament circuit when a-c operated, cancel out.

(D) Elimination of the by-pass condenser across the grid bias resistor. This is especially advantageous when pentode tubes are used, for if a single pentode is employed, a by-pass condenser of about 8 or 10 mf. is required across the grid bias resistor to eliminate serious degenerative effects on the low audio frequencies.

(E) Less iron and copper required in the output transformer or choke.

These advantages have made it a very valuable form of amplifier. The push-pull principle can be adapted to resistance coupling, and the Clough coupling system very satisfactorily.

Fig. 333 shows a two-stage audio amplifier with push-pull output stage. The first tube (at the left) is resistance coupled to the input. Next comes the push-pull input transformer, then the push-pull tubes, and the output transformer is on the right with the output binding posts. The three terminals on the secondary of the input transformer and on the primary of the output transformer are plainly shown. The circuit diagram is shown in Fig. 331. The fact that for equal input signal voltage, a push-pull amplifier stage delivers about twice as much power to the load as a single tube stage would (using same type tubes) does not mean that the sound issuing from the loudspeaker will sound twice as loud. Doubling the power output means a gain ratio of 2 in the power. Referring to Fig. 304 we find that this is an increase of three decibels. One decibel is about the smallest difference that can be detected with the ears. Therefore an increase of three decibles is noticeable, but of course it does not mean that the sound will be anywhere near twice as loud.

448. Dual push-pull amplification: High-gain a-c operated audio amplifiers designed particularly for use in public-address systems, and in sound picture work, frequently make use of two '50 type power amplifier tubes in push-pull in the output stage in order to handle the large signal voltages existing there and to deliver the large amount of power required.

If these tubes are operated at their maximum rated voltages, in order to obtain as much undistorted power output from them as they are capable of handling, a maximum "peak" signal-voltage (in one direction) of about 80 volts must be developed across each half of the secondary winding of the push-pull *input transformer* and applied to the grid circuit of *each* tube. (Note: This is equal to the value of the negative grid-bias voltage, see Fig. 214). Assuming this transformer to have the common ratio of 2 to 1, the signal voltage across its primary would have to be 80 divided by 2, or approximately 40 volts. If the amplifier tube feeding into this transformer has an effective "mu" of 8, then the signal voltage applied to its grid must be about 40 divided by 8, or 5 volts, for this output. To prevent the possibility of overloading, the negative grid-bias for this tube should therefore be at least 6 or 7 volts.

Since powerful amplifiers of this type are usually 3-stage amplifiers, it is common to make both the second and the last stages of the push-pull

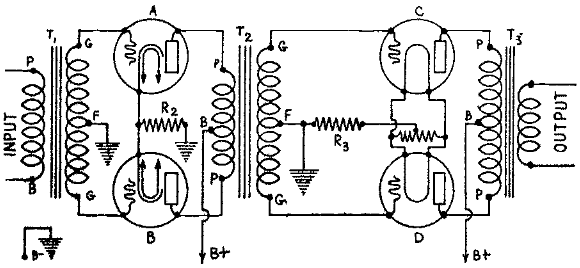


Fig. 334—Typical 2-stages of audio-amplification with "dual push-pull" stages. This form of amplifier circuit is commonly used in heavy-duty power amplifiers used in sound amplifier systems.

type, as shown in Fig. 334. This is called a *dual push-pull amplifier.* The first stage may be of the single-tube type. The use of the push-pull stages eliminates any "second-harmonic" distortion which might otherwise occur in the last two stages, besides providing the other advantages which have already been pointed out during our study of push-pull amplification.

In the circuit diagram of Fig. 334, the special interstage push-pull tranformer T_2 has a center tap on both the primary and secondary windings. The push-pull action is the same as has already been described in Article 447. Push-pull tubes A and B obtain their negative grid bias voltage by the fall of potential in resistor R_2. Tubes C and D obtain theirs by the fall of potential in R_3.

449. Parallel output tubes: Greater undistorted power output handling capability than a single tube provides, can also be obtained by connecting two or more tubes with their grid circuits in parallel and their plate circuits in parallel, as shown in Fig. 335. The filaments may

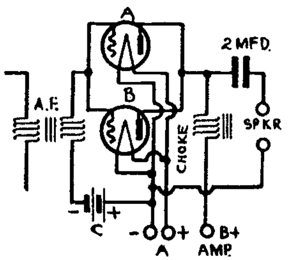


Fig. 335—Typical transformer-coupled a-f amplifier circuit with two output tubes connected in parallel.

also be connected together in parallel as shown. Evidently it is possible to connect more than two tubes this way if desired, but for the purposes of explanation we will consider the connection with two tubes in parallel. Since the signal-voltage variations are applied to both grids simultaneously, both tubes really work in phase. Therefore both the fundamental and harmonic waves are present in the output, i.e., this connection does not eliminate the harmonic distortion caused by the tubes, as the push-pull circuit does. This is one of the objections to the parallel-tube connection.

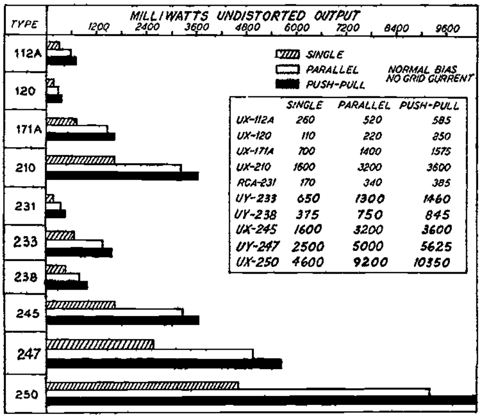
The amplification constant of the combination is equal to the constant of a single tube, if both tubes are similar. If one of the tubes has a high mu and the other a low mu, the resultant amplification of the two is equal to the average of the two mu's. Thus if the mu of one tube is four and that of the other is seven, the resultant amplification constant is 5.5.

For similar tubes, the resultant plate impedance will be equal to half the impedance of a single tube and if unlike tubes are used, the impedance can be calculated from the laws governing resistances in parallel. The greatest power output is obtained when the two tubes have identical plate resistances and amplification constants, but a very large fraction of the total power of the two tubes can be obtained even if they differ greatly. Since the plate circuits of both tubes are in parallel both as regards direct plate current flow and the variations due to the signal, the a-c plate resistance of the combination is equal to half that of a single tube—if both tubes are similar. This makes the output a-c plate resistance rather low. This is sometimes advantageous where the tubes are to supply power to a load of low impedance. For a given input signal voltage and 2 parallel tubes feeding into a load impedance equal to twice the combined plate resistance of the tubes in parallel, twice as much undistorted power can be obtained as could be obtained from a single tube feeding into a load impedance equal to twice its plate resistance. The total power delivered to the load in any case, is simply the sum of the powers delivered by each of the parallel tubes.

Possibly the greatest drawbacks to this system are that second-harmonic distortion is not eliminated, and that the maximum peak signal voltage which can be applied to the grids without overloading is equal to that specified for a single tube (about equals to the grid-bias voltage). This differs from the push-pull arrangement, where the allowable total input signal voltage is double that for a single tube, because due to the push-pull connection only half the total input signal voltage actually acts on each tube.

It would also be possible to connect four or more tubes to form a push-pull parallel tube arrangement, with two or more tubes in parallel on each side of the push-pull arrangement. This arrangement secures the benefits of lowered plate impedance and retains the advantage of greater allowable input signal voltage and elimination of tube distortion which is characteristic of the push-pull connection. This would only be resorted to in special public-address or sound-picture amplifiers in which a very large amount of undistorted output power would be required.

450. Output power required: We have seen how the power output delivered by any tube, or combination of tubes, to the load connected in the plate circuit, can be calculated if the types of tubes employed and the signal voltage applied to the grid circuit, are known. The next question which arises is, just how much electrical power is required from the last audio stage? Assuming that the electrical power output from the last amplifier stage drives the diaphragm of the loud speaker, the problem resolves itself into a determination of how much sound power in watts is required to produce the necessary volume of sound, and what the efficiency of the loud speaker is, i.e., how many watts of sound energy it delivers for every watt of electrical energy put into its windings by the amplifier. The answer to this first problem is one which depends upon many conditions such as size of the room, absorption properties of the walls and drapes in the room, volume of sound required, etc., so that no figure which would be true for all cases can be given. The loud speaker efficiency is also a variable quantity. Speakers of different types and manufacture have different efficiencies—unfortunately all very low, as we shall see in the next chapter. The following power values may be considered as giving some basis for average radio reception at the volumes ordinarily used in the home. It may be safely assumed that a power of from $\frac{1}{4}$ to $\frac{3}{4}$ of a watt should be supplied to each permanent-magnet type cone speaker employed, and about 1 or 2 watts for each medium-sized electro-dynamic speaker employed. For the large type electro-dynamic speakers designed especially for auditorium work, a power of from 2 to 20 watts may be supplied for full volume. These are average figures given merely to give the reader some idea of how much power must be supplied to the loud speaker. It may vary greatly in individual cases. In the chart of Fig. 336, are arranged for convenient comparisons, the undistorted power output in watts which the various power amplifier tubes will deliver to loads of proper impedances (see Fig. 214), connected in the plate circuit, (or by a proper impedance-adjusting transformer), when a signal voltage having a peak value equal to the maximum which the tube can handle without overload-



Courtesy R. C. A. Radiotron Co.

Fig. 336—Chart showing graphically the maximum undistorted power outputs which may be obtained from various standard types of power amplifier tubes connected singly, in parallel, or in push-pull, when the maximum allowable signal-voltage input (see Fig. 214) is applied to the tube or "combination" in each case.

ing, (about equal to the grid-bias voltage), is applied. Separate values are given for single output tubes, for 2 tubes in parallel, and for two tubes in push-pull. In each case it is assumed that the maximum plate and grid voltages specified for the tube in the table of Fig. 214 are applied to the tubes.

It must be understood that the power output requirement is not the only consideration in the selection of a power amplifier tube in any specific case. The "power sensitivity" i.e., the measure of the input signal voltage required to produce a given power output is very important. Thus, a '47 type pentode will deliver more undistorted power output for a given signal voltage applied to the grid, than say a '45 type tube, i.e., its "power sensitivity" is higher. Therefore it is usually more satisfactory than a '45 type tube, because for a given power output, less amplification of the signal in the preceeding stages is required. This consideration has made the pentode type of tube very important as a power amplifier.

451. Tone control: As radio receivers designed for the reproduction of speech and musical programs must operate under varied acoustic conditions in the many types of rooms in which they are used, and must also please the individual acoustic tastes and preferences of the listeners, the incorporation of a tone control in the audio amplifier has become quite common. Many people prefer reproduction with the bass over-accentuated and the high notes suppressed, others prefer the bass reduced and the high notes brought out, so that the speech sounds such as "s", "sh", "z", etc., are reproduced clearly and sharply. Others may want the audio system to amplify and reproduce equally, the entire range of audio-frequencies concerned in the reproduction of speech and music, with a suitable control provided for either suppressing or over-accentuating either the bass or the high-note range for certain types of speech or music, if they so desire. The latter form of tone control is possibly the ideal type.

Many tone control arrangements consist of a simple high-pass or low-pass filter, (see Articles 180 and 185), which act to reduce the amplification of the high audio frequencies. This suppression of the high notes produces the effect of making the speech or music sound low-pitched. Thus a deep note effect is produced without actually increasing the amplification of the low frequencies. However, this form of apparent low-note boosting does not produce really natural reproduction, for sinc the high frequencies are cut off, the sound loses its brilliance and crispness. This is especially true for many of speech sounds. The possible types of tone control systems are very numerous. The circuit of a typical simple tone control of this kind which has been used extensively on account of its simplicity is shown at (A) of Fig. 337. This consists of a .002 mf. fixed condenser in series with a variable non-inductive resistor 500,000 ohms maximum value. At (A) this control is shown connected in the plate circuit of the detector tube. At (B) it is connected across the secondary of the input transformer of the push-pull output stage. In either case, the effect is to by-pass the high frequencies by means of the condenser, the adjustable resistor in series determining the amount of by-passing

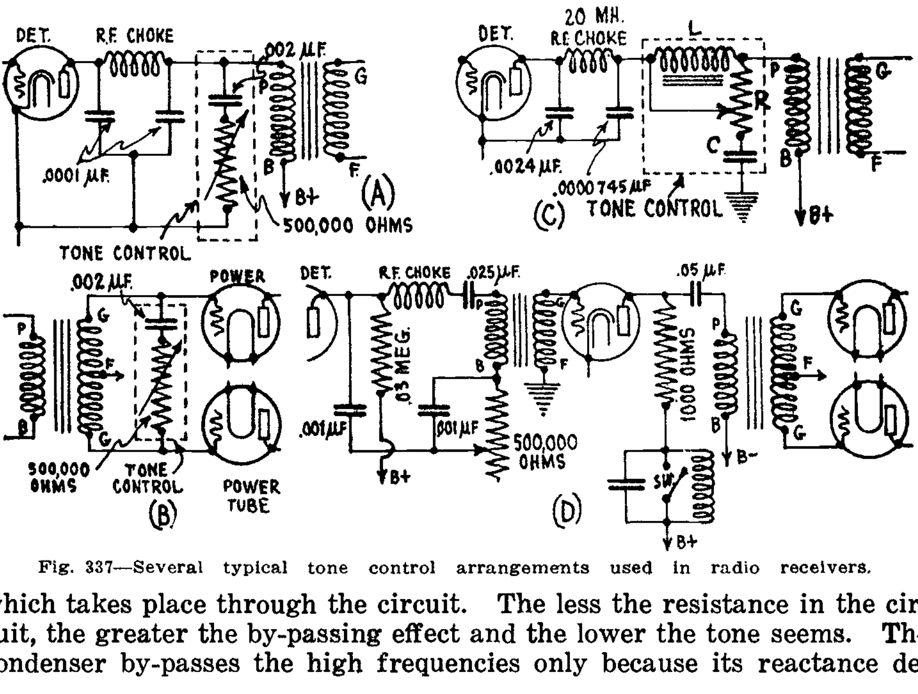


Fig. 337—Several typical tone control arrangements used in radio receivers.

which takes place through the circuit. The less the resistance in the circuit, the greater the by-passing effect and the lower the tone seems. The condenser by-passes the high frequencies only because its reactance decreases as the frequency increases. At (C) a very satisfactory tone control, also of the "suppressor type," is shown. This consists of an inductance L, of about 2 henries and 1300 ohms; a potentiometer R, of 40,000 ohms; and a condenser C, of .025 to .05 mf. depending on the audio characteristics of the receiver. The advantage of this circuit is that either the low or the high frequencies may be suppressed. It is usually connected in the detector plate circuit. As the arm of the potentiometer is moved toward the condenser terminal, the resistance of the condenser by-pass path is reduced and the high frequencies are by-passed, resulting in a deep tone. As the arm is moved toward the choke terminal, the condenser by-passing is reduced and the resistance of the shunt path across the choke decreases. This reduces the amplification of the low frequencies.

The tone controls just described are typical of the "frequency suppressing" or "de-amplifying" type. The audio amplifier has a certain a-f response, and the tone control reduces the amplification of the low frequencies or the high frequencies to below the normal value. In order to bring up the volume, it is necessary to manipulate the volume control whenever the tone control has been adjusted. No actual boosting of the amplification at any frequency can be produced by this form of tone control.

A form of tone control which actually enables the operator to either increase or decrease the amplification of the low or high audio frequencies if desired, is shown at (D). This is particularly adjusted to the resonated primary arrangement in the "Clough coupling" system as shown.

Varying the value of the 500,000 ohm resistor across the .001 mf. condenser varies the current flowing in the resonated primary circuit and therefore varies by as much as 15 decibels, the amplification of the lower audio frequencies below 100 cycles to which the primary is resonated. The amplification of the high audio frequencies can be either lowered or raised by means of the switch. In the plate circuit of the first a-f tube, is included a tuned circuit consisting of a capacity and inductance resonated at the higher audio frequencies to increase the impedance of this circuit at the higher frequency. This results in a very considerable boost of the order of about 22 db. at the higher audio frequencies in the neighborhood of 4,000 cycles. A switch is seen shunting this tuned circuit, which, when closed, throws it completely out of circuit and results in weakening of the higher audio frequencies. This is desirable in locations showing a very high noise level, in the reception of very weak stations, or where the personal taste of the user favors an accentuated bass response for certain music. This system is shown connected in a complete superheterodyne receiver circuit in Fig. 283.

Other systems of tone control wherein the amplification at either the high or low audio frequencies may be either increased or decreased have been developed, but many of them are too costly and complicated for general use in radio receivers, although they are employed in amplifiers used for public address and sound picture work. They usually provide for a series of controls which enable the operator to accentuate or attenuate any particular frequency or any particular groups of frequencies which he may desire. Thus, it is possible with an amplifier so designed, to not only compensate for losses in recording and reproduction, but also to attentuate those particular frequencies which are emphasized because of resonance in the electrical or mechanical network, or by the particular physical conditions existing in the place where the reproduction takes place.

REVIEW QUESTIONS

1. What is meant by the term "audio frequency"? What is a-f amplification?
2. At what point in a radio receiver is a-f amplification used? Why? What does it accomplish?
3. What are the practical advantages and disadvantages of doing all of the amplifying of the radio signal voltages in an r-f amplifier ahead of the detector?
4. What advantages and disadvantages does audio amplification following the detector present?
5. Draw a simple block-diagram and explain the various changes which an incoming modulated r-f signal voltage undergoes as it proceeds through the t-r-f amplifier, detector, audio amplifier, and loud speaker.
6. Why has the use of power detectors resulted in a change in the ratio of r-f (or i-f) amplification to a-f amplification employed in receivers, so that most of the amplifying is now being done in the r-f (or i-f) amplifier?
7. Name two practical limits to the amount of r-f amplification that can be used satisfactorily in a practical radio receiver?
8. Modern broadcasting stations are equipped to transmit all sound frequencies up to 8,000 or 10,000 cycles. Why do they actually transmit only up to about 5,000 cycles?
9. In order to obtain true reproduction of the sound programs, what must the entire radio receiver equipment considered as a whole, accomplish?
10. State some of the important characteristics of the human ear, as regards the power in sounds of equal loudness but different frequencies; and as regards the effect on the intelligibility if either the low frequencies up to 1,000 cycles, or the high frequencies above 3,000 cycles, are eliminated from speech sounds.
11. What is meant by "masking" of the high notes? What causes it?
12. What frequency characteristic should the audio amplifier and loud speaker in a receiver have, if the sideband frequencies have been suppressed in the r-f amplifier by too-sharp tuning? Explain and show by means of the frequency-response curves.
13. What improvement would be noticed in the reproduction of broadcasted musical programs if all sound frequencies up to 10,000 cycles were transmitted and reproduced faithfully instead of the present 5,000 cycle upper limit?
14. Define the "decibel". Of what practical importance is the decibel system of comparing power ratios?
15. A loud speaker having an efficiency of 10 per cent (only 10 per cent of the electrical power put into it appears as useful sound

power), is operated by an audio amplifier feeding 1.5 watts to it. The sound is to be made twice as loud. How much power will the amplifier have to deliver to the speaker for this condition?

16. What is the difference in voltage amplification, expressed in decibels, between an amplifier giving a voltage amplification of 400 and one giving an amplification of 800?
17. A certain amplifier is capable of outputting a maximum undistorted power of 1.5 watts. How much louder will be the sound if the output is raised to 5 watts by the use of larger tubes and more amplification? Will this increase in power be worth while?
18. Why should audio-frequency response curves be plotted to logarithmic scales instead of to ordinary uniform or equally-divided scales?
19. The plate resistance of a '27 type amplifier tube is, say 10,000 ohms. The inductance of the primary of the a-f transformer which is connected after it, is 50 henries, and it has a turns-ratio of 3 to 1. What is the amplification produced by this stage at 60, 100, 1,000 and 10,000 cycles (neglecting the ohmic resistance of the primary). Draw a graph showing the frequency response, with amplification plotted against frequency. Repeat this for a primary inductance of 200 henries. What is the advantage of using the primary of larger inductance?
20. What frequency range should an a-f amplifier be capable of amplifying uniformly for ordinary sound programs?
21. What three main methods of coupling may be employed between the tubes in a-f amplifiers?
22. Describe the construction of a typical a-f transformer? Why is the core *laminated*? What is the advantage of using a steel core instead of an air core?
23. Explain the action of an a-f transformer in an amplifier stage. Why is it desirable to have a high primary impedance, and a low distributed capacity in the windings?
24. Why is it common practice to use a low-ratio a-f transformer following a detector tube?
25. How does the use of a core of large cross-section area reduce the magnetic saturation effect in an a-f transformer? By what special circuit arrangement may this magnetic saturation effect be eliminated?
26. Explain how resonance is obtained in the Clough audio system and show why this resonance increases the amplification obtained at the resonance frequency. What are the advantages of this method?
27. Draw a circuit diagram of a typical complete battery-operated receiver employing two stages of tuned r-f amplification, grid-bias detector and two stages of transformer-coupled a-f amplification.

28. Explain why an a-f amplifying stage employing a transformer of low turns-ratio may sometimes produce more amplification than one using a cheaper type of transformer of high turns-ratio.
29. Explain the action of the resistance-coupled a-f amplifier, bringing out the effects produced by increasing or decreasing the values of the plate resistor, leak resistor and blocking condenser.
30. What limits the value of the resistance which can be employed in the plate circuit in a resistance coupled amplifier?
31. What particular advantage does resistance-coupling following a power detector tube have?
32. Explain the causes of "motorboating" in an amplifier. Show how this may be eliminated.
33. Draw a circuit diagram, and explain the operation of the impedance-coupled type of a-f amplifier. What advantage does this possess over the resistance-coupled type?
34. What is the advantage of the autoformer impedance-coupled amplifier over the ordinary impedance-coupled type?
35. Explain the operation of a 2-tube Loftin-White a-f amplifier, showing how the various plate and grid bias voltages are obtained, and how the hum voltage is neutralized. What are the advantages of this system over the ordinary resistance-capacity coupled amplifier?
36. What are the particular characteristics desirable in an interstage amplifier tube; in a power amplifier tube? What special features in the construction of power amplifier tubes are responsible for these characteristics?
37. A '45 type power amplifier tube is to feed its electrical output to a loud speaker connected in its plate circuit. If the a-c plate resistance of the tube is 1750 ohms, what must be the impedance of the speaker in order that *maximum power* be delivered to it, for a given signal voltage? How much power will this be if mu=3.5, and the peak signal voltage is 30 volts?
38. What must be the speaker impedance in problem 37, if the maximum *undistorted* power output of the tube, for this signal voltage, is to be put directly into the speaker. What would this output be?
39. Assume the speaker in problem 38 to have an impedance of 15 ohms. What must be the primary impedance and turns-ratio of an impedance-adjusting coupling transformer to couple it to the tube, if the maximum *undistorted* power output for this signal voltage is to be obtained?
40. Draw a circuit diagram of, and describe the operation of a choke-condenser type of output coupler for coupling a magnetic type cone speaker to a power tube. Why is this needed? Why should the speaker circuit be returned directly to the filament circuit?

41. Explain the difference between "frequency distortion" and wave-form distortion of an a-f amplifier. Explain with the aid of diagrams, the various operating conditions which may cause each.
42. Explain the action of the push-pull amplifier in detail. Explain how it eliminates the "second harmonic" distortion.
43. List three advantages of the push-pull connection over the single tube, and parallel connections, and explain.
44. A single '45 type tube operated at maximum rated plate voltage is to be used as a power output tube. (a) What maximum peak value of signal voltage may be applied to it; (b) What maximum undistorted power may be obtained from it when this signal voltage is applied; (c) What value of load impedance is required for this condition? (Use chart of Fig. 214.)
45. The amplifier stage in question 44 is replaced by a push-pull stage using '45 type tubes. (a) What is the value of the undistorted power output which will now be obtained if the same signal voltage as specified in question 44 is applied to *each* tube; (b) what value of load impedance is required for this? Compare your results with those found in question 44.
46. An output stage for an a-c electric radio receiver is to be designed. The peak value of the signal voltage applied across the primary of the 3 to 1 a-f transformer which couples this stage to the preceeding amplifier tube is 15 volts. What type of output stage and tubes would you employ? What undistorted power output would be supplied to the load when this signal was applied?
47. The push-pull output stage of a public-address amplifier must supply electrical power to operate four permanent-magnet magnetic, and three medium-size electro-dynamic loud speakers, at full volume. About how much power must it supply. What type of tubes and what connection would you employ in the output stage, single, parallel or push-pull? Why?
48. Draw the circuit diagram of a tone control which will reduce (a) the low frequency response; (b) the high frequency response; (c) either of the two. Explain how each affects the sound issuing from the loud speaker, as judged by the ear. Which type is more desirable?
49. What features of the push-pull connection make it desirable for use in "power amplifiers"?
50. Draw a sketch showing the connections for a 2-stage dual push-pull amplifier. What is the advantage of dual push-pull?

CHAPTER 25

LOUD SPEAKERS

TASK OF THE LOUD SPEAKER — PARTS OF A LOUD SPEAKER — CLASSIFICATION OF DRIVING UNITS — IRON DIAPHRAGM UNIT — BALANCED ARMATURE — INDUCTOR TYPE DRIVING UNIT — MOVING COIL DRIVING UNITS — THE MOVING COIL SPEAKER WITH ELECTROMAGNETIC FIELD — THE FIELD OR "POT" — THE "VOICE-COIL" AND INPUT TRANSFORMER — THE INPUT FILTER OR "EQUALIZER" — FIXED EDGE CONE DIAPHRAGM — FREE EDGE CONE DIAPHRAGM — CONSTRUCTION OF THE DIAPHRAGM — COMPLETE MOVING COIL SPEAKER — BAFFLE — PERMANENT MAGNET MOVING-COIL SPEAKERS — HORN SPEAKERS POSSIBLE SHAPES OF HORNS — EXPONENTIAL HORN — CUT-OFF FREQUENCY EXPONENTIAL HORN DESIGN — MATERIAL AND SHAPE OF HORN — HIGH FREQUENCY HORN SPEAKER — CONNECTING SEVERAL SPEAKERS — CONDENSER TYPE SPEAKER — DESIRABLE SPEAKER CHARACTERISTICS — COMBINING SPEAKER CHARACTERISTICS — REVIEW QUESTIONS.

452. Task of the loud speaker: We have advanced in our progressive study of radio receivers to the output circuit of the audio amplifier. Here we have the amplified audio-frequency voltage or current whose wave-form is continually changing in accordance with the waveform of the sound acting on the microphone of the broadcasting station at th time. The next link in our radio receiving system is to convert the electrical power delivered by the power amplifier stage in the audio amplifier, into sound energy or waves of similar wave-form, which travel out to the ears of the listener and produce the sensation of sound in the brain, (see Fig. 300). We found during our study of the simple crystal-detector receiver system that earphones could be used for this purpose, but these are not satisfactory since they must be held close to the ears. Modern standards of home reception demand that the reproducer handle a sufficient amount of electrical energy to enable it to produce sound waves sufficiently intense to be easily heard and distinguished anywhere in a room of at least ordinary size. For public-address and sound-picture work, the volume of sound produced must be sufficient to be heard by large assembled audiences everywhere in large halls, auditoriums, theatres, etc. This is accomplished by the *loud speaker* or *reproducer.* The loud speaker really converts the electrical energy which is supplied to it, into sound waves, or sound energy. For this reason it is sometimes called an *electro-acoustic transducer.* Before proceeding with the study of the various types it would be well to understand just what the requirements for a satisfactory loud speaker are.

The loud speaker should be reasonably free from wave-form distortion, i.e., at every instant it should produce a wave of sound pressure exactly corresponding to the wave-form of the electrical voltage impressed on it at that instant. It should also be reasonably free from frequency-distortion, which means that it must respond fairly uniformly to all audio frequencies which may be applied to it. Another requirement is that a loud speaker should have a linear response with respect to the strength of the signal-voltage applied to it. This means that its sound output must be directly proportional to the electrical input, or in other words, it must be free from *volume distortion* over the volume range required. Of course must also be able to stand the ordinary amount of abuse and misuse and should be economical in initial cost, maintenance and operation.

The question of the frequency-distortion of loud speakers is a rather flexible one, for, as we shall see later, it is possible to obtain very satisfactory overall results with a loud speaker whose frequency response is not uniform, simply by designing the audio amplifier system preceeding it, with a non-uniform frequency response which corrects that of the speaker. This is a common procedure in commercial receiver design.

The efficiency with which commercial forms of loud speakers convert the electrical energy supplied into sound energy is very low. Most of them have efficiencies of less than 5 per cent, the poorer grades having efficiencies of around 1 per cent. The best type in common use in sound-picture work has an efficiency of only about 30 per cent!

Many types of loud speakers, operating on a number of basically different principles, have been invented. The reaction between a coil and eddy currents set up in a disc; the electrostatic attraction or repulsion between two charged metal plates; thermal expansion and contraction of a wire with variation of current through the wire; the "talking" arc; the expansion and contraction of crystals under the influence of an alternating electric field; all these and many other schemes have been used with more or less success. Practically all commercial speakers now in use depend upon the variation in the pull of a fixed magnet (permanent or electromagnet type) on an iron bar, armature, iron diaphragm, or a coil carrying a current. Present-day loud speakers are by no means perfect, but they are capable of very satisfactory results.

453. Parts of a loud speaker: Most loud speakers consist of two main parts. That which changes the varying audio-frequency voltage or currents into mechanical vibrations is called the *motor, driving unit,* or *receiver.* The other part, which acts in conjunction with the "driving unit" to produce the vibration of the air particles may be either a *flat surface,* a *conical surface,* or a *horn.* We will study the construction and operation of the various types of driving units first and will then proceed to a consideration of the commercial forms of loud speakers and see how these driving units are applied to change the electrical energy to sound energy. Since the electrostatic type of speaker does not have a separate and distinct driving unit, it will be considered separately, later.

454. Classification of driving units: Any device in which motion is produced when a varying electric current flows through it, constitutes the basis of a loud speaker driving unit. The object is to produce as large a movement of the diaphragm as possible, with the least amount of variation of the current. Loud speaker driving units may be broadly classified into the following two types:

(a) *moving iron* type
(b) *moving coil* type.

In the *moving iron* type, the attraction between the pole pieces of a permanent magnet and a magnetic diaphragm, rod, or reed is made to vary in accordance with the variations of the signal current flowing through coils of wire. Moving iron type driving units may be further subdivided into "iron diaphragm" and "balanced armature" types. In the *moving coil* type, the mechanical forces and motion are developed by the interaction of the varying magnetic field produced by the flow of the signal current in a conductor, and that set up by the strong magnet provided. This may be either a permanent magnet or an electro-magnet. Loud speakers in which the moving iron type driving units are employed, are commonly called *magnetic speakers* and those with the moving coil type of driving unit are commonly called *dynamic* or *electro-dynamic* speakers. These names are unfortunate, because properly speaking, both types of speakers are "magnetic" in that the mechanical forces developed result from magnetic reactions. Also, properly speaking, all forms of loud speakers are "dynamic", because the motion is caused by a force. However, these popular terms are in common use and have become so firmly entrenched in the language of the radio industry that it is doubtful if they will ever be changed.

455. Iron diaphragm unit: The iron diaphragm type of loud speaker unit is of the "moving iron" type, and has the same general construction as the ordinary earphone described in Articles 250 and 251.

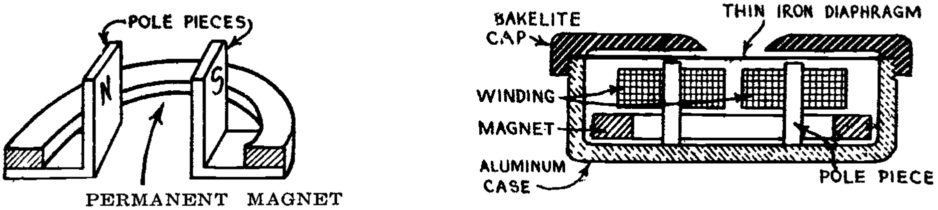


Fig. 338—Iron diaphragm type of loud speaker unit. The horseshoe shaped permanent magnet and soft iron pole pieces are shown at the left. A cross-section of the complete assembled unit is shown at the right. The windings are placed over the pole pieces.

However, when built for use in a loud speaker, it is constructed with a larger magnet, coils and diaphragm since it must handle more energy than when used in earphones. Fig. 338 shows the arrangement of the U-shaped permanent magnet and soft-iron pole pieces. A cross-section view of the entire unit assembled, is also shown. It operates in exactly the same way as described in Article 251, the movements of the diaphragm setting up the vibrations of the air particles directly.

A serious objection to this type of unit is that the diaphragm is under stress and is deflected by the magnetic field of the permanent magnet even when no signal is being received (see Fig. 181). This limits the amplitude of vibration of the diaphragm possible without rattling by striking against the pole pieces, when a strong signal is being received. If a unit of this type is to be sensitive, the air gap between the diaphragm and the pole pieces must be kept small so the field will be strong. This reduces the working amplitude of vibration possible without striking the pole pieces, and makes the unit unsuited for large volume. If the air-gap is made larger to permit of the large amplitudes of vibration necessary for large volume, the unit is not sensitive on weak signals. Also, the diaphragm being of iron, is comparatively stiff. This makes it difficult to build a unit of this type having good frequency-response. The diaphragm usually resonates at certain frequencies, causing abnormal response to notes of these frequencies. For these reasons, this type of loud speaker unit is no longer used much, although it was the most popular type in the early days of radio.

456. Balanced armature: The *balanced armature* driving unit was developed in an effort to eliminate the objectionable features of the iron diaphragm unit, as regards "rattling" or "chattering" on strong signals, and low sensitivity on weak signals. The "initial pull" or deflection caused

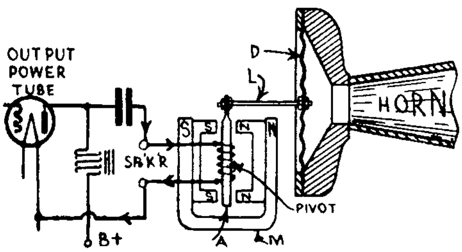


Fig. 339—Balanced armature driving unit with its coil connected to the plate circuit of a power tube through a choke-condenser coupling. The armature drives the diaphragm in the throat of a horn.

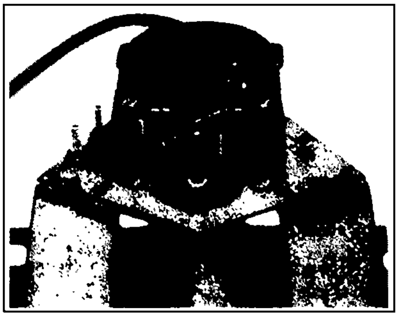


Fig. 340—A balanced armature driving unit with its armature arranged to drive the paper cone in a moving-iron cone type loud speaker. Notice the horseshoe shaped permanent magnet, and the pole pieces at the end, with the small rectangular iron-armature between.

by the permanent magnet in the iron diaphragm type unit is eliminated by a clever construction which *balances* the initial pull of one pole against that of the other. Hence the name *balanced armature* unit.

Fig. 339 shows a diagrammatic sketch of a balanced armature type unit connected through an output filter to the output circuit of the power tube in the audio amplifier of a receiver. This particular unit is designed to vibrate the diaphragm D, in the throat of a horn speaker. A short, soft-iron bar, armature, or reed, A is pivoted at its center, so its ends are free swing back and forth like a see-saw about this pivot. Each end of the armature moves between two pole pieces of the permanent magnet, and these are arranged with the relative magnetic polarity shown. Around the armature is a stationary coil consisting of several thousand turns of fine wire through which the signal current is sent. Enough clearance is provided between the armature and the inside of the coil so the motion of the armature is not restricted.

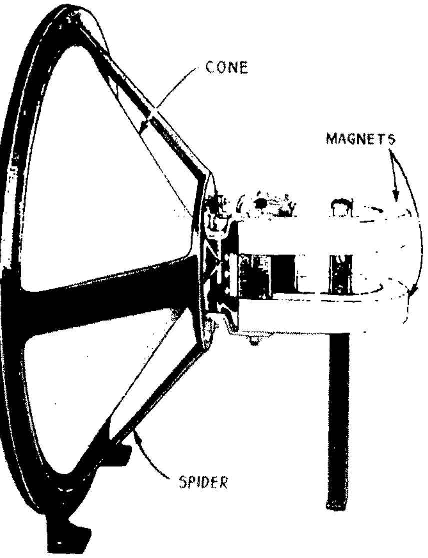
When no current flows through the coil, the armature takes a "center", or "balanced", position between the pole pieces, since the pulls of the pole pieces neutralize each other. Hence, the name "balanced armature unit". When the signal current flows through the coil, it magnetizes the soft iron armature rod. Suppose the direction of the current is such that the top end becomes a N pole and the bottom end becomes a S pole. Then the top end will be repelled by the N pole-pieces of the magnet and attracted by the S pole-piece. Therefore it would tend to move to the left. Since the bottom end is attracted by the N pole at the right, and repelled by the S pole at the left, it moves to the right. Hence, the two actions assist each other. The amount of deflection of the armature is nearly proportional to the strength of the signal current flowing through the coil, so it moves in accordance with the variations in the current. When an audio signal current flows through the coil, the armature vibrates back and forth very rapidly between the pole pieces. It may be fastened either directly as in Fig. 339, or by a simple lever system as at the left of Fig. 348, to either a flat diaphragm in the base of a horn, or a cone diaphragm, so as to impart its motion to the diaphragm in order to vibrate a larger volume of air and thus create a louder sound. As equal pulls are produced at each end of the armature, the motion is "balanced". The amplitude of vibration of the diaphragm may be increased and the pushing force decreased, or the motion may be decreased and the pushing force increased, by suitable mechanical lever linkages between the armature and the cone or diaphragm.

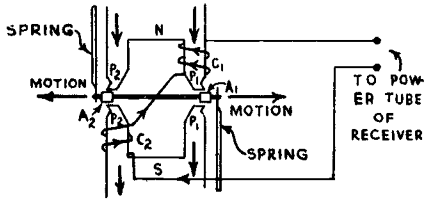
Units of this type made for use with long horns usually have a wide flat, thin armature, to secure a great driving force. The diaphragm can be made of a flat thin piece of mica or aluminum, for lightness. Fig. 340 shows a unit of this type which is used as the driving unit for a cone speaker diaphragm. Notice the pole pieces at the end of the permanent horseshoe magnet. Another unit of this type is shown in Fig. 51. It is important that an output coupler consisting of a choke coil and condenser as in Fig. 339, or an output transformer, (see Article 446), be used with units of this type to keep the direct plate current of the power tube out of the winding, and allow only the varying signal current to flow through.

The balanced armature driving unit has been developed to a high degree of perfection and will give very good performance if it is operated properly with some regard for its limitations. It was the most popular type of unit for several years, and is especially useful in connection with battery-operated receivers. One of its serious limitations is that for good sensitivity, the air gap between the armature and pole pieces must be made very small to reduce the reluctance of the magnetic circuit and obtain a strong magnetic field. This is objectionable when receiving loud low notes, since the movement of the armature may be so great that its ends strike the pole-pieces, causing a rattling sound. If the air-gap is made large in order to provide for greater amplitude of vibration, the strength of the field decreases, with proportionate loss in sensitivity. If this is compensated for by increasing the number of turns on the coil, the high frequencies will not be reproduced, because of the increased distributed capacity of the coils causing a by-passing effect to the currents of these frequencies. However, for moderate amounts of volume, this type of unit is satisfactory especially when the cost is considered as a factor.

457. Inductor-type driving unit: The inductor driving unit is a moving iron type speaker of the balanced armature type in which the armature moves longitudinally between the pole pieces instead of crosswise. In this way the limitation due to the armature striking the pole pieces, on loud signals is overcome. This type of driving unit is often called an inductor dynamic unit. It uses two powerful U-shaped permanent magnets, (see Fig. 341), to supply the steady magnetic field. Instead of the usual moving coil or armature bar, the armature consists of two separate iron rods, A_1 and A_2, in Fig. 342, connected by tie rods as shown, each bar working between its respective pole faces.

The armature has a reciprocating motion instead of a swinging one. The coils C_1 and C_2 are connected in series and consist of several thousand turns of fine magnet wire wound on bobbins which are slipped over the pole legs. The action is as follows:





Left.—Fig. 341—Complete inductor-type driving unit attached to the spider frame and paper cone diaphragm to form a complete speaker.

Right—Fig. 342 — Cross-section view showing the relative positions of the pole tips, coils, armature, rod and springs in the inductor-type driving unit. The armature A1—A2 moves sidewise.

The armature assembly rides freely between the pole pieces P_1 and P_2. A signal current flowing through the winding in the direction indicated, will increase the flux (magnetic field) through the pole legs P_1 and decrease the flux through the pole legs P_2 (remembering that the magnetic lines of force of a magnet flow from the north pole across the air gap to the south pole as shown by the arrows). The flux, seeking the path of least reluctance, exerts a greater force on the armature bar A_1 than on bar A_2 since it is nearer to the pole piece, and the force on A_1 is greater than that on A_2, thus moving the armature to the left. On the reverse of the cycle the armature moves in the opposite direction in the same manner. The pole legs are cut to the shape indicated, to reduce the leakage flux and to bring the greatest flux density to the most desired point.

If the inside spacing between the armature bars is equal to the center spacing of the pole faces, the flux in the magnetic circuit P_1 A_1 P_1 varies 180° out of phase with the flux in the circuit P_2 A_2 P_2 as the armature is moved to its two extremes. This would give extreme sensitivity but there would then be no magnetic restoring force. If the armature bars are brought closer together, a distance corresponding to 18 electrical degrees, the resulting sensitivity is slightly decreased but there will be a restoring force set up, which will restore the armature to its initial position. The total flux is greatest when the armature is in its "at rest" position and represents the magnetic restoring force, or, the "magnetic stiffness." This is the design used in practice. It is evident that any d-c component of current flowing through the windings would change the position of the armature by moving it to one side or the other, thus reducing its limit of motion in one direction. For this reason there must be no d-c flowing through the windings, thus making it necessary to use an output transformer or a choke and condenser. However, if the loud speaker is to be used with a push-pull amplifier, its winding may be used as an output choke and connected directly in the plate circuit of the push-pull tubes. A third lead may be taken from the windings at the point where the two coils are connected together and used as the mid-tap of the windings. This corresponds to the mid-tap on the primary of the usual push-pull output transformer. Doing away with the output transformer in this manner does away with its attendant losses and the gain is readily noticed by the ear.

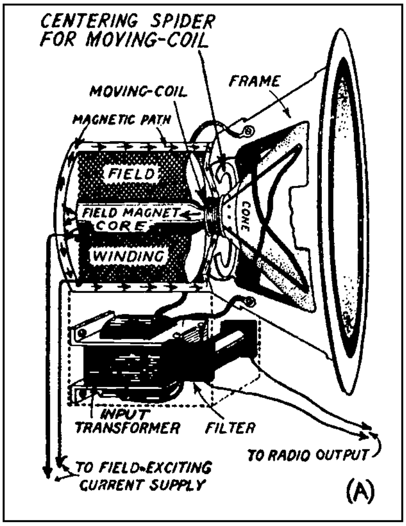
It has been found that matching the impedance of the inductor dynamic to that of the amplifier with which it is to be used is of great importance. If the loud speaker has too high an impedance for that of the amplifier tubes with which it is used, the efficiency is lowered at the higher frequencies and increased at the lower frequencies. Since these loud speakers are made in several different models, each having a different impedance, and distinguished by a different color marking on the chassis, this feature affords the listener a chance to select a loud speaker which will give the balance of high and low frequencies which is most pleasing to him. A complete loud speaker of this type is shown in Fig. 341. The unit drives a cone-shaped paper diaphragm, both being supported by the rigid metal frame. Notice the two horseshoe-shaped permanent magnets.

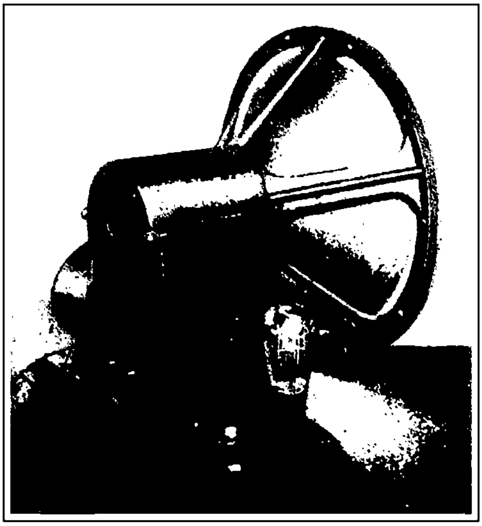
The advantages of this type of speaker are, that since the armature moves in a line parallel to the pole faces, it can be constructed to be sensitive due to the small air gap, and yet produce large amplitudes of vibration without striking the pole pieces. The armature moves over one-eighth inch when reproducing loud, low notes. Also the use of strong permanent magnets makes the unit cheap and simple and there is no possibility of objectionable hum being introduced by the speaker when used in electrically operated receivers, since it does not contain any electric light power supply, rectifiers, etc. It is particularly adapted for use with battery operated receivers for home use, in automobiles, etc.

The name *inductor-dynamic* originates from the fact that the motion or force ("dynamic") is derived from a magnetic induction action ("inductor") similar to that in an a-c induction motor, where a rotor revolves under the influence of a changing magnetic field. Units of this type are usually used to drive 10 or 12 inch speaker cones for setting the air in vibration and producing sound waves.

458. Moving-coil driving units: In the moving-coil type of driving unit, a very small, exceedingly light cylindrical coil of wire (voice-coil) carrying the signal current, moves back and forth in the annular magnetic field between two concentric strong magnetic poles. The coil is attached (usually directly) to a paper cone, or a non-magnetic diaphragm when used with a horn. The magnet may be either a permanent magnet or an electro-magnet. The latter type will be studied first, as it is the most popular.

459. The moving-coil speaker with electromagnet: The moving-coil type of speaker unit (commonly called the electro-dynamic speaker), differs from those already described, in that the audio-frequency signal current flows through a small exceedingly light, cylindrical coil of wire called the *moving-coil* or *voice-coil*, mounted so it "floats" in the intense radial magnetic field in the small circular gap between the central core and the end ring of a powerful electromagnet, as shown in Fig. 346A. The current flowing through the coil produces a magnetic field of its own. The action of the two fields produces a force which moves the coil along the axis of the core. Since the signal current varies in strength, the force acting on the voice-coil also varies accordingly. so it vibrates back and





Courtesy Jensen Radio Mfg. Co.

Fig. 343—Left: Cut-open view of an electro-dynamic type loud speaker having a moving coil driving a cone type diaphragm. The construction of the field magnet winding, field core and outside shell are clearly shown.
Right: A typical auditorium type electro-dynamic speaker designed to handle large input power. The rectifier tube in the foreground is for supplying the d-c field current from the a-c electric light socket.

forth in the direction of the axis of the central circular core, the movement being proportional to the increase or decrease of the current at every instant. Since the coil moves along the axis of the core, it may vibrate over large distances without striking anything, hence it may be used for loud reproduction of even the lowest notes without danger of rattling due to striking pole-pieces, etc. This is one of the most important advantages of this form of driving unit. The relation of the various parts is shown at (A) of Fig. 343. This shows a section view of a moving coil unit with an electromagnet supplying the strong magnetic field. The moving-coil is attached directly to a cone-shaped paper diaphragm of the free-edge type, as shown at Fig. 346A. A typical commercial electrodynamic loud speaker of this type, suitable for use in large auditoriums, is also shown in Fig. 343. This will handle as much as 20 watts of electrical energy fed to it by a power amplifier. We will now proceed to study the design and construction of the various parts of a driving unit of this type. These are shown in Fig. 350.

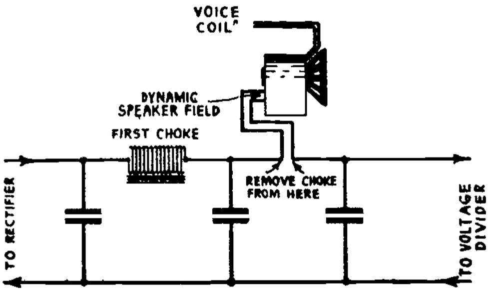
460. The field or "pot": The electromagnet which supplies the strong steady magnetic field in which the voice coil is suspended, is commonly called the *field magnet* or the *field pot.* The stronger the audio currents through the moving coil and the greater the value of the steady flux due to the field, the greater is the movement of the cone and therefore the louder is the sound produced. It is of advantage therefore to produce as high a flux-density as possible in the air-gap. Commercially, the loud speaker manufacturer designs the units for maximum flux density consistent with reasonable cost and a reasonable amount of power consumption from the source supplying the field power. In order to secure as strong a field as possible, the field winding is wound on the center core-leg and is surrounded by the magnetic steel shell which forms part of the magnetic circuit (see Fig. 343). This forms an iron-clad magnet. And since the lines of force have practically a complete path in the steel, a very strong field is produced for a given number of ampere-turns in the field winding.

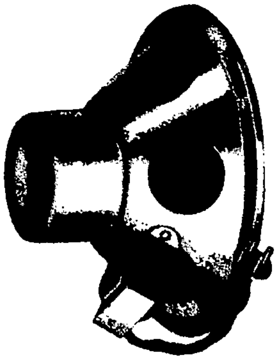
Two general types of field magnet structure are to be found, cast and stamped. Cast steel or malleable iron is usually used with the cast design, while ingot or Swedish iron is used in many cases when the stamped design is used. Ingot iron is a better magnetic material than the cast product so that a lighter field assembly is permissible. Any material of a magnetic nature can be used with equal results if sufficient weight is used. In the case of cast iron, for instance, the total weight required would be so much greater that it is not economical. The increased tendency toward the use of stamped field pots (see Fig. 350), is due to this higher efficiency and to the elimination of many machining operations necessary with the cast product.

The field winding consists of a large number of turns of enameled copper wire wound to fill the space between the center core and the outside part of the field pot (see left of Fig. 343). About 800 ampere-turns are arbitrarily used in small speakers, and from 1,000 to 2,000 ampere-turns are used in the larger ones. A greater magnetizing force is thus employed in the larger units. Electric power to energize the field winding may be obtained from a storage battery, from the filter system in a "B" power supply unit, or from the electric light socket.

When the field current is supplied from a 6 volt storage battery, the field coil is wound with rather thick wire (about No. 20 B. & S.), since it must have a low resistance in order that the 6 volts may force about 1 or 2 amperes through it. Most fields of this type are designed to operate at medium field strength direct from a 6 volt storage battery, or at increased strength from a 12 volt battery. A typical field winding of this type contains about 1600 turns of No. 20 wire, its resistance being 8.5 ohms. At 6 volts it takes 0.7 amp., and 4.2 watts of electrical energy are being used in it steadily merely to produce the intense magnetic field.

In most electrically operated receivers, the field winding of the electrodynamic speaker is used as a choke in the filter circuit of the "B" power supply device by connecting it in the filter as shown in Fig. 344. The steady direct "B" current furnished by the "B" power supply flows through this field winding and so energizes it. In this way the problem of field current supply is solved simply and the cost of a choke coil in the





Courtesy Best Mfg. Co.

Fig. 344—Left: Connection of the speaker field as a filter choke in the B power supply unit. In this way the energizing field current is supplied and the field performs a very useful purpose besides.
Right: A typical dynamic speaker with a 2500 ohm field coil designed to be connected as a filter choke in the power supply unit of the radio receiver with which it is used. The input transformer is at the lower right.

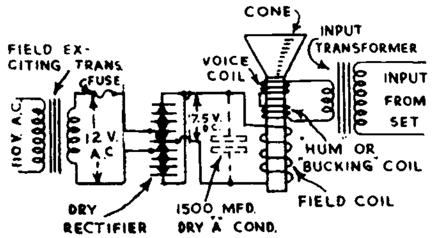
filter system is saved, since the field coil consisting of many turns of wire wound on a magnetic core has quite a high inductance, and acts as an excellent choke coil. It also saves the cost of a power transformer and rectifier which would otherwise be required for the speaker, as we shall see. In many cases the field coil of the speaker is the only choke used in the filter of the "B"-supply system. Several ways of connecting the field will be studied in detail later when "B"-supply systems are considered. As we shall see in Art. 510 the voltage drop across the speaker field may also be made to serve as a voltage-divider or as a source of grid-bias voltage in the receiver, thus saving the cost of the separate resistors which are ordinarily used for thus purpose.

It is evident that satisfactory results with this method of field supply can only be obtained when the proper value of current which is required to fully energize the field is sent through it. It may be necessary to connect a bleeder resistor across the line at some point following the speaker, in order to increase the current to the proper value required by the field. Fields designed to receive their energizing current in this way are made with various values of resistance and with various current requirements. Representative windings of this type are: 22,000 turns of No. 34 wire, resistance 2,500 ohms, operated on 110 volts, 44 milliamperes; 39,000 turns of No. 36 wire, resistance 7,500 ohms, 180 volts, 24 milliamperes. Other field resistances which are commonly employed are 650 ohms, 1,000, 1,200, 1,400, 1,600, 1,800, 2,000 2,250, 3,000 and 5,000. A speaker of this type is shown at the right of Fig. 344. Where a 110 volt or 220 volt d-c electric light line is available, the field winding may be energized by connecting it directly across this line, providing the field has the proper resistance and current rating.

When current from the 110 volt a-c electric light line is to be used to energize the speaker field, as in the case of public-address systems, outdoor announcing, small theatres, etc., some form of rectifier and filter must be employed, for if alternating current were sent through the field an alternating magnetic flux would be produced. This of itself would cause the voice-coil and the attached diaphragm to vibrate in accordance with these field variations, producing a loud, objectionable, low-pitched hum. The current supplied to the field must be absolutely uniform and smooth in order to create a field always in one direction, and unchanging in value. Two types of rectifiers are used for changing the a-c to d-c. One is the dry-plate copper-oxide or cupric-sulphide type (see Article 214) and the other is the common vacuum tube type.

When a dry-plate rectifier is employed, the 110 volt a-c line voltage is usually stepped down to about 12 volts at about ½ ampere by a step-down transformer (see (G) in Fig. 350). The secondary connects to the copper-oxide rectifier, and the rectified current flows through the speaker field, as shown at the left of Fig. 345. A speaker of this type is shown at the right of Fig. 346.

The current supplied by a rectifier of this type is a pulsating direct current with ripples of 120 cycles. It is evident that the magnetic field produced by this current will also fluctuate. Since the voice-coil is in the field of this flux, there will be a reaction between it and the varying magnetic flux and the coil will tend to move, its movements h ving the same frequency as that of the field current. If the diaphragm



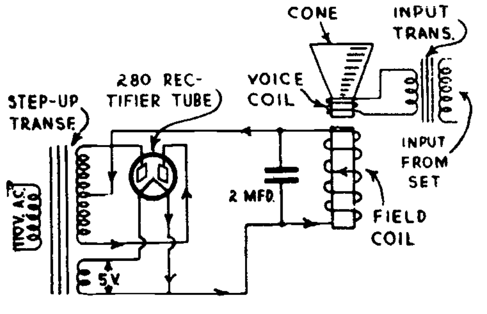
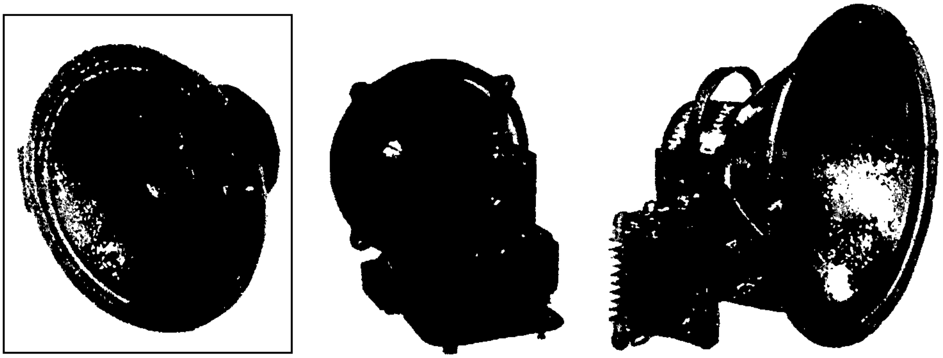


Fig. 345—Left: How a dry-plate rectifier may be connected to the speaker field coil. Hum may be reduced by a dry electrolytic filter condenser or a "hum bucking" coil.
Right: How a vacuum tube rectifier and power transformer may be connected to change the a-c line current to smooth d-c for the field coil.

or cone moves, sound waves of this frequency are produced, and an audible hum results. The effect of this pulsating field current can be reduced greatly by a small stationary "*bucking*" or "*hum neutralizing*" coil which is wound around. the pole-piece of the electro-magnet (see Fig. 345) and near the moving coil. It is connected in series with the moving coil and the secondary of the coupling transformer. As the bucking coil is also in the magnetic field, it has induced in it a hum-voltage corresponding in frequency so that of the pulsating field current. By making the bucking coil of the proper number of turns, and connecting it in the proper direction, its induced hum-voltage can be made equal and opposite to that induced directly into the moving coil by the pulsating magnetic flux of the *field coil*. Therefore, these two induced hum-voltages will balance each other and the hum is prevented, or at least greatly reduced.

One disadvantage of the bucking coil is that it also tends to reduce the response to signals around the hum-frequency of 60 and 120 cycles and therefore results in slightly weakened low-frequency response.

Obviously the bucking coil method of hum reduction is only practical when the coil can be included in the speaker at the time of manufacture. A very effective way of eliminating hum in any existing dynamic speaker which uses the low-voltage type of dry-rectifier, is shown at the left of Fig. 345. A dry "A" electrolytic low-voltage type filter-condenser of from 1,500 to 2,000 mfd. capacity is connected across the field coil. This large capacity serves to filter or smooth out all ripples in the field current. It should be remembered, however, that these condensers can be used only on speakers in which the low-voltage (about 15 volts) type of dry-rectifier is used, as they have a very low breakdown voltage.



Courtesy Jensen Radio Mfg. Co. *Courtesy Rola Co.* *Courtesy Magnavox Co.*

Fig. 346—Left: Front view of an electro-dynamic speaker, showing felt ring F. cone C, and spider S.
Middle: Electro-dynamic speaker with vacuum tube rectifier on the left. The input transformer is directly under the tube.
Right: Electro-dynamic speaker with dry-plate rectifier mounted at its left.

In connecting the dry "A" condenser across the circuit, it is important to make sure that the negative (black) lead of the condenser is connected to the negative side of the circuit, and that the positive (red) lead of the condenser is connected to the positive side of the circuit. The polarity of the circuit should be first determined with a voltmeter.

Another arangement has been developed in which the hum-voltage induced in the voice-coil is counteracted and balanced out by electrical means instead of magnetic. In practice, this takes the form of a small adjustable-resistance having a value of approximately 2 or 3 ohms and connected in series with the *field* winding. The alternating current voltage drop across this resistance is applied in opposite phase relationship in series with the voice-coil circuit, causing the hum-voltage to be completely opposed, and resulting in zero hum. This device has the advantage that if the hum is introduced into the speaker from the radio set, it can also be balanced out, providėd it is in phase, or in opposite phase, to the hum-current flowing in the movable-coil. Special high-voltage rectifier circuits using dry-plate rectifiers have also been devised, in which the rectifiers are connected directly to the line-circuit and have an output around 60 volts. The field winding of the speaker may have a resistance of 250 to 300 ohms in this case.

Instead of using a dry-plate type rectifier for rectifying the 110-volt alternating line current for field supply, a vacuum tube rectifier may be employed and connected as shown at the right of Fig. 345, provided the field power requirements are not too great. The power transformer at the left has a high-voltage secondary winding connected to the plates of the rectifier tube and a low-voltage winding for furnishing filament current to it. The connection of the tube is the same as is employed in the usual "B" power supply unit used in radio receivers. The pulsating output current is filtered or smoothed out by one or more 2 mf. filter condensers in combination with the choking action of the high-inductance field coil itself, so as to eliminate any a-c hum which would be set up by the speaker due to the 120-cycle fluctuations in field current. This does away with the necessity for any "hum-bucking" coil. Also, the vacuum tube rectifier used is more reliable in operation than the dry-disc type of rectifier, and can very easily be replaced by the non-technical owner by simply plugging a new tube in the socket. The higher voltage used for the field makes filtering easy. Also since the current delivered to the field coil by the rectifier tube is in the order of 120 milliamperes, the field is wound with possibly 20,000 turns of fine wire of about No. 28 B. & S. A speaker of this type is shown at the right of Fig. 343. This is designed particularly for public-address work and can handle the output of amplifiers delivering as much as 20 watts of undistorted power.

When the rectifier in a dynamic speaker is nearing the end of its useful life, the volume of the music diminishes and the hum increases to a high level due to the imperfect rectification produced. When in this condition, the rectifier must be replaced. The density of the magnetic flux in the air gap in which the voice-coil is placed, is as high as 120,000 lines of force per square inch in some speakers, thus insuring great sensitivity and freedom from distortion, at great power.

461. The "voice-coil" and input transformer: A typical voice-coil is wound with about 90 turns of No. 32 enamelled wire in several layers on a light thin, tubular form usually of Bakelite. Since the end turns must always be taken off from the same end of the coil, an *even* number of layers of wire are generally used, usually two or four. The voice-coil form is rigidly fastened to the cone-shaped paper diaphragm. As the clearance between the sides of the voice-coil and the field core is only a few thousandths of an inch, the coil is usually kept permanently centered in a "floating position" by means of some sort of flexible "spider" arrangement which does not seriously interfere with the motion of the coil. The thin spider S shown in the speaker at the left of Fig. 346 is an example of this construction. Its center is bolted to the center of the center core leg, and its out side edge is fastened to the cone.

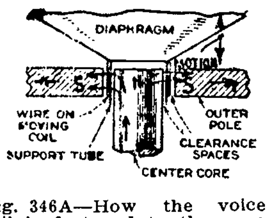


Fig. 346A—How the voice coil is fastened to the cone and is suspended in the annular space between the center core and pole piece of a moving-coil type speaker.

It is necessary that the voice-coil be free to move in and out of the gap at all times without touching any part of the field structure. In cases where the coil touches, a loud buzzing or scratching sound destroys the quality of the speaker. In this case it must be re-centered in the air gap. To do this, loosen the spider-fastening screws, or the center screw on the spider if one is provided. Roll a piece of wrapping paper into the form of a small tube, such that it may be slipped between the center core-leg and the inside of the moving-coil form. This centers the coil. Now tighten the fastening screws and remove the paper. The cone should now be centered so it moves freely. In many cases, the cone on a well-designed speaker will move a total distance of three-sixteenths to three-eighths of an inch. This motion occurs when loud low-frequency notes are being reproduced, and causes a large variation in the air pressure at a given instant between the front and back of the cone.

As the voice coil contains a comparatively few numbers of turns, its inductance is small. Therefore it has a low impedance and acts practically like a pure resistance, its impedance increasing very little with increase in frequency over the audio range. This latter feature is very desirable since it is desired to have the speaker respond alike to all frequencies. In one commercial unit, the d-c resistance of the 92-turn moving coil is 4.3 ohms. The impedance of voice coils in moving coil speakers is considered as being about 10 ohms. However, there are a few makes of speakers with a voice coil consisting of a single turn of thin copper or duralumium ribbon having an impedance of less than .001 ohm. Since the impedance of the moving coil is much less than the plate resistance of any power amplifier tube it might be worked out of, in order to secure an efficient transfer of undistorted power from the plate circuit of the tube to the voice coil, an impedance-adjusting transformer of proper design must be used. This transformer is often called an *output transformer* when referring to the receiving set and an *input transformer* when referring to the speaker, (see Arts. 445 and 446).

Practically all electro-dynamic speakers contain an input transformer (the input transformer on the speaker at the right of Fig. 344 is clearly shown), designed with a high enough primary impedance to work efficiently out of standard types of 3-electrode tubes. When pentode tubes are used, a transformer having a special impedance ratio for them is necessary. The input transformer consists, like an audio transformer, of two coils of insulated wire wound on a laminated iron core. It is wound to match the plate impedance of the power tube to the lower impedance of the moving coil. As the impedance of a coil varies as the square of the number of turns, the transformer is designed so that the *square* of the ratio of the secondary turns to the primary turns is equal to the ratio of the voice-coil impedance to the desired primary impedance (see Art. 445). This may be illustrated by the following problem.

Problem: The 10 ohm voice coil of a moving coil speaker is to be efficiently coupled to the plate circuit of a '45 type power tube whose plate resistance is 1900 ohms. What must be the primary impedance and turns-ratio of the input transformer?

Solution: For maximum undistorted power output, the load impedance for a 3-electrode tube should be equal to about twice the plate resistance. Since the primary of the input transformer is the load impedance in this case, its impedance should be $1900 \times 2 = 3800$ ohms. Therefore the turns-ratio is found from

$$\left(\frac{T\,sec}{T\,prim}\right)^2 = \frac{10}{3{,}800}$$

$$\text{or}\quad \frac{T\,sec}{T\,prim} = \sqrt{\frac{10}{3{,}800}} = \frac{1}{19.5}\quad \text{Ans.}$$

The primary should have enough turns so as to have an impedance of 3800 ohms, and the secondary should have 1/19.5 as many turns as the primary.

When a push-pull output stage is used, it must be remembered that the output plate resistance is equal to twice that of one of the tubes. Thus, in this problem, if two 245 tubes in push-pull had been specified, the output plate resistance would be 2 × 1,900, or 3,800 ohms. In order to secure the maximum undistorted power output, the plate load would have to be 3,800 × 2, or 7,600 ohms. For two similar output tubes connected in parallel, the output plate resistance is equal to one-half that of a single tube.

The connection of the input transformer T, between the voice coil and power amplifier tube of a receiver is shown in Fig. 347. The proper input transformer is usually included with the dynamic speaker, so that when a dynamic speaker is connected to a receiver which has an output transformer or output filter in it, the output transformer or filter should be disconnected from the receiver first, and the dynamic speaker input terminals connected directly in the plate circuit of the power tube. Some manufacturers use a tapped primary on the input transformer so that proper matching can be obtained with any type of tube, for best performance. Because coupling ratios are not critical, it is fairly safe to say that any commercial dynamic loud speaker unit may be satisfactorily connected to the output of almost any receiver, unless pentode tubes are used. In cases where power pentode tubes are used, more efficient results can be obtained by using a special coupling transformer designed for them.

In receivers having push-pull output, satisfactory operation will be obtained with most commercial dynamic speakers by connecting them directly to the set output terminals (secondary terminals of push-pull output transformer in set). Some sets use a special push-pull output transformer having only a few secondary turns matched to operate directly into the voice coil winding of the conventional type of dynamic speaker, omitting the input transformer in the speaker. In this case, the push-pull output transformer secondary should be connected directly to the voice coil only, or else the regular dynamic speaker input terminals should be connected directly to the outer terminals of the primary of the set output transformer, ignoring the secondary terminals of this transformer entirely.

462. The input filter or "equalizer": Many makes of electrodynamic loud speakers have some form of filter or *equalizer* included as an integral part of them. These filters or equalizers cut off the reproduction above certain frequencies, or cause a power loss at some frequencies in order to reduce the abnormal loudness which would otherwise occur at those frequencies because of some "resonance condition," etc.

The most general type of filter consists of a simple "pi" low-pass filter consisting of a 100-200 millihenry inductance in series with the primary of the input transformer, and a 0.01 to .02 mfd. condenser across the line at each side of the inductance. This form of filter cuts off the frequencies above its natural resonant frequency of about 4,000 cycles and has practically no effect on the lower frequencies.

A 4000-cycle cut-off is very difficult to notice as far as speech is concerned but some of the brilliance is lost, especially for music.

Another form of filter or equalizer, shown in the diagram of Fig. 347, consists of a resistance, inductance and capacitance in series, connected across the primary of the input transformer. At the resonant frequency of this circuit the attenuation is greatest. By proportionating the values in this equalizer, the "dip" may be made sharp or broad, and deep or shallow, to remove a resonant peak in the loud speaker output. This form of equalizer may be used to remove the peak where the wave-motion and plunger motion combine to cause an increased sound output.

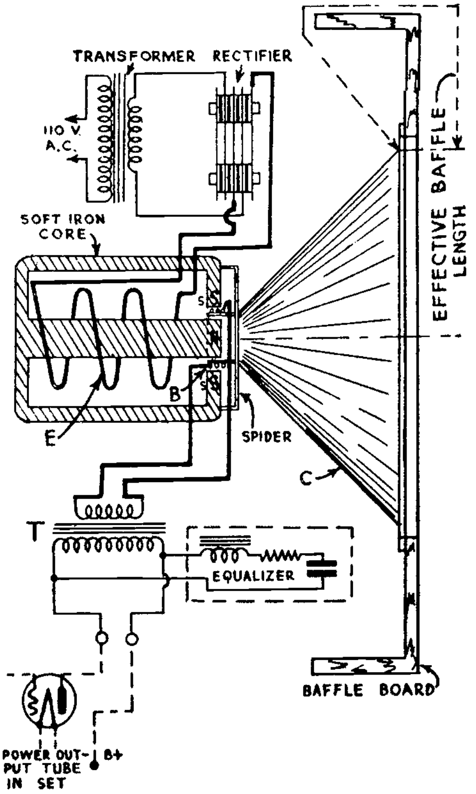


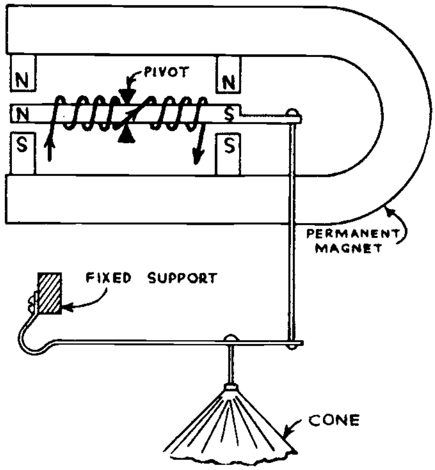
Fig. 347—Electro-dynamic speaker with the voice-coil connected to the power amplifier tube through an input transformer T with an "equalizer." A hole is cut in the baffle board to allow the sound waves to get through.

463. Fixed-edge cone diaphragm: The vibrating armature of a moving-iron driving unit, or the voice-coil of a moving-coil unit do not set enough air in motion, to create loud enough sound waves. Therefore they are always used to drive some form of *sound radiator* which may take the form of a flat diaphragm operated at the neck of a horn, or a cone-shaped paper diaphragm. In the moving-iron type of driving unit, the armature usually drives the apex of the cone, through a simple lever system of the form shown at the left of Fig. 348.

Cone-shaped diaphragms may be of either of two types, the *fixed*-edge or the *free*-edge. In the fixed-edge cone, shown at the left of Fig. 349, the base of the cone A, is fastened to the base of a second cone B (or else to a frame), and the driving rod C, extends from the driving unit D, (rigidly fastened to the frame), to the apex of the cone. Thus the outside edge of each cone is not free to move independently. The cone speaker shown at the right of Fig. 348 is of this type. Well-designed and constructed speakers of this type have good frequency-response. In most of them, an adjustable apex set-screw or chuck arrangement is provided to compensate the small changes in the tension of the paper cone due to atmospheric changes. Moving-iron type cone speakers should always be used with an output filter following the output power tube in the receiver.

At low frequencies, the cone acts as a sort of piston or plunger which pushes the air directly in front and in back of it. At the high frequencies, the inertia of the outside edges keeps them from vibrating while the center or apex region moves, thus tending to make the cone vibrate in sections instead of as a complete unit.

464. Free-edge diaphragm: In a free-edge cone, (shown at (A) of Fig. 349), the driving unit "A" drives the paper cone "B" whose base is free to move. The weight of the cone is usually supported by



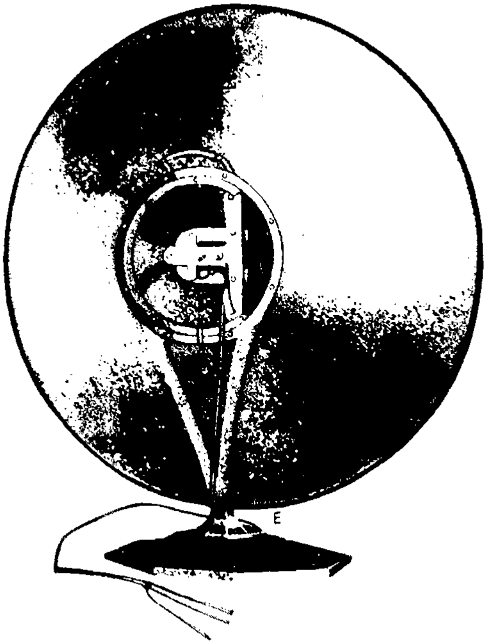


Fig. 348—Left: Lever system for balanced armature speaker unit driving a cone diaphragm.
Right: Rear view of Western Electric fixed-edge cone speaker with rear cover plate removed.

mounting it on a rigid ring D by means of a thin flexible leather or chamois ring "C" which allows almost perfect freedom of movement of the cone. This type of speaker being unrestrained in its movement acts more nearly like a plunger or piston, and is capable of excellent reproduction. The cone is often corrugated or moulded in ridges in order to stiffen it and assure true plunger-like movement. Free-edge cones are used extensively. The speakers of Figs. 341, 343 and 346 all have free-edge cones. In each case, the cone is fastened to the metal supporting frame by means of a circular piece of thin, flexible chamois or goat skin.

465. Construction of the diaphragm: Cone shaped diaphragms are usually made of special grades of paper or other materials which do not absorb moisture readily and which have the most satisfactory combination of light weight, stiffness, freedom from rattling, etc. Heavy paper causes an energy loss due to the added weight and also reduces the high-frequency response due to the increased stiffness. The size of the cone also affects the frequency response. Special materials known under such trade names as Burtex, Tym-flex, etc. have been developed to supply the special properties required for the cones used in electro-dynamic speakers.

The cone diaphragms vary from about 6 inches in diameter for the small sizes, to 12 inches for the larger sizes used in auditoriums and public address work. Using a larger diaphragm results in a good low-frequency response, since for the same amplitude of motion there is, of course, a much greater amount of air set in motion. Conversely, for the same sound output the larger diaphragm does not have to move as far, which simplifies construction somewhat.

For low frequencies, 30 to 100 cycles per second, the amplitude of motion for good sound output is quite great. A motion of ¼ to ⅜ inch is not uncommon. Such great

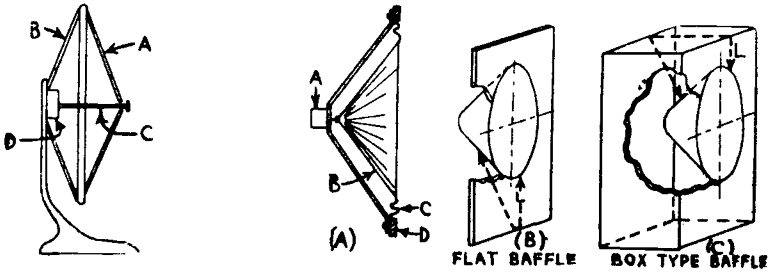
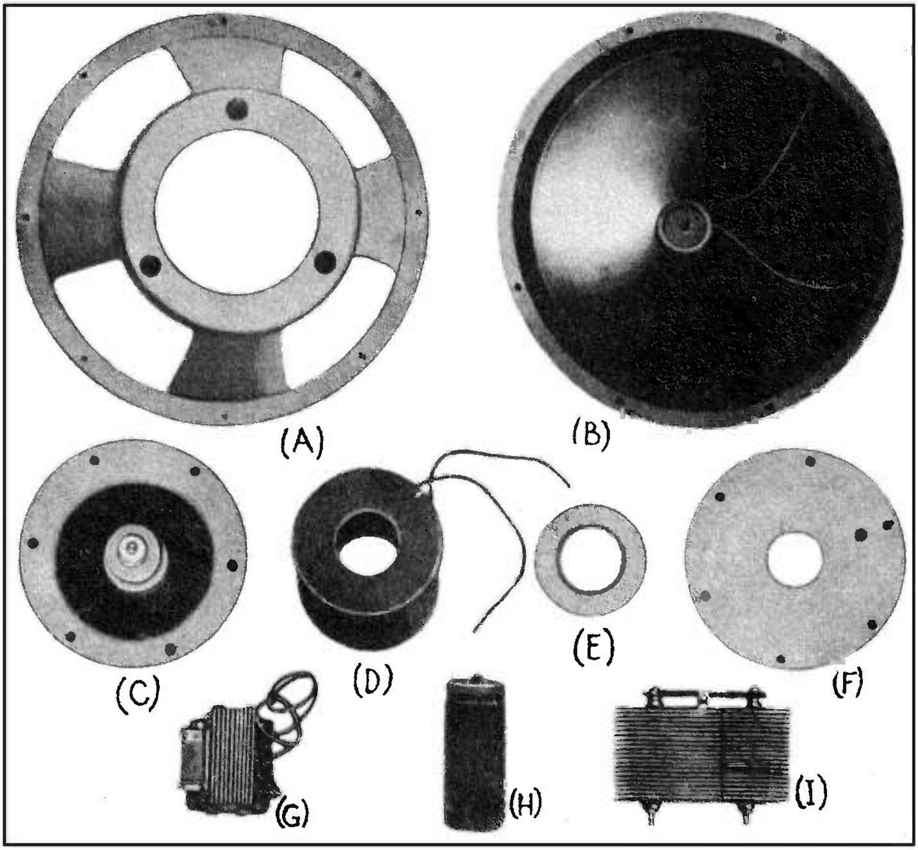


Fig. 349—Left: A fixed-edge cone speaker. The edges are not free to move unrestrictedly Right: (A), free-edge cone. The edge is unrestricted, and may vibrate freely. (B), A flat baffle. (C), A box-type baffle.

motion may cause crystallization of the springy centering-spider pieces, causing them to break in time. With the larger diaphragm, the motion is much less, so this tendency to break is greatly lessened.

466. Complete moving-coil speaker: The various main parts of a complete moving-coil type of speaker of modern design, with cone-shaped diaphragm is shown in Fig. 350. The metal cone bracket (A), supports the cone (B). The voice coil which is constructed very light, is fastened to the apex of the cone as shown at (B), its two ends connecting to the secondary of the input transformer. The outer edge of the diaphragm is fastened to a flexible cloth ring, and the latter is held by the spider frame. The stamped magnetic-steel field pot (C) has a center core over which the field winding is slipped. The copper shading ring (E) serves as an equalizer to reduce the response at a frequency range where a peak would otherwise occur—thus "equalizing" the response. The front plate (F) fastens to the top of the field pot, leaving a small annular air-gap around the central core-leg, in which the voice-coil moves up and down. The low voltage for the dry rectifier (I) is provided by the stepdown transformer (G), and an electrolytic condenser (H) is shunted across this to smooth out the current through the field winding and so eliminate the hum which would result if the field current were pulsating. The input transformer is not shown here.

467. Baffles: Before proceeding with the study of baffles, the reader is advised to study Fig. 2 which shows in detail how sound waves are produced by the vibrating cone of a loud speaker. A free-edge cone need not be large and unwieldy in order to reproduce the low-frequency notes, but it should be attached to a large baffle for this purpose. The



Courtesy Wright De-Coster Inc.

Fig. 350—The various parts which go to make up a typical, modern electro-dynamic cone type loud speaker. See Art. 466.

baffle is necessary, because as shown in Fig. 2, both the front and back of a cone diaphragm set up air waves. Those of low frequency would alternately reinforce and neutralize each other, and seriously affect the volume of the low-frequency notes, if it were not for the baffle.

When the loud speaker is producing sound waves, the cone is in vibration, that is, first it moves forward in the direction shown by arrow A, in (A) of Fig. 351 and the next instant it moves in the direction of arrow B. The cone is shown attached to a dynamic speaker driving unit for simplicity. If the audio current flowing through the voice-coil has a frequency of say 100 cycles, then the cone moves in the direction A 100 times every second, and in the direction B 100 times every second. Each time it moves in direction A, it compresses the air in front of it. At the same instant, the air in back of it is *rarefied* or *decompressed,* since the cone on moving forward has left more space behind for the air to fill. These differences in air pressure (more pressure in front and less pressure in the rear), immediately tend to equalize each other; the crowded air particles comprising the compression in front, immediately tend to move around the edge of the cone to the rear where there is a rarefaction.

But sound waves are caused by movements of air due to tiny air pressures. If these pressures are allowed to neutralize each other, there will be no movement of air out directly from the front or the back of the speaker toward C or D, and hence no sound will be produced. If they partially equalize each other, very little sound will be produced. Consequently, something must be done to prevent the compressions produced at the front of the cone, from travelling around the edge from the front to the back *in time to equalize the corresponding rarefactions being produced at the same instant at the back,* (or vice versa).

This is accomplished by placing a baffle around the cone, taking either of the forms shown at (B) and (C) of Fig. 349. The air vibrations must now take the long path L around the baffle in order to get from one side of the cone to the other. By making this path long enough, the compressions cannot get from the front to the back of the cone(or vice versa) in time to equalize the corresponding rarefactions, as will now be explained.

It must be remembered that the current flowing through the voice coil is an alternating current (in the case of a speaker coil connected directly in the plate circuit of an output tube without coupling transformer, the current is a pulsating direct current, but the same reasoning also applies to this case). This alternating current may be represented by the familiar form shown at (B) of Fig. 351, although the wave-form of actual voice currents is much more complicated than this, as shown at B of Fig. 171. Since the movement of the cone follows the variations in the current, the air pressure variations will follow the same wave-form. In terms of air pressure in front of the cone, we can decide that from 1 to 2, the pressure is increasing above normal value, from 2 to 3, it is gradually decreasing to normal, from 3 to 4, it is decreasing below normal (a rarefaction); and from 4 to 5 it is gradually increasing to normal. The air pressure in front of the cone, therefore, goes through four distinct changes during one complete cycle (one forward and backward movement of the cone). If the current has a frequency of say 100 cycles, there would be four times 100, or 400 changes in pressure per second. Sound waves travel about 1130 feet per second. Therefore, in the case of a 100 cycle note, during any one change in pressure (each of which takes place in one 400th of a second), the sound pressure wave will travel 1130 divided by 400, or 2.82 feet. Keep that in mind for a moment. Now if we allow the pressure wave from the front to go around directly to the back of the cone it will neutralize the rarefaction wave there. But if we make this pressure wave travel around a distance at least equal to 2.82 feet, it will take it at least one 400th of a second to get to the back of the cone. But we calculated that this is the time required for one change in pressure. Therefore, by the time the pressure wave from the front gets to the back, the cone has changed its direction of motion and the back is now producing a pressure wave, so that the two waves do not neutralize each other but actually reinforce each other, making the sound appear somewhat louder.

It is evident then that the purpose of the baffle is simply to *delay* the meeting of the front and back sound waves by artificially increasing the distance of the sound-wave-path from the front to the back of the cone. It is evident, that to fully reproduce any note, the shortest length of the sound-wave path from the front to the back of the cone (distance L in Fig. 349) must be made at least equal to the distance the sound travels during the time it takes to complete one quarter of a cycle of that note (see (B) of Fig. 351), or during the time it takes the cone to move from the center position to the extreme position in either direction. The distance in feet, which the sound travels during one complete cycle is defined as the *wavelength* of the sound and is equal to the velocity of sound (1130 feet per second) divided by the frequency in cycles per second. Therefore, the minimum length a baffle should be, to permit full reproduction of any frequency, can be easily calculated by the simple rule, that the baffle length in feet is equal to one-quarter the wavelength of the note to be reproduced. That is,

$$\text{Baffle length} = \tfrac{1}{4}\ \text{W. L.} = \tfrac{1}{4} \times \frac{1130}{\text{Frequency}} = \frac{282}{\text{Frequency}}$$

A baffle to permit full reproduction of tones as low as 30 cycles must be at least

$$\frac{282}{30} = 9.4 \text{ feet in effective length (L)}$$

Referring to Fig. 8, the frequency ranges of the various musical instruments may be seen, and the lowest note which any instrument can produce may be ascertained. To reproduce the lower notes with a free-edge type of cone speaker, a baffle must be used. The graph of Fig. 352 shows the minimum size of baffle required for complete reproduction of

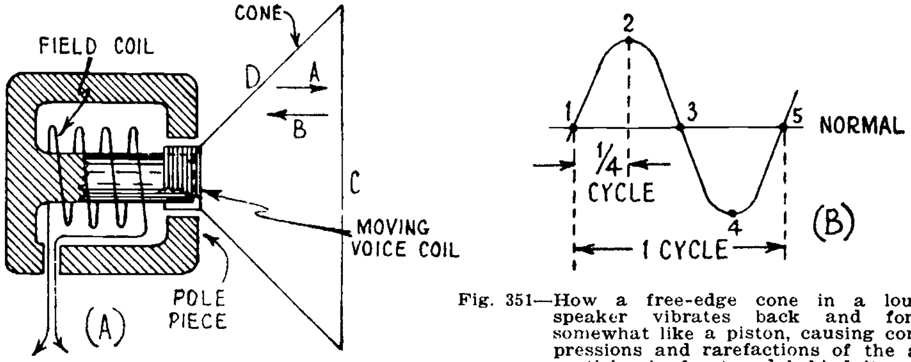


Fig. 351—How a free-edge cone in a loud-speaker vibrates back and forth somewhat like a piston, causing compressions and rarefactions of the air particles in front and behind it.

the various frequencies. These values were calculated by the above formula. The bafflle size is given in inches, for convenience. This is obtained by multiplying the values obtained by the above formula by 12. At the top, the lowest frequencies of the various musical instruments are noted. This chart can be used to determine the size of baffle required for full reproduction of the lowest-frequency note of any musical instrument

A study of Fig. 352 shows that the required length of the baffle air path decreases as the frequency goes up. At 2000 cycles for example, the air path need be only 1.63 inches. Since the distance from the front to a point near the center of the back of an ordinary 10-inch diameter cone is about five inches, it follows that the cone itself is an effective baffle at the high frequencies. Therefore the baffle is only important at the low frequencies and its size is determined by the *lowest* frequency to be reproduced.

It is difficult to define exactly what the baffle length is, since, strictly speaking, all parts of the cone are helping to produce sound. Some authorities define the baffle length as the distance from a point in the center of the front of the cone to a point in the center of the rear. This length would be slightly longer than that taken throughout this discussion. However, as the baffle lengths are usually worked out for low

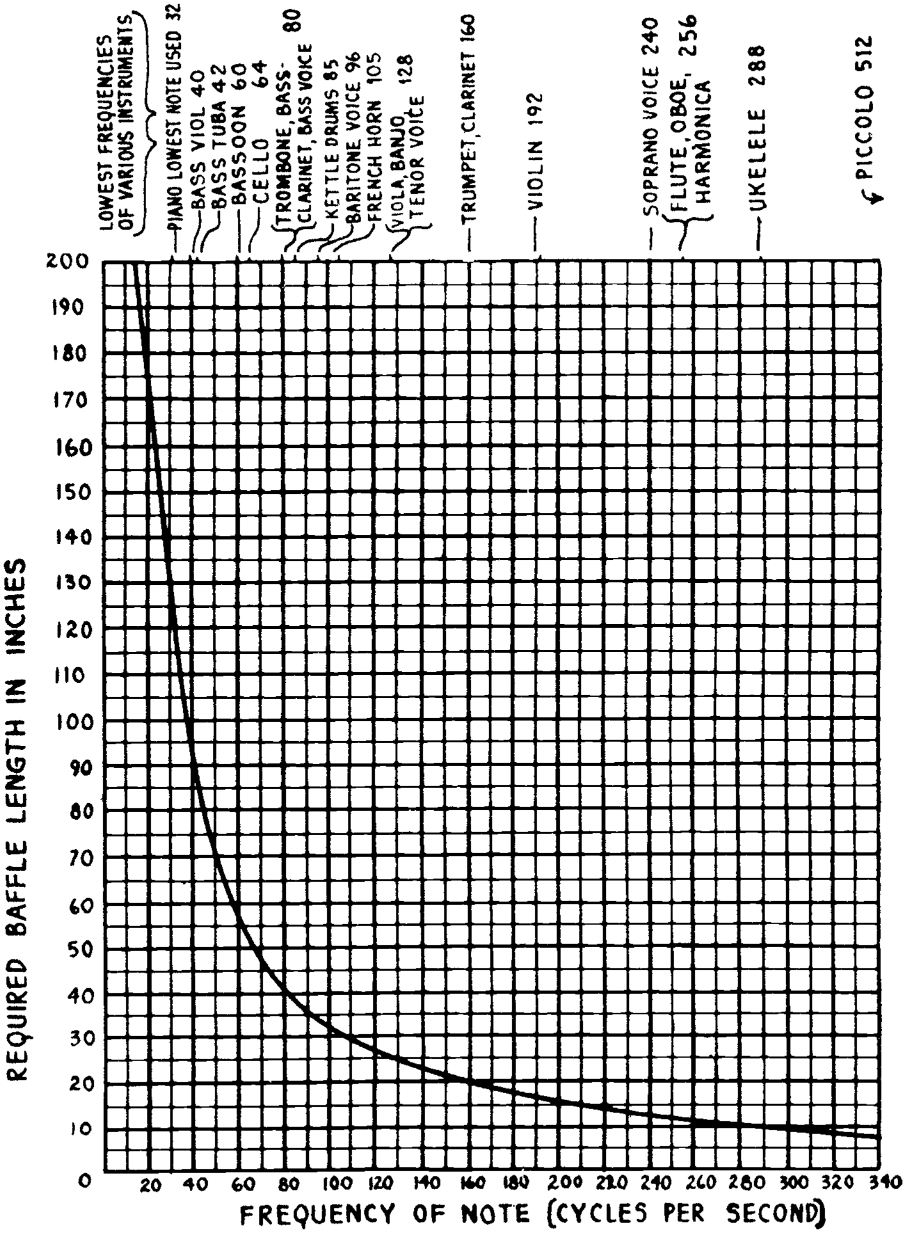


Fig. 352—By means of this graph, the baffle length required for the full reproduction of low-frequency notes of various frequencies by a free edge cone, may quickly be determined.

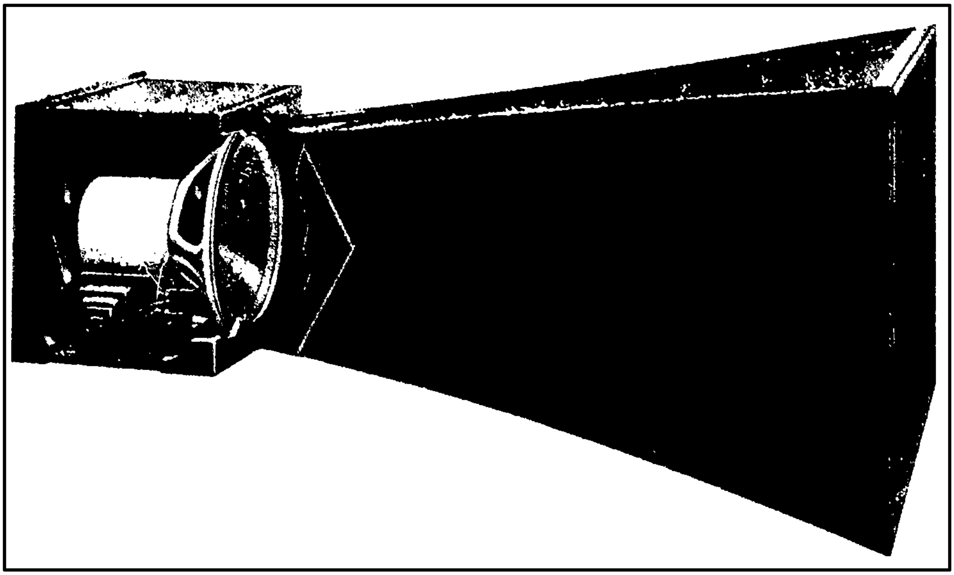
frequencies, and these lengths work out in most cases to 36 inches or more (see Fig. 352), a difference of an inch or two in considering the baffle length does not make much difference in the result.

As it makes no difference how the length of air path for the baffle is obtained, baffles take many forms in actual practice. Flat baffles are probably the best types as they are not usually troubled by resonance effects, but their large size and ungainly appearance hardly make them suitable for use in homes. (B) of Fig. 349 shows a straight square baffle in position on a cone. In this type, the length of each side of the baffle is made equal to the length given in the chart of Fig. 352, since the total effective baffle length is about equal to twice the length of half a side.

(C) of Fig. 349 shows a box-shaped baffle which is more compact. This type is used extensively in homes because of its compactness and better appearance. The box type baffle is sometimes made up into artistic looking cabinets which blend in with the rest of the furniture in a room. The back of the box or cabinet-type baffle should be left open, to allow free circulation of the air. If it is closed up or restricted, resonance effects will be set up in the cabinet, resulting in better reproduction of some frequencies than others, and resulting in "barrel tone". The response of a cabinet-type speaker can often be improved by lining it with some non-resonant material such as thick felt, Celotex, etc. When a speaker is mounted in a console cabinet, the front, sides, top and bottom of the cabinet act as a box-type baffle, since sound waves issuing from the front of the speaker diaphragm must travel all the way around the sides of the cabinet to the back, and then forward inside the cabinet to the rear of the cone, in order to cause any neutralizing action. As this distance is quite long in most cabinets, good baffling is secured. It is well to point out here however, that the speakers in midget-type receivers are unable to reproduce the low notes fully, on account of the insufficient baffling which the small midget cabinet presents. While many of them appear to have a deep tone, this is simply because of the fact that the high audio frequencies have purposely been suppressed by the particular circuit design employed.

When a dynamic unit is operated in the same cabinet with the radio receiver, the entire system may break into continuous oscillation due to the mechanical vibrations being set up in the elements of the detector tube by the sound vibrations. The remedy for this is to wrap the detector tube in thick felt, or weigh it down with a heavy metal cap to damp the vibrations. The back of the cabinet should be left open, to reduce acoustic resonance effects in the cabinet itself. When mounting a cone-type speaker on a baffleboard, the felt ring (see F in the speaker at the left of Fig. 346) on the front of the cone housing should be pressed evenly and tightly against the baffle. A hole equal to the inside diameter of the felt ring should be cut in the baffle of course. Fig. 353 shows a horn type of baffle attached to an electro-dynamic speaker with a cone diaphragm. The baffle is cut away to show the speaker inside. Baffles of this kind are used in auditoriums, theatres, and outdoor public-address work. They not only act as baffles, but also make the speaker directional, so as to direct the sound waves to the audience. Notice that the top side is practically straight. This tends to keep the sound off the ceiling. The bottom flares down, and the sides flare out toward the opening. A unit of this kind will take care of a 400 seat house, if it is not over 25 or 30 feet wide. Otherwise two or more such units may be used.

It must be evident that baffles do not act as "sounding boards" as many people think. They are not supposed to vibrate or emit sound waves themselves at all, although sometimes baffle resonance effects are



Courtesy Wright De-Coster Inc.

Fig. 353—A dynamic speaker mounted in a 48-inch horn baffle for public-address and sound picture work. It is 30x21½ inches at the opening. Speakers of this type may be mounted outdoors if required.

designed to accentuate the response of some frequencies which the speaker itself is deficient in. Baffleboards should be made rigid and usually of soft wood at least three-quarters of an inch thick. Baffleboards made of Celotex, at least one inch thick, are also very good, as this is a non-resonant material, but in some cases the absorption reduces the high-frequency response. For very low-frequency reproduction, the wall or ceiling of a room may be used as a baffle by cutting a circular hole in it large enough for the cone to fit through, but usually the volume of sound is reduced by this since the sound waves produced at the rear of the speaker are not heard at the front and vice versa.

If a baffle is made smaller than the size required to reproduce a certain frequency, it does not mean that this frequency will be completely suppressed—it simply means that notes of this frequency will be partially suppressed, the extent of this suppression being determined by how much smaller the baffle is than the correct size. If notes below the actual "cut-off" frequency of the baffle are impressed on the loud speaker, the resulting tone is made up mostly of the higher harmonics of these notes. Thus, while a baffle may not be large enough to permit of reproduction of a 60 cycle note, it may be large enough to permit of reproduction of the second harmonic frequency of 120 cycles. Thus this note would be partially reproduced, but, of course, not in its true tone. This accounts for the partial low-note reproduction effect produced by speakers having small baffles. Of course, it is assumed that the receiving set passes the low frequency signals to the speaker driving unit, and that it is capable of operating the cone at these frequencies. For instance, it would be foolish to design a 56-inch baffle to permit reproduction of 60 cycle notes, if the set and speaker combination was unable to reproduce any frequencies below 200 cycles. In this case a 17 inch baffle would suffice, and the reproduction with it would be just as good on this particular set and speaker as it would with the 56 inch baffle. With ordinary receiving equipment it is not necessary to use baffles larger than about 48 inches, since these give a cut-off frequency of about 70 cycles. Very few medium-priced commercial receivers really produced sound waves of as low a frequency as this.

Magnetic speakers of the free-edge cone type are also ideally suited for mounting inside of a radio cabinet and are usually cheaper to construct than the fixed-edge type. The construction makes a short driving rod possible and this helps to reduce distortion. They provide practically uniform frequency-response over a wide band of frequencies.

468. Permanent-magnet moving-coil speakers: In some applications of loud speakers, the supply of current for the field coil of the electromagnet of the type of moving-coil speakers already described, is not readily and conveniently available. Instances of this occur in battery-operated receivers used in the home, in receivers used in automobiles and in hotel and apartment house centralized radio systems, etc. For cases of this kind, a special form of moving-coil speaker may be used. All of the advantages of the moving coil type speaker are retained, but a permanent magnet is used instead of the electromagnet. Several permanent magnet arrangements have been developed for such speakers, one of which is shown at (A) of Fig. 354. It consists of four outside arms having similar poles, which join a common flat pole-piece at the top. This forms one pole. The pole piece surrounds the central core-leg with a small air-gap in between, in which the moving coil is suspended as shown at (B). The central core-leg forms the other pole, and the flux in the air-gap is almost radial. The relation of the magnet, center core, pole piece and moving coil are shown in the sectional view at (B). Magnets for speakers of this type are usually made of steel containing about 9 to 15 per cent cobalt, (see Article 82). The object to be attained in the design is to produce a very strong permanent magnet having low magnetic leakage, and of reasonably small dimensions, at a reasonable price. The moving coil and cone design are practically similar to those of the types of moving-coil speakers already described. While it is not possible to make these permanent magnets as strong as the electromagnets which are used on the ordinary moving-coil speakers, they are made strong enough to produce satisfactory

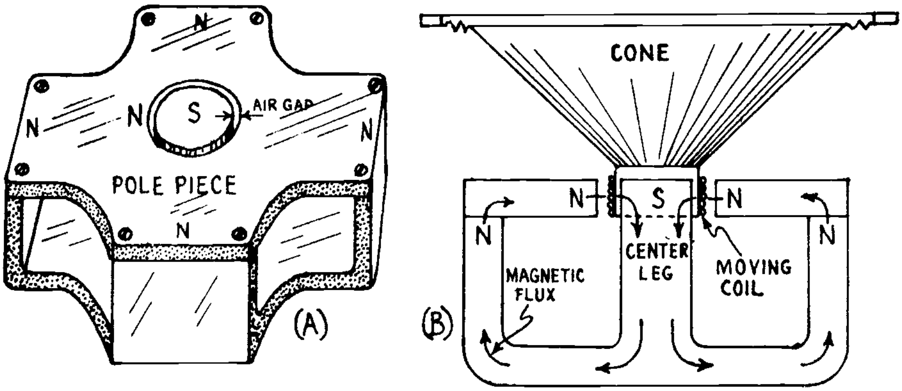


Fig. 354—(A) Permanent magnet arrangement for moving-coil type speaker.
(B) Arrangement of permanent magnet, pole piece, moving-coil, and cone in a permanent magnet moving-coil speaker.

speakers of this type. When the magnet in a speaker of this type becomes weak due to age, the volume decreases greatly and it must be remagnetized (see Article 93).

469. Cone and horn speakers: We have considered the use of a light-weight cone-shaped diaphragm operated by one of the forms of driving units which we have studied. The cone is used to set a large volume of air in motion. The use of a horn for this purpose has also been common for many years, but the proper design of the horn was neglected for some time. In the horn type of speaker, a diaphragm, usually of rather small size, may be driven by any one of the forms of driving units just described, and placed at the small end or *throat* of the horn. The function of the horn seems to be rather generally misunderstood. Possibly the following simple experiment will illustrate the effect of the horn convincingly.

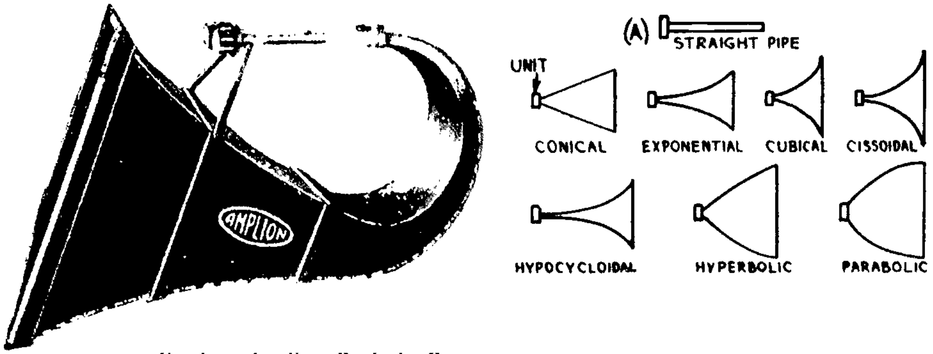
Experiment: Remove the driving unit from a horn speaker and connect it to a radio receiver or phonograph amplifier which is operating at medium volume. The diaphragm in the unit will vibrate in accordance with the signal impulses but since there is very little restraining force on it, it will rattle. Also since it is small, it does not act on very much air and consequently the sound produced is very weak.

Now attach the horn to the unit. The rattling ceases because the diaphragm is now loaded since it pushes against the column of air in the horn, and the volume increases because a larger volume of air is being set in motion.

The horn adds nothing to the original intensity of the sound waves; all of the sound waves which are to come out of any kind of horn must be produced by the vibration of the diaphragm at the small end of the horn. However, if this diaphragm is allowed to vibrate freely in the air, without any kind of horn in front of it, it creates relatively little sound. The reason is that the diaphragm does not adequately "couple" with the air, that is, the area of the diaphragm is so small that only a very small amount of air is set into vibration by it. The sound waves which proceed outward from this center of disturbance are relatively feeble ones. The advantage of the *cone* loud speaker over a simple vibrating diaphragm, (like the diaphragm of a telephone), is that the cone possesses a much larger vibrating surface. Accordingly, it sets much greater masses of air into vibration. This produces and discharges far more intense waves of sound.

The advantage of any form of *horn*, comes from a similar ability to set more air into vibration in correspondence with the vibration of the diaphragm. The diaphragm at the inner end of the cone of air contained inside the horn, sets this entire cone of air into vibrations like those of the diaphragm itself. In effect, the radiating surface from which sound waves are emitted becomes, not the relatively small surface of the diaphragm itself, but the entire front surface of the cone of air contained within the horn. The horn causes the air pressure per square inch over the surface of the diaphragm to be many times greater than if the diaphragm were to vibrate in free space. It therefore enables it to transfer its energy more efficiently to the atmosphere by means of the column of air inside the horn. The horn really makes the diaphragm work harder!

470. Possible shapes of horns: Horns can be made in many different shapes and sizes as shown at the right of Fig. 355, but it has been



Courtesy Amplion Products Corp.

Fig. 355—Left: A 12-foot air column horn for public address and sound picture work. It has two moving-coil driving units with a total power capacity of 50 watts. The bell opening is 45 inches square.
Right: Various horn shapes which conform to well-known mathematical equations.

proved experimentally that certain shapes are most suitable as they produce best results in practice.

Straight pipes of uniform diameter are unsuited for loud speaker horns because they are efficient resonators only within certain narrow frequency limits corresponding to the fundamental tone, and may increase the sound energy in these narrow frequency bands thousands of times. Outside of these narrow frequency-bands, no increase in sound energy is brought about. Horns of various shapes have been designed and any one of these is better than a straight pipe for a loud speaker, because horns have less pronounced resonant properties than pipes.

The straight pipe (A), and horns of various possible shapes are shown in Fig. 355. The manner in which the cross-section area increases as we proceed from the *throat* to the *mouth* or *bell* of these horns, is determined by well known mathematical equations. The results obtained with horns of these shapes differ greatly. The shape which seems to give best performance for practical loud speaker work is that which follows the "exponential law", or a slight modification of it. Of all the horns having a given size (i.e., same length and terminal areas) the exponentially shaped horn is the most uniform sound radiator over the required range of audio frequencies. Since this is the best, the other shapes will not be considered here.

471. Exponential horns: A true *exponential*-shaped horn is one whose cross-section area doubles for equal increases in length, that is, the area of the horn varies as an exponent of the length. That is all there is to the exponential law. The law says nothing about how long the intervals of length should be—they may be any value we please. For instance we may have a horn whose throat area is say one square inch. The horn may be shaped so that its cross-section area doubles for every three inches of length, for every six inches of length or for every five feet of length, etc. Each of these would be a true exponential horn. If the area doubled for every foot of length, the area would be 2 square inches at 1 foot from the throat, 4 square inches at 2 feet, 8 square inches at 3 feet, 16 square inches at 4 feet, etc. The amount by which the horn increases in cross-section area for each unit of its length is called its *expansion ratio.* This may be varied, making long narrow horns of slow expansion, or short wide horns of rapid expansion, all of them still retaining the essential exponential principle; the principle by which the cross-section area of the horn increases by the factor two for each equal increase in length. This exponential rate of increase is sometimes called the *law* of *organic growth,* as it is the same rate at which most plants, trees and other organic bodies increase in size. The shell of a snail for instance, is an example of a true exponential horn.

As may be shown mathematically from its detailed theory, the advantage of the exponential horn, is that it permits the preliminary communication of the sound to the internal cone of air, and thence to the general air outside, to take place with the minimum of interference and resistance. In technical terminology, the exponential horn "loads" the diaphragm more completely and with less distortion for a wide band of frequencies, than can be accomplished with other existing shapes of horns. The increase in cross-section area is such, that as the sound wave disturbance travels from the diaphragm at the throat of the horn out to the bell, it expands uniformly over a wider and wider area without any sudden changes or restrictions. Also, the bell of the horn is of such shape that the sound wave disturbance communicates to the outside air smoothly at the point where it leaves the horn. A typical commercial form of folded exponential horn used in public-address work is shown at the left of Fig. 355. Other forms are shown in Fig. 356.

472. Cut-off frequency: When correctly designed, an exponential horn radiates the sound waves uniformly over a wide range of frequencies. It reproduces these frequencies uniformly down to a certain definite frequency called the *lower cut-off* frequency, below which very little or no radiation takes place. The low frequency cut-off is determined by the rate of expansion of the horn. A horn which doubles in area for every foot of length will reproduce down to 64 cycles per second; one expanding half as rapidly (area doubles for every two feet of length) will respond down to 32 cycles; one expanding twice as rapidly (area doubles for every 6 inches of length) will respond down to 128 cycles per second, etc. The greater the rate of taper, the higher is the frequency of cut-off.

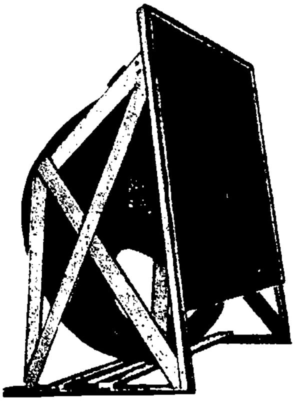
473. Considerations in horn design: The length of the horn is determined by several factors. First, a properly designed horn should be free from noticeable resonance. To prevent this, the mouth of the horn should be made large enough to transmit the sounds coming from it to the surrounding atmosphere without any great amount of restriction, since this would cause a back-pressure to be developed which would oppose the sound waves. It has been found that if the diameter of the mouth is made comparable to one-quarter of the wavelength corresponding to the cut-off frequency of the horn (as determined by its rate of expansion), the resonance in the horn will be negligible. The wavelength of sound in feet is determined by dividing the velocity of sound in feet per second (1130) by the frequency. So the horn should be extended until the mouth has a diameter about one-quarter the wavelength corresponding to the cut-off frequency. If the horn section is approximately square, the area of the mouth should be as large as that of the circle having this diameter. For instance, following out this reasoning a horn whose cut-off frequency is 64 cycles, (corresponding to a wavelength of 1130 divided by 64, or 17.7 feet), should have a mouth about 17.7 divided by 4, or 4.4 feet in diameter if circular; or about four feet by four feet if square.

The diameter of the small end, or throat of the horn, depends on several factors. Since the diaphragm really acts like a piston, sending waves of compression and rarefaction up and down the air column, if the area of the throat is small compared to the area of the diaphragm, practically all of the movement of the layers of air molecules near the surface of the diaphragm will cause a larger motion of the molecules through the throat. However, if the throat is made too small, compared to that of the diaphragm, a throttling effect will result due to the restriction of the air waves. If it is made too large, the diaphragm is not loaded properly. Also, in order to use a slow rate of expansion of the horn to obtain low cut-off frequency, the initial opening should be large or else the horn must be made too long to be practical, since it should be made long enough so that the diameter of the opening of the mouth or bell is at least equal to ¼ the wavelength of the lower cut-off frequency. A compromise must therefore be made between these factors in the design of the horn. A special form of throat design which eliminates many of the troubles which usually occur at this point will be described in Article 476.

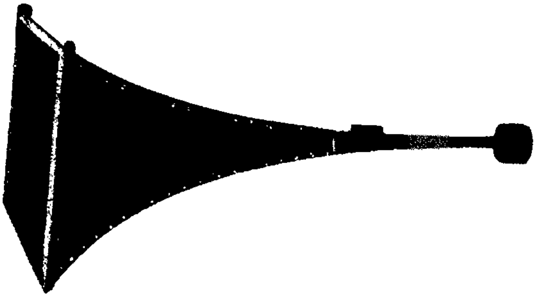
474. Design of an exponential horn: As an example of how exponential horns may be designed, let it be required to design one having a cut-off frequency of 32 cycles and to be used with a driving unit having a ⅝ inch diameter opening. The design procedure follows:

If the cut-off frequency is to be 32 cycles, the exponential horn must double in cross-section area every two feet. The cut-off wavelength will be 1130 divided by 32, or about 35 feet. The diameter of the mouth or bell should then be 35 divided by 4, or about 8.75 feet.

The area of the throat is equal to the square of the diameter times 0.7854, or 0.314 square inches. As the area doubles for every two feet, at a point two feet from the throat the area is $0.314 \times 2 = 0.628$ square inches, at six feet it is $1.256 \times 2 = 2.512$



Courtesy Racon Elect. Co.



Courtesy Amplion Products Corp.

Fig. 356—Left: 14 foot coiled exponential horn used for reproduction of speech and music in theatres.
Right: A typical 6 foot exponential trumpet or horn used for reproduction of speech only, in public address systems. It has a bell 28 inches square.

square inches, etc. This is carried out until such length when size of the mouth or bell, determined by the cut-off frequency is reached. This figure for the bell size must be converted into area. Actually, the length of this horn would have to be about 28.5 feet. It is evident that such a "true exponential horn" would be large and unwieldly for home use. In practice, so-called exponential horns built for home use are not true exponential horns but are about seven or ten percent exponential. That is, each succeeding area is not double that of the previous section but is about seven per cent of this double value.

The results obtained with such horns are not as good as with those of the true exponential type, but the sacrifice in operating quality must be made on account of the small allowable size of the horns if they are to be used in homes. This is probably the most important reason why horn speakers are not used extensively in home radio receivers—simply because speakers of this type designed to have a low cut-off frequency, and give good reproduction of both speech and music, are necessarily too large and unwieldly. However, they are used extensively in connection with sound pictures, and public-address and announcing systems, where their large size is not particularly a disadvantage, but their comparatively high efficiency and directional properties are important. An exponential horn of large size used in theatres and public-address systems is shown at the left of Fig. 356. Horns of this type are capable of splendid reproduction of speech and music. An exponential trumpet for the reproduction of speech only, typical of the type used in public address systems, is shown at the right. Since this is not called upon to reproduce frequencies as low as those which are encountered in music, its cut-off frequency may be higher, and its length is therefore much shorter.

475. Material and shape of the horn: The material of which the horn is made, is important. Although a horn may be well designed and constructed to correct size, total length, rate of expansion, etc., it may still fail to provide good reproduction, simply because of resonance effects in the material used for it.

The material used should have no marked resonant frequency, unless this resonant frequency is very low. One manufacturer uses a special construction of fleeced underwear cloth moulded together to correct shape and impregnated by a special binder compound. Another uses a special composition consisting of wood sawdust held by a binding compound and moulded to correct shape. Others are made of papier-maché. Large horns and trumpets are usually made of selected wood, properly treated. The inside surface of the horn should be smooth, to prevent the formation of eddies due to the moving air.

It is evident from the calculations in Art. 474, that the old types of short horns one or two feet in length, cannot possibly reproduce the low notes in music. The best they can do is reproduce the higher harmonics of these notes, and the ear responding to these makes it appear as though some of the low notes were being heard. Exponential horns which do reproduce the low notes must necessarily be long. In order to make these speakers more compact than they would be if straight, they are constructed in coiled or folded form, and even divided into parts. This does not harm the reproduction in any way, provided the bends are not too sharp and the cross-section areas follow the design equations chosen. A straight exponential horn is shown at (A) of Fig. 357. The cross-section area doubles for each equal increase of distance along the length, as represented by the dotted lines. This corresponds to the horn shown at the right of Fig. 356. At (B), the same horn is shown coiled or folded up to make it compact. This corresponds to the horn shown at the left of Fig. 356. The horn may also be folded as shown at the left of Fig. 355 A compact type of folded exponential horn developed by the engineers of the Bell Telephone Laboratories is shown at (C) of Fig. 357. The path of the sound waves is shown by the arrows, the driving unit and diaphragm being placed at the opening in the center of the rear side. The mouth of the speaker is toward the right in the illustration. Notice that the sound wave path divides into two identical folded paths which both terminate at adjacent sides at the mouth of the speaker. Horns of this general type are employed in the "orthophonic" phonograph, in fact, exponential horns are sometimes called *orthophonic horns*. Large horns, of special folded construction to make them very flat, are used in moving picture theatres in connection with the sound accompaniment. They are mounted directly on the back of the special motion-picture screen and are raised and lowered with it, as shown at the left of Fig. 495.

476. Moving-coil horn units: The balanced type moving-iron form of driving unit provided with a suitable diaphragm, is used on many horns employed in public-address systems, simply because it eliminates running the two extra wires required for the field supply current. This, of course is an important advantage where a network of speakers is mounted over a wide area on poles or buildings, etc. However, where a large

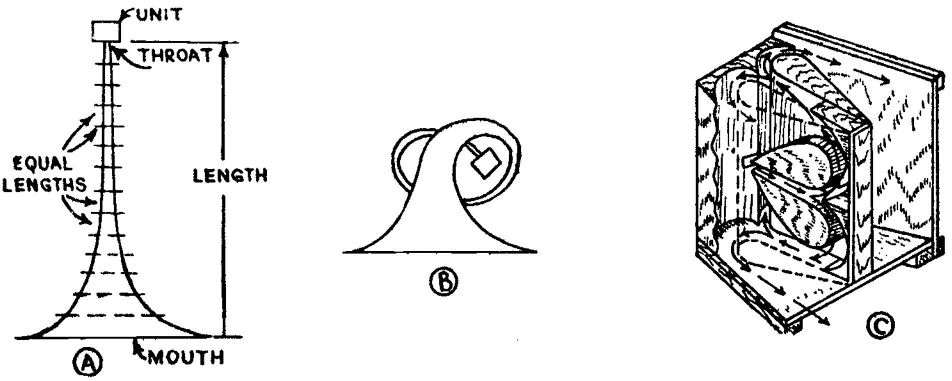


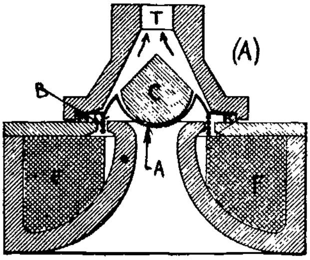
Fig. 357—A given horn may be made straight, as at (A); coiled as at (B); or folded as at (C). Its characteristics will be the same in each case, provided the bends are gradual and not sharp.

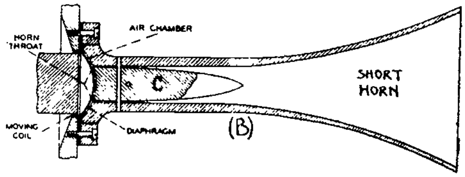
volume of sound is to be produced, the moving-coil type of speaker unit is usually employed, to prevent rattling. This is especially true in speakers used in theatres and halls, where a large volume of sound must be produced and the driving units must handle a considerable amount of power. A cross-section view of a very efficient form of moving-coil driving unit developed by the Bell Telephone Laboratories for this purpose, is shown at (A) of Fig. 358.

The field magnet F, is an electromagnet of efficient design providing a very strong field in the air gap in which the moving coil B, is suspended. This coil consists of a single layer of aluminum ribbon .015 inch wide and .002 inch thick, *wound on edge*, the turns being insulated and held together by a thin film of insulating lacquer. The impedance of the coil is practically a pure resistance, and nearly constant at various frequencies. The coil is attached to a duraluminum diaphragm A, which is of unusual shape.

One of the things which may limit the sound-radiating efficiency of the horn type of loud speaker is the interference between the air waves as they pass through the chamber between the diaphragm and the throat of the horn. In this speaker, the air chamber is so constructed, that no serious phase differences can occur within the useful range of frequencies. The stationary conical block C, is responsible for this.

Another factor, is the desirability of having the diaphragm vibrate to and fro as nearly like a rigid plunger as possible. An ordinary flat piece of metal clamped around a circular edge assumes a domed shape when vibrating at low frequencies. The diaphragm can be made to vibrate with its central portion essentially unflexed by adopting a shape which makes it less rigid near the edge, and more rigid toward the center, and then applying the force uniformly around the outside of the central portion.



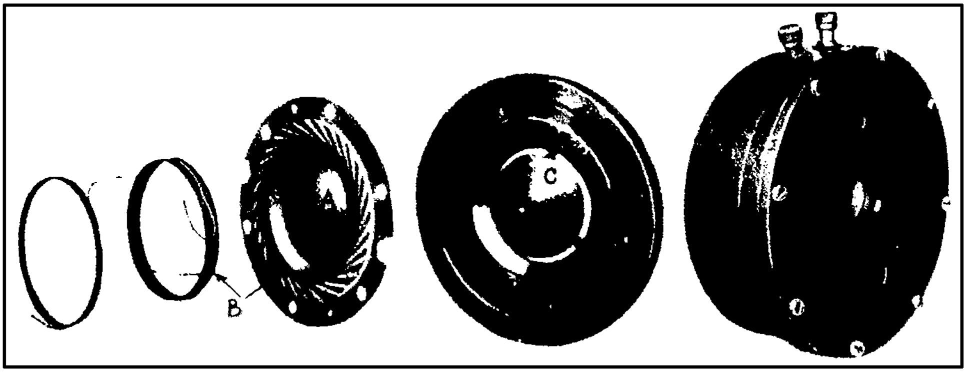


Courtesy Bell Telephone Laboratories

Fig. 358—(A) Sectional view of the moving coil driving unit shown in Fig. 359. (B) Sectional view of special short-horn speaker designed for high audio-frequency reproduction only. This speaker is shown in Fig. 360.

These things are accomplished by the shape of diaphragm illustrated by A. It is made of a single piece of sheet aluminum alloy 0.002 inch thick. To this is rigidly fastened the driving coil B of circular form. In the assembled receiver, it moves up and down in the annular space between the ring-shaped pole pieces of the electromagnet. Between the coil and the clamped edge, the diaphragm is corrugated tangentially to prevent resonance.

The damping action of the thin air chamber between the conical block C, and the diaphragm, together with the loading effect of the horn, produces a constant load on the diaphragm, and a very flat frequency characteristic. The tapered opening under the diaphragm is to avoid resonance effects at its rear. The parts of the unit are



Courtesy Bell Telephone Laboratories

Fig. 359—Details of the construction of the high-efficiency moving-coil horn speaker unit shown at (A) of Fig. 358. The driving coil B, is attached to the diaphragm A which fits under the conical piece C. The tangential corrugations on the disc are plainly visible.

shown unassembled in Fig. 359, each part being labeled with a letter to correspond to that in Fig. 358. The cone shaped diaphragm A, and the tangential corrugations are plainly visible, as is also the conical block C. The complete unit is shown in its case, at the right.

An outstanding feature of this special form of driving unit is the high efficiency with which it converts the electrical power fed to it, into that of sound. In the commercial models, efficiencies as high as 30 per cent are realized—as compared with about 5 per cent for the usual cone type moving-coil speaker. When it is recalled that the resulting sound intensities are only a few decibels lower than those to be obtained at one hundred per cent efficiency, it will be understood that little is to be gained from any further increase in efficiency, except insofar as reduction in the percentage of loss enables greater power to be handled without exceeding a safe operating temperature. When coupled to a suitable horn, *fifteen watts* of sound power can be radiated. It reproduces frequencies from 60 to 6,000 cycles per second without distortion, and reproduces down to 40 cycles and up to 8,000 cycles with distortion so slight that it is almost impossible to detect it.

477. Special high-frequency loud speaker: The frequency range above 5,000 cycles contributes greatly to the naturalness of reproduction of certain sounds. Many instruments of the orchestra, such as

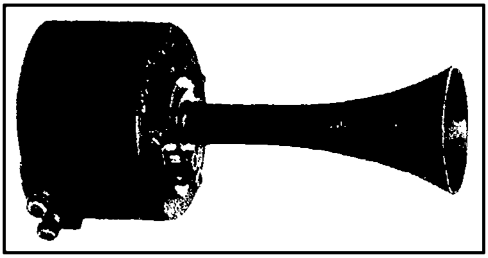


Fig. 360—A special form of moving-coil loud speaker designed for the efficient reproduction of only the high audible frequencies from 6,500 to 12,000 cycles per second. A section view is shown at (B) of Fig. 358. Notice the short horn employed.

High-frequency horns of this general type are commonly called "tweeters" because they produce the very high-frequency sounds.

Courtesy Bell Telephone Laboratories

the violin, flute, snare drum, clarinet, cymbals, as well as voices (particularly female voices), have harmonics above 5,000 cycles which if suppressed, cause an appreciable change in the character of the sounds. This alteration in some cases is not especially objectionable, but in the reproduction of many common sounds of an impulsive character such as result from hand clapping, footsteps, tearing or rustling of paper, or the jingling of keys or coins, the suppression of the high frequencies may cause the reproduced sounds to bear but little resemblance to the original. Extension of the frequency range of the reproducing system to include the very high frequencies results in a marked improvement in the reproduction of these impulsive sounds and in the naturalness, color, and brilliance of reproduced speech and music.

Since ordinary forms of loud speakers are inefficient for reproduction of these audio-frequency sounds, due to the excessive mass and stiffness of the vibrating structure, etc., a special form of speaker is required for their reproduction. A special form of speaker by which it has been possible to obtain efficient radiation of the high frequencies up to about 12,000 cycles is shown at (B) of Fig. 358. This speaker is intended as an addition to either a usual cone or horn type speaker to extend the range of efficient performance to about 12,000 cycles. Its *lower* cut-off point occurs at about 6,500 cycles. This corresponds to the *high* cut-off point of most speakers. The removal of the necessity for low frequency reproduction with this speaker permits a more delicate mechanical structure having less mass, and makes it possible to extend the high frequency cut-off.

The diagram is a sectional view showing on an exaggerated scale the diaphragm, air chamber, and horn construction. The diaphragm is of .005 cm. duralumin, with a spherically embossed section at the center 2.5 cm. in diameter to provide rigidity; the edge outside this formed center is plane. A self-supporting moving coil of edgewise wound aluminum ribbon is attached directly to the diaphragm at the junction of the embossed and plane sections. A shoulder on the horn clamps the plane section of the diaphragm on a diameter, to increase the edge stiffness. The mass of the diaphragm plus the moving coil (within the clamped surface) is only about .16 gram. Since the frequencies to be reproduced are high, the horn has a mouth only two inches in diameter. The angle of the flare is 90 degrees. The efficiency of the unit is about 20 per cent.

Satisfactory results have been obtained by using this loud speaker in conjunction with both baffle and horn type loud speakers of the ordinary types which reproduce up to about 6,000 cycles. It may be mounted with the horn mouth extending through a baffle board adjacent to one or more baffle speakers or it may be suspended in the mouth of a large horn. The combination is most suitably coupled electrically by means of a network that causes the electrical power within a pre-determined frequency range to be delivered to the particular loud speaker that is efficient in that frequency range. This avoids a loss in efficiency and at the same time prevents rattling or damage to the high-frequency loud speaker which might be caused by large amounts of power being fed to it at low frequencies.

478. The condenser-type loud speaker: The *condenser* or *electrostatic type* of loud speaker has many worthwhile inherent advantages over the magnetic forms of speakers, although it has not been entirely successful commercially in the United States. It operates on the principle of the electrostatic attraction and repulsion of two electrically charged plates in accordance with the well known principle of electrostatics that *like charges repel* and *unlike charges attract.* The speaker itself really forms a large 2-plate condenser. It operates as follows:

When two conductors of electricity are separated in space by an insulator, and a difference of electrical potential is maintained between them they form an electrical capacitor or condenser. If they are both charged positively, they tend to repel each other, if they are both charged negatively they also tend to repel each other; if one is charged positive and the other is negative they attract each other (see Article 13). Suppose these two conductors are large, flat, metallic plates of equal area, separated by a thin film of air as shown at (A) of Fig. 361. If a difference of potential or voltage is applied to these plates, a force will be exerted tending to draw these plates together, and the force will be proportional to the area, A, of one side of one plate; it will be proportional to the square of the voltage between the two plates; and it will be inversely proportional to the square of the distance, D, between them.

From the above it is seen that the greater the voltage the greater the force, the larger the size of the plate the greater the force, and the smaller the distance between the plates the greater the force. If we make one of these plates quite heavy and stationary and the second plate very light and movable as shown in (B), the application of a varying voltage to them will tend to draw the light movable plate to the heavy stationary plate with a force which will increase *as the square of the voltage.* If an alternating voltage (for example the usual 60-cycle 110-volt house current) is applied between the two plates, the movable one will tend to move in and out at double the frequency of the applied voltage which, in this case, would amount to 120 times per second. This result would be obtained since the plates tend to pull together both on the positive and on the negative *halves* of each alternating-voltage cycle. Thus instead of obtaining a 60-cycle tone by virtue of the motion imparted to the surrounding air by the movable plate, we would obtain a 120-cycle tone. This is a perfect instance of complete distortion, since the original tone is absent and is replaced by one of double the frequency, (one octave higher). Suppose that this alternating house current be replaced by the voice current from the output of a broadcast receiver. Then the light movable plate, which we shall henceforth call the diaphragm, would produce a hopelessly distorted sound since it would move in accordance with the *square of the voice voltage* and at *double the voice frequencies.*

479. The polarizing voltage: Let us now see how these difficulties are eliminated in a practical speaker of this type.

Suppose a high direct voltage, say 500 volts, is applied to the plates of our crude condenser speaker. There will be a strong steady attraction between them, due to the charges placed on them by this difference of potential. This is called the *polarizing*

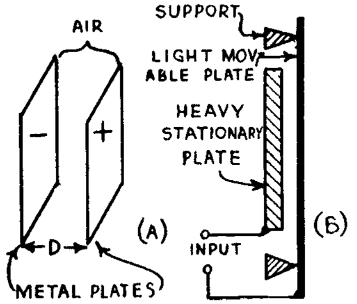
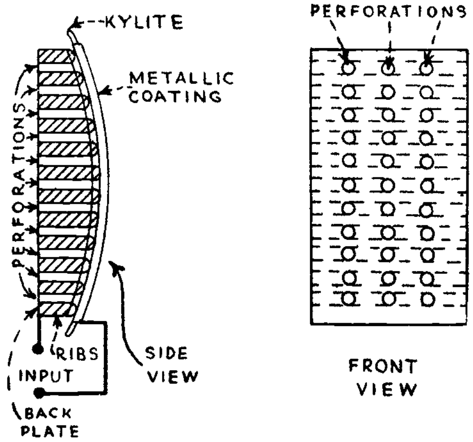


Fig. 361—(A) Formation of simple condenser with 2 plates. (B) Simple electrostatic loud speaker with one rigid plate and one light, movable plate.

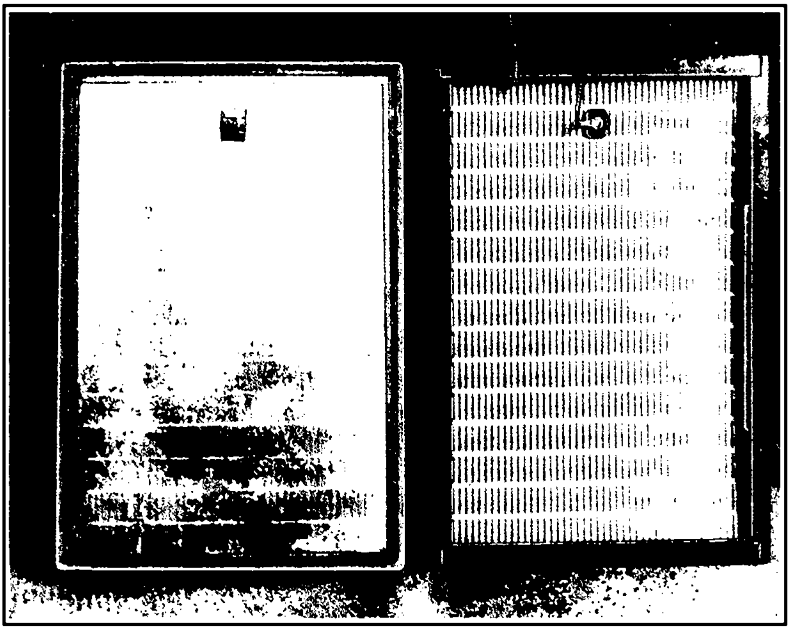


Right: Side and front views showing the construction of the Kyle condenser speaker shown in Fig. 362.

voltage. If now, we superimpose the much weaker a-c signal voltage upon these same plates at the same time, this alternating voltage will tend to increase and decrease slightly the steady direct potential difference which we have already established between the plates. In other words, the force will alternately become a little greater and a little less than the initial force due to the direct voltage, but, since the potential of one plate will always be of one polarity with respect to the other plate, this tendency toward double frequency response is greatly reduced.

It can be shown mathematically, that the motion of the diaphragm under these conditions will be approximately in accordance with, and proportional to the alternating voltage applied between the plates. The smaller the ratio of the alternating voltage to the constant applied direct voltage, the more accurately the diaphragm will follow the alternating voltage variations. It is exceedingly important to note that there will always be a component of the motion which is *twice* the frequency of the original voltage and also that the motion will never be *exactly* directly proportional to the applied alternating voltage. In other words, in this type of loud speaker, as well as in the magnetic and electro-dynamic types, there is always some inherent distortion. A mathematical analysis of the condenser-type loud speaker shows that the greatest response is obtained when the plates are as close as possible together and both the constant direct voltage and the alternating applied voltage are as great as possible.

480. Practical form of condenser-type speaker: The back or stationary plate of the commercial form of condenser-type speaker shown at the right of Fig. 361 and in Fig. 362, is rigidly made of stiff metal, either iron or aluminum. Aluminum is preferable due to its non-corroding properties. The back plate is perforated with slots to prevent compression of the air between the plates. In order to obtain a large force on the moving plate, the dielectric must be as thin as possible, must have a high dielectric constant, and a high breakdown voltage, and must be very flexible. In the speaker shown in Fig. 362, the back plate is covered by a thin, stretched, rubber compound called "Kylite". This is about .005 inch-



Courtesy United Reproducers Corp.

Fig. 362—The simplicity of the construction of a condenser speaker is shown here. The movable foil surface is shown at the left and the rear view showing the rigid aluminum stationary perforated plate is at the right. No coils, magnets, cones, horns, etc. are employed.

es thick, has a dielectric constant of about 3, and has a breakdown voltage of at least 2,000 volts for this thickness. A thin, beaten tinfoil leaf about .0001 inches thick, is cemented on the outside surface of the Kylite sheet. Units about 8 x 12 inches in size are made up in this way. Any number of these units may be connected in parallel, in order to obtain a large surface from which to radiate the sound waves. The capacitance of each section is about .004 mf.

Just as with loud speakers of the free-edge cone type, it is necessary to use a baffle-board or baffle cabinet in order to radiate the lower audio-frequency tones. The same rules apply to the calculation of baffles for this purpose as in the case of cone-type loud speakers, (see Art. 467).

481. Connections of the condenser-type speaker: When a speaker of this type is used, the radio receiver with its associated audio-frequency amplifier must have the same properties as those required for good reproduction with magnetic and electro-dynamic loud speakers, with the exception of the arrangement of the circuit for the output of the last audio-frequency stage, and the provision of a suitable polarizing voltage.

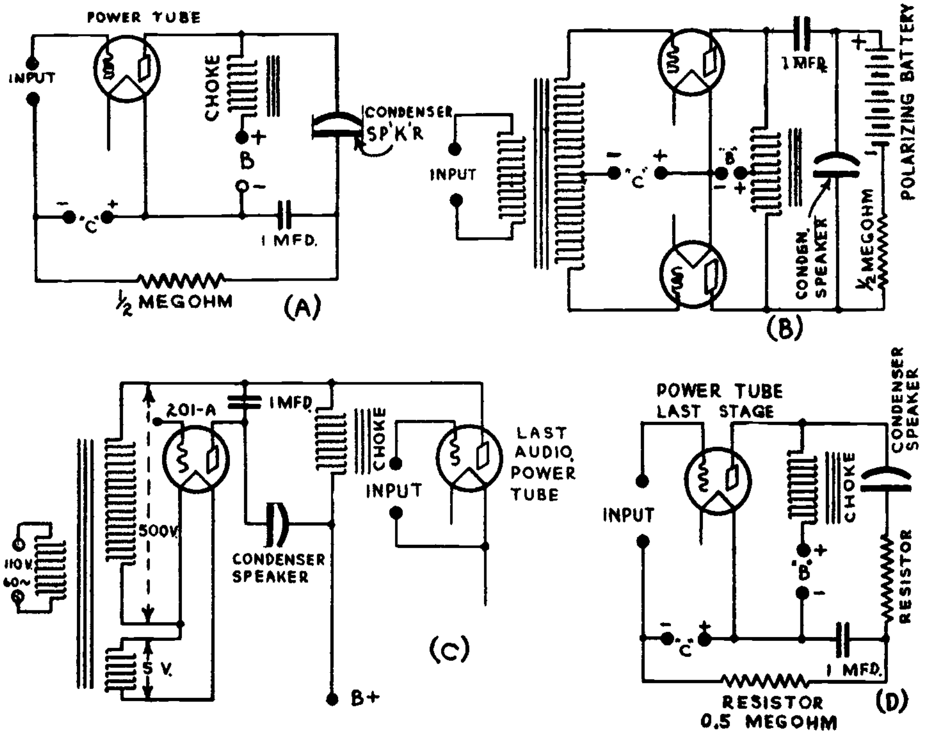


Fig. 363—Several possible circuit arrangements for connecting a condenser type loud speaker to the power amplifier stage of the radio receiver.

Whereas the impedance of the moving-coil type loud speaker is usually very low, averaging approximately 25 ohms at 1000 cycles, and the impedance of the average magnetic-type loud speaker is about 4,000 ohms at 1000 cycles, the impedance of the condenser-type loud speaker is very high; that is, of the order of magnitude of 50,000 ohms at 1000 cycles. It is, therefore, evident that circuit arrangements must be somewhat different in the case of the condenser loud speaker, in order to obtain the proper impedance relationship. If a transformer is used to couple the loud speaker with the output tube of the audio frequency amplifier, it must have a step-up impedance ratio instead of the step-down ratio which is usually employed for other types of loud speakers. The last tube may be impedance-coupled as shown at (A) of Fig. 363. However, if a low plate impedance power tube is used in the last stage, this is a very inefficient method of connection. A method for connecting this loud speaker with a push-pull amplifier is shown at (B). Where the last tube in the set is a power tube, such as the 210 or 250, the "B" voltage may also be used as the polarizing potential for the condenser loud speaker, as shown at (A). Sometimes it is desired to use a separate source of polarizing voltage in which case a step-up transformer, a 201-A type tube, and a 1 mfd. filter condenser are connected as shown at (C), to provide the polarizing voltage. As the polarizing voltage is operative only when connected so as to give a closed d-c path for the biasing charge, a ½ megohm grid leak resistor has been shown in these diagrams where the output circuit contains a condenser. This completes the d-c path, and the 1 mfd. condenser allows the completion of the a-c path through the speaker.

Since the impedance of the condenser-type loud speaker is inversely proportional to the frequency, the division of voltage between the resistance of the last stage tube and the condenser-type loud speaker will change with the frequency; the voltage across the loud speaker being greatest at low frequencies and smallest at high frequencies. This quality can be compensated by proper design of the coupling transformer or by the introduction of resistance in series with the condenser-type loud speaker, as shown at (D). The resistor used must be of the best quality in order that no extraneous noise shall be introduced into the loud speaker circuit. The latter method improves the frequency-response characteristic at the expense of the sensitivity of the loud speaker, hence a compromise must be effected between the two. A value of about 15,000 ohms is recommended for a single section Kyle speaker, about 25,000 ohms for four sections, etc. It is, of course, possible to design the audio-frequency amplifier of the receiving set in such a manner as to have a rising frequency-response characteristic which will compensate the falling frequency-response characteristic of the condenser-type of speaker. In this way, maximum response may be obtained, with a fairly flat overall audio frequency-response characteristic.

482. Limitations and advantages of the condenser-type speaker: One of the first limitations of this type of speaker is that we must apply the direct polarizing voltage which must be very much larger than the alternating signal voltage applied, in order to minimize distortion. Second, the polarizing voltage must not be increased beyond 500 or 600 volts because of the danger of break-down between the fixed plate and the diaphragm. Further, it is not safe nor practical to generate much higher voltages than 600 for such a purpose. Third, the distances between the plates cannot be made indefinitely small for several reasons: (a) because the polarizing voltage would tend to puncture the insulation between the two plates if the distance were too small; (b) there must be sufficient distance so that the diaphragm may move back and forth in order to impart a mechanical wave-motion to the air in front of it; (c) if this distance were too small, the diaphragm might actually strike the stationary plate causing a short-circuit if too great a voice voltage were applied or if resonance existed either in the electrical circuit or in the mechanical construction of the loud speaker. Hence, it is seen that compromises must be effected throughout in the design of this type of loud speaker just as in the case of the magnetic and electro-dynamic loud speakers considered in previous articles.

As a result of these compromises, the sensitivity and efficiency of the condenser loud speaker is, in general, low. Due to the small permissable distance between the diaphragm and the back plate the large amplitudes of motion necessary for the adequate radiation of low tones is difficult to attain in a practical speaker of this kind. This makes it difficult to obtain adequate response at the low frequencies, although the audio amplifier used ahead of the speaker can be designed with over-accentuated low-frequency amplification to compensate for the decreased sensitivity. The problem of developing a suitable dielectric material which has all of the desirable properties mentioned above and yet which does not deteriorate rapidly, has probably been the greatest problem in the successful commercial development of this form of speaker.

One of the main advantages of the condenser-type speaker is its simplicity of construction and very low cost. It has but one movable part and contains no coils or magnetic field construction. It can be made very compact. The diaphragm is attracted as a whole over the greater part of its surface, instead of being actuated at a point as in most moving-iron and moving-coil constructions. This reduces the effects of complicated modes of vibration of the diaphragm with resultant multiple resonances. Another advantage is the practicability of using exceedingly thin non-magnetic diaphragms of great flexibility and low inertia, thereby making possible the reproduction of the higher audio frequencies. Also a large flat surface is usually better adapted to the radiation of sound than is a cone or horn, since directional effects are reduced, and the sound seems to come from all directions rather than from any one place.

483. Comparison of various types of loud speakers: The question of which of the type of speaker described in this chapter is best, does not permit of any single definite answer—for all of them have special operating characteristics which make them particularly desirable for certain classes of work. Ignoring electrical characteristics and confining attention to acoustic ones, there are three essential characteristics of a loud speaker. One of them is the *sensitivity,* that is, the sound intensity which the loud speaker emits for a certain electrical input (or a certain amplitude of vibration) of the diaphragm. The second is the amount of *distortion* which is produced, which means the degree (if any) to which the apparatus changes the acoustic characteristics of the sound vibrations emitted by the diaphragm. The third is what is called the *"cut-off".* This means the points of low frequency and of high frequency below which, and above which, sounds are not produced efficiently.

There is no doubt that among the magnetic class of speakers, the moving coil type is most suitable for normal requirements in modern radio receivers, on account of its ability to handle large signal voltages without rattling. The question of whether a horn or a cone should be used with the coil driving unit, is also one whose answer depends on the particular applications of the speaker.

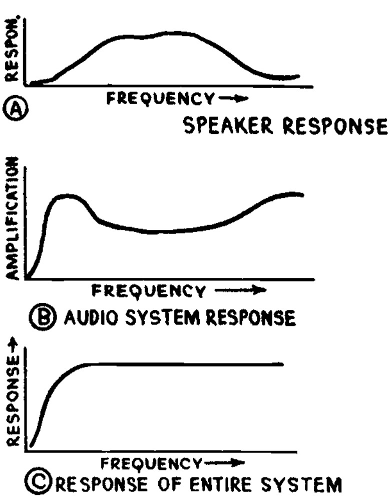
In freedom from distortion the exponential horns are quite satisfactory, but it is possible to avoid distortion with other types of loudspeaker also. The same is true of the matter of cut-off. The lowest frequency which a horn will emit, which determines its low-frequency cut-off, is not fixed by the exponential principle, but merely by the length and width of the horn and by similar characteristics. Either an exponential horn or a cone loudspeaker or some non-exponential variety of horn can be designed to have a low and favorable cut-off, emitting frequencies down to fifty or sixty cycles or even lower.

It is the first factor, that of sensitivity, which brings the exponential horn its greatest victories. With a relatively small amount of energy emitted from the diaphragm itself, the cone of air, expanding as the horn enlarges in accordance with the exponential principle, transmits an exceptionally large fraction of this diaphragm energy to the outer air. If the exact dimensions of the horn provide the desirable low cut-off and if the details of design are adjusted to minimize distortion, it is possible to obtain great volume, which means loudness, without interfering with the absence of distortion which is so necessary for first-class musical reproduction.

It is for this reason that the horn type of speaker with an efficient form of moving coil driving unit, has been so very popular in all those applications where loudness is an essential factor; for example, where large audiences are being entertained as in theatres, halls, etc., or where music is to be provided for marching or for dancing.

For use in home radio receivers where the space available for the loud speaker is very limited, the cone type seems to fill the requirements best, because horns capable of reproducing down to the low audio frequencies are necessarily very long and large, even if they are of the folded type, whereas a cone speaker is small and compact. If the condenser type of speaker can be developed to a satisfactory commercial form with a suitable dielectric of long life, it is possible that it may yet supplant the cone type speaker for home use, on account of its relative cheapness and excellent reproduction when used with an audio amplifier designed especially to compensate for its deficient reproduction of the low-frequency sounds.

484. Desirable loud speaker characteristics: While it is desirable from the point of view of "naturalness of reproduction" in speech and music to reproduce faithfully all sounds up to 8,000 or 10,000 cycles per second, the use of any loud speaker, or speaker combination, that efficiently reproduces these extreme high frequencies imposes severe requirements upon the system with which it is operated. In systems using recorded programs, the "surface" or "ground noises" on both film and disc records becomes much more troublesome because much of this noise



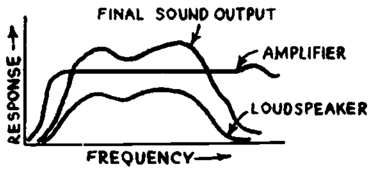


Fig. 364—The frequency-response of the audio amplifier (B), and that of the speaker (A), must both be considered, since the results obtained (C), is really the combustion of both. The r-f amplifier should also be considered, since the high audio frequencies will be lost, if sideband suppression takes place in the r-f amplifier. Deficiencies in the frequency response of the speaker may often be compensated for in the r-f or a-f amplifier.

energy is in the high frequency range. To realize the full value of improved high-frequency performance in the loud speaker, recordings with very low noise levels must be used, as otherwise the increased noise may be more objectionable than the loss of the high frequencies. Even in programs supplied by broadcasting circuits where there is no recording process, special care must be taken to exclude extraneous noises due to stray electrical disturbances such as are caused by atmospheric "static", electrical machinery and "power" leaks, etc. These might be quite tolerable if the system did not respond efficiently to the high frequencies. Amplifier overloading and any other distortion in the system is also much more readily detected by the ear when the high frequencies are present.

This tends to make it necessary to use higher powered amplifiers and better equipment throughout.

At the present time, these and other considerations seem to preclude the general use of a loud speaker capable of efficiently reproducing the entire audible frequency range. While the reproduction of the extremely high frequencies is an accomplishment greatly to be desired, it is nevertheless a refinement which cannot be achieved through improvement of the loud speaker alone; development of better apparatus and technique in the rest of the transmission and reproducing system must keep pace.

485. Combining audio amplifier and speaker characteristics: If definite knowledge regarding the frequency-response characteristics of a certain loud speaker is at hand, the audio frequency amplifier for use with it can be designed to supplement the loud speaker at its weak points, that is, at the frequencies for which the loud speaker is deficient, the amplifier can be designed to increase the response and conversely where the loud speaker response is more than normal, the amplifier can be arranged to reduce the response. As an example of this, (A) of Fig. 364 shows the response curve of a certain speaker. The low note reproduction is weak, the middle frequencies are normal and the high frequencies are weak. Obviously the audio amplifier should be designed to have the frequency response characteristics shown at (B), with the low and high frequency amplification exaggerated, and relatively lower amplification over the middle register. The approximate resultant response curve of the speaker and horn combined is shown at (C). Notice that the deficiencies of the speaker have been nearly corrected by proper design of the a-f amplifier. Obviously this amplifier would only give these good results when used with this particular type speaker, if another speaker were used the resulting response would be totally different.

Transformer-coupled or shunt-feed coupling by the Clough system lends itself nicely to this sort of work, since the amplification characteristic of the transformer can be modified easily. Also, certain frequencies can be suppressed by band filters, or strengthened by resonant circuits. This practice of compensating for the deficiencies of one electrical circuit by over-exaggerating the corresponding characteristics in another circuit in a system, is used extensively in telephone work. It is also possible in many cases to make up for certain deficiencies in the receiver characteristics by means of a loud speaker having special design features. Thus the high-frequency audio suppression caused by an r-f amplifier which is so selective that it cuts sidebands can be compensated for by the use of a loud speaker which properly over-accentuates the high-frequency notes.

It is evident from a study of the curves of Fig. 364, that all types of loud speakers will not operate equally well with all audio amplifiers. This is the reason why a certain loud speaker will appear to work very well with a particular set and may give only average results when connected to a different receiver. As a matter of fact, an audio amplifier having ideal straight-line frequency-response intensifies the poor frequency response of a loud speaker of average worth, as shown, and really makes it sound worse than shown in the diagram at the upper right of Fig. 364.

It must be kept in mind however, that the difference in hearing facilities of different persons makes it impossible to produce one sound-reproducing system which is absolutely satisfactory to every person. Compromises must be made. Some persons are pleased with reproduction where all of the low notes are reproduced. Others are pleased with reproduction which includes only part of the low-note range, etc. Tone controls in the audio amplifier help to provide an adjustment of the frequency response to suit the individual tastes of the listener. It must be remembered that the compensating possibilities of the audio amplifier apply to frequency-response and not to any correction for wave-form distortion which may occur in either the amplifier or the speaker. This form of distortion is not so readily corrected.

Loud speakers should never be compared by listening to their reproduction when connected to a poor receiving set, since the better of the speakers will sound worse. This is due to the fact that the better the frequency-response curve of the speaker the more the defects of the receiver (especially overloading), will appear in the reproduction. If, however, two loud speakers are connected to a double-pole double-throw switch, the blade posts of which are connected to the ouput of a *good* set, which set is tuned to a *good local* broadcasting station, a useful comparison may be made. The relative intelligibility of speech is an indication of the presence of the higher audio frequencies. If "f," "s," "v," "b," "p," and "th" are *clearly* distinguishable, the loud speaker has a good high-frequency characteristic. If, when listening to the piano, the tones are deep and rich, the low-frequency characteristic is good; on the other hand, if the piano sounds thin and tinny the low-frequency characteristic of the speaker is deficient. If the voice is full and clear and intelligible, and yet has an unnatural metallic quality, there is at least one high peak in the middle or upper range of the frequency-response curve.

486. Connecting several speakers together: The methods of connecting several speakers to the output circuit of the power amplifier stage of the audio amplifier will be considered in Chapter 30.

REVIEW QUESTIONS

1. What is the function of the loud speaker in the radio receiving system?
2. What is a loud speaker driving unit? Name three types of driving units?
3. What is the difference between a "moving iron" and a "moving coil" type driving unit?
4. Explain the operation of the iron diaphragm type of unit. What are its disadvantages?
5. Explain the operation of the balanced armature type of unit. What are its advantages and disadvantages?
6. Explain the operation of the moving coil type of unit. What are its advantages?
7. Describe the construction and operation of an electro-dynamic speaker designed to have its field operated from 110 volts a-c Why is the rectifier used?

8. What is the function of the coupling transformer between the plate circuit of the power tube and the voice-coil of an electro-dynamic speaker?
9. A speaker input transformer is to be designed to couple a 10 ohm voice-coil to the plate circuit of two '50 type tubes in push-pull. What must be the impedance of the entire primary of the transformer and the turns-ratio for most efficient transfer of the maximum undistorted output?
10. What is the purpose of the hum-bucking coil in a moving-coil speaker employing a dry-plate rectifier?
11. What are the advantages of obtaining the field supply current for an electro-dynamic speaker by connecting it as a choke in the B power supply unit?
12. How could you tell whether the voice-coil in a speaker needed re-centering or not? How would you proceed to re-center it?
13. What is a cone speaker? Define free-edge cone, fixed-edge cone. What is the function of the cone?
14. What is the function of the baffleboard used with a cone speaker? What baffle length is required for full reproduction of the 40 cycle note of a bass viol by a free-edge cone?
15. A cone-type speaker is installed under the radio receiver in a console cabinet. What must be the distance from the edge of the front face of the cone around the outside of the cabinet and inside to the back face of the cone, in order that sounds of frequencies as low as 100 cycles may be fully reproduced?
16. The cabinet of a midget type receiver measures 12 inches across, 18 inches high and 9 inches deep. The speaker having a 6 inch diameter cone is mounted directly in the center of the front of the cabinet. To what lowest frequency will the cabinet act as an effective baffle? If the diaphragm and driving unit are capable of vibrating as low as 100 cycles, will the notes down to 100 cycles be heard at all when this cabinet is used as a baffle?
17. A certain electro-dynamic speaker operating with a dry-plate rectifier delivering 2 amperes, and having a 1,000 ampere-turn field coil, is to be changed and connected so as to obtain its field current supply by connecting it as a choke coil in the filter system of a "B" power supply unit. When connected this way, 100 milliamperes will flow through the field. If the field is to be re-wound for the new condition, how many turns of wire must it have, and will it be re-wound with smaller or larger wire than before? Are any other changes in the speaker necessary?
18. Explain the operation of the inductor type speaker unit. What are its advantages?
19. What is the function of the horn on a loud speaker? What characteristics should the horn material possess?

20. What is an exponential horn? What determines its cut-off frequency? What are its advantages over other types of horns?
21. What is the advantage of the electromagnet type of moving-coil speaker over the permanent magnet type? For what applications does the latter type have special advantages?
22. Why is the horn used on the horn type loud speaker? How should the cross-section area vary along the length of the horn for best reproduction?
23. An exponential horn is to be designed with a throat ½ inch in diameter, and is to have a cut-off frequency of 64 cycles. What must be the length of the horn and what is the size of the bell, if it is square?
24. Why is the horn type speaker not used extensively in radio receivers designed for home use? Why is it used extensively in public-address and sound picture work?
25. What is the advantage of using two loud speakers, one designed to reproduce the low and medium frequencies and the other designed to reproduce the high frequencies?
26. What is the principle of operation of the condenser type loud speaker? Why is a polarizing voltage used?
27. What are the limitations of the condenser speaker? What are its advantages?
28. Draw a diagram of a condenser type speaker connected to a power output tube of a receiver, showing the necessary polarizing-voltage tube.
29. What characteristics are desirable in a practical speaker used with an ordinary radio receiver?
30. Draw the frequency-response characteristic of a loud speaker which does not reproduce either the middle or the high frequencies efficiently. Now draw the frequency-response characteristic of an audio amplifier system to work with it, such that it will tend to compensate for the deficiency of the speaker.
31. Why is it not advisable to employ loud speakers which will reproduce the audio frequencies up to 8,000 or 10,000 cycles, with present radio systems? What is lost by employing systems which only reproduce sounds of frequencies only up to 4,000 or 5,000 cycles?

CHAPTER 26

THE BATTERY OPERATED RECEIVER

TYPES OF BROADCAST RECEIVERS — APPLICATIONS OF BATTERY-OPERATED RECEIVERS — RECEIVER CIRCUITS — THE FILAMENT CIRCUIT AND SUPPLY — T-R-F RECEIVER — DETAILED ACTION OF THE RECEIVER — RECEIVER WITH SELF GRID BIAS — VOLTAGE AMPLIFICATION PRODUCED BY THE RECEIVER — LOUD SPEAKERS FOR BATTERY-OPERATED RECEIVERS — SUPERHETERODYNE BATTERY-OPERATED RECEIVER — REVIEW QUESTIONS.

487. Types of broadcast receivers: Now that we have studied the characteristics, construction and circuits of the various components which go to make up a radio receiving system, we may proceed with the study of complete receivers themselves. We will consider those receivers designed for reception of signals in the ordinary broadcast band of frequencies from approximately 500 kc to 1500 kc, first. Short wave receivers will be studied in a later chapter, as they present special design and construction problems.

Radio receivers for broadcast reception may be classified according to the source of power which is used to operate their vacuum tubes. In one class we have the *battery-operated receivers* which employ either primary or storage batteries for this purpose; in the other are the *electric* receivers which obtain this power from the d-c or a-c electric light mains. The battery-operated type will be studied now.

488. Applications of battery-operated receivers: While it is true that electric operation of radio receivers possesses many important advantages over battery operation, there are many fields of application in which electrically operated receivers cannot be employed, simply because no suitable or economical source of electric current is available. For instance, millions of farm and country homes are not supplied with electric current for lighting purposes, and therefore must resort to battery operated receivers. Even in many city homes, the same condition exists. Battery operation is also necessary for receivers operated in automobiles and aircraft. (The special forms of receivers for the latter purposes will be considered in Chapter 29). There is, therefore, a very definite field for battery-operated receivers which shall produce results as nearly as possible equal to those obtained from electrically-operated receivers.

489. Receiver circuits: There are two main types of circuits employed in battery-operated receivers; namely, the tuned radio-frequency circuit and the superheterodyne circuit. The perfection of screen-grid, general purpose, and pentode tubes for economical operation from batteries has done much toward furthering the development of these circuits to a point where splendid performance is obtained. Since the detector tubes available for battery operation are not able to handle signal voltages as large as those which are commonly employed in electric receivers, the amplification obtained in the r-f amplifier must be kept down to a value such that the signal will not overload the detector tube. This means, in most cases that two stages of audio amplification are used following the detector in order to bring the signal strength up to good loud speaker volume.

490. The filament circuit, and supply: Most tubes used in battery-operated receivers (excepting those used in aircraft and automobile receivers), are of the direct-heater type, in which the filament current flows through the coated filament which is also the cathode, (as shown at (B) of Fig. 189). The construction of a three-electrode tube of this type is shown in Fig. 193, and that of a screen-grid tube is shown in Fig. 226. The filaments are connected in parallel across the source of filament voltage, usually with a variable rheostat included in the circuit to enable the operator to compensate for the drop in voltage of the battery as it nears the discharged condition, and thus maintain a more uniform voltage at the filaments. Circuits of this kind are described in Article 53. The parallel filament circuit of a typical battery-operated receiver is shown in Fig. 32. In Fig. 33 combination of five tubes is shown connected so that two rheostats are used to control the filaments. The source of filament voltage may be either dry cells, a storage battery or an Air-cell battery (see Article 65). Filament operation with dry cells is really so expensive and bothersome that it has nothing to recommend it unless the receiver is to be made very light for portable use. Likewise, the use of a storage battery is bothersome due to the necessity for frequent charging and the likelihood of sulphuric acid getting on to furniture, rugs, etc. However, there are many receivers still in use, which employ a storage "A" battery for filament supply. The development of the improved types of tubes having filaments designed for 2-volt operation, together with the perfection and use of the 2-volt Air-cell battery described in Article 65, has led to the development of very efficient battery operated receivers. Dry cell B batteries (see Article 62) of either the cylindrical cell or Layer-bilt construction are employed for "B" voltage supply.

The ordinary form of dry cell, described in Article 60, is not perfectly satisfactory as a source of filament voltage and current in radio receivers which are to be operated by batteries. Due to the fact that the internal resistance of dry cell increases greatly as it becomes older, the available voltage at its terminals (*p.d.*) when it is delivering current, drops lower and lower with use. Therefore, in order to maintain a constant voltage at the filaments of the tubes in a receiver using dry cells for filament voltage supply, a combination of dry cells initially supplying higher voltage than the filaments are designed for, must be used, (two or more 1.5 volt dry cells must be connected in series to obtain this voltage). A variable resistance (called the filament rheostat, Fig. 30) must be connected in series in the circuit to absorb the excess battery voltage when the cells are new. As the receiver is used and the terminal voltage of the cells drops, the resistance of the filament rheostat must be gradually reduced, so as to maintain a constant voltage across the tube filaments. This arrangement is rather bothersome, and in actual practice the tubes are usually being burned above or below their rated voltage due to improper or careless adjustment of the rheostat. This results in very much shortened tube life.

The Air-cell "A" battery was developed to overcome this trouble, by providing practically constant voltage at its terminals throughout its entire useful life—that is, its internal resistance does not increase greatly with use. This makes it more suitable than the ordinary dry cell for the purpose of supplying a steady voltage to the tube filaments of battery operated receivers. Part (B) of Fig. 40 shows an interesting comparison of the voltage actually delivered at the filaments of a battery-operated radio receiver using seven tubes of the 2 volt type, drawing a total filament current of about 0.55 ampere. The set was used three hours daily. When a bank of 8 dry cells (2 groups of 4 cells each, the cells in each group being connected in parallel and the two groups connected in series to give 3 volts) was used to supply voltage to the filaments, it required 4½ dry battery renewals and installations (total of 36 dry cells) to operate the set for 1,100 hours. In each case the bank of dry cells was discarded when its total voltage dropped to 2 volts (the rating of the tube filaments). Notice from Fig. 40, how the dry cell voltage drops as the cells are used. Each bank of dry cells was only good for about 250 hours of operation. When the same receiver was operated from an Air-cell "A" battery, the voltage applied to the filaments remained practically constant (as shown in Fig. 40), throughout the entire life of the battery, (about 1,100 hours). As the cost of 36 dry cells is about double the cost of the Air-cell battery, and the latter provides the correct filament voltage throughout its entire life (600 ampere-hours capacity) its advantages are apparent.

Receivers designed especially to take full advantage of the characteristics of the 2-volt type of vacuum tubes will now be considered. These tubes are the '30 type general purpose tube, the '32 type screen-grid tube, the '31 type 3-electrode power tube, and the '33 type power pentode (see Fig. 214).

491. T-R-F receiver: A typical battery-operated receiver of the t-r-f type, designed for home use, is shown in Fig. 365. The r-f amplifier contains three tuned stages employing screen-grid tubes. The detector is of the grid-bias type and also uses a screen-grid tube. This is followed by one stage of resistance-capacity coupled a-f amplification feeding into a pentode power amplifier tube. By using resistance coupling, it is possible to place quite a high impedance plate load in the detector tube circuit in order to obtain efficient voltage transfer, since the a-c plate resistance of a screen-grid tube operated as a grid-bias detector is very high. The last audio tube is of the pentode type, for high power sensitivity. If an ordinary moving-iron type speaker is used, the use of a 30-henry choke and 2 mf. condenser for coupling it to the pentode tube as shown, is satisfactory. If a moving-coil type speaker is used, it must have an input transformer designed especially for operating between power pentode tubes of this type and the low-impedance voice-coil.

The four tuning condensers C_2, may be a single 4-gang condenser for single-dial tuning control. Choke coils L and by-pass condenser C are for eliminating interstage coupling in the common resistance of the "B" batteries. Volume control is obtained by means of the potentiometer R, which enables the screen grid voltage on the r-f tubes to be varied, and the amplification controlled. Rheostat R_1 provides a control for the filament voltage. The connections of the various batteries are shown. Three 45 volt "B" battery blocks are connected in series to obtain the 135 volts necessary for the proper operation of the plate circuits of the tubes. Dry cell "C" batteries supply the proper grid-bias voltages.

492. Detailed action of the receiver: The various changes which an incoming signal voltage causes in the grid and plate circuits of the various tubes is shown above the circuit diagram. This should be studied carefully as it gives a graphic picture of what actually occurs in a radio receiver. The modulated r-f signal voltage induced in the antenna cir-

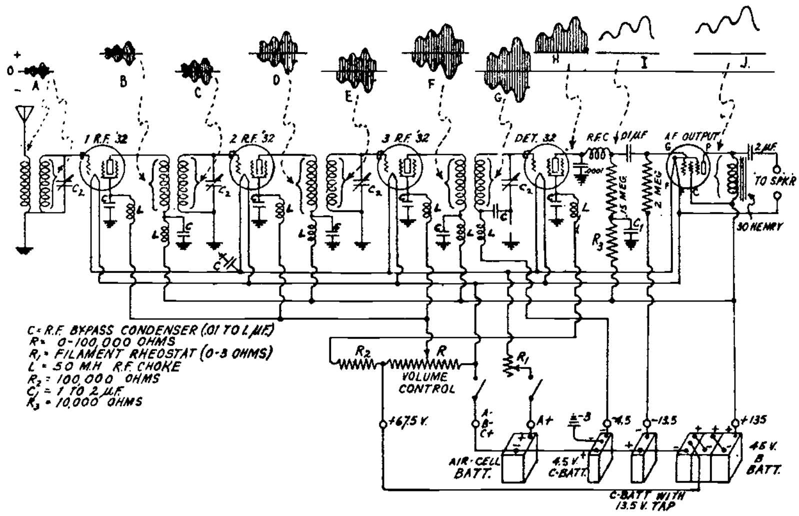


Fig. 365—Typical screen grid t-r-f receiver using 2-volt type tubes and operated by an Air-cell "A" battery and dry cell "B" and "C" batteries. A pentode power amplifier tube is used in the last audio stage. The changes which the modulated r-f signal voltage causes in the grid and plate circuits of the successive tubes when it acts on the input of the receiver, are shown by the graphs above. Standard screen grid type tuning coils and .00035 mf. tuning condensers may be employed. The graphs for the grid circuits represent the varying signal voltages applied to the grid. Those for the plate circuits represent the varying plate currents, caused by the signal voltage variations.

cuit is transferred to the grid of the first r-f tube by the antenna coupling transformer. This alternating signal voltage is represented at A, and is applied to the grid circuit of the first r-f tube. This causes the plate current to vary in exact accordance with the r-f variations in it. The r-f varying unidirectional plate current flowing through the primary of the r-f transformer in its plate circuit, causes amplified voltages to appear across it as shown at B. The varying voltage is transferred to the secondary winding by transformer action, and acts on the grid circuit of the second r-f tube. This is repeated in each r-f stage, amplification taking place in each stage, and the voltages appearing as at C, D, E, F and G. Of course this desired signal is selected from all others by the tuned circuits of the r-f amplifier. In the plate circuit of the detector a very important action occurs. First of all, since the tube is operated at the lower bend of its characteristic, practically no plate current changes are produced when each negative half cycle of the signal voltage is applied to the grid circuit (see (D) of Fig. 236). Hence, the lower halves of the signal variations are eliminated. The result of this action is shown at H. Due to the action of the by-pass condenser in the plate circuit, the r-f variations are removed from the plate current flowing through the 150,000 ohm coupling resistor, and the result is a current varying at audio frequency as at I, whose modulations are the same as those of the modulated r-f signal voltage at A. This audio-frequency voltage is amplified by the audio amplifier tube. The amplified output, appearing as at J, is fed to

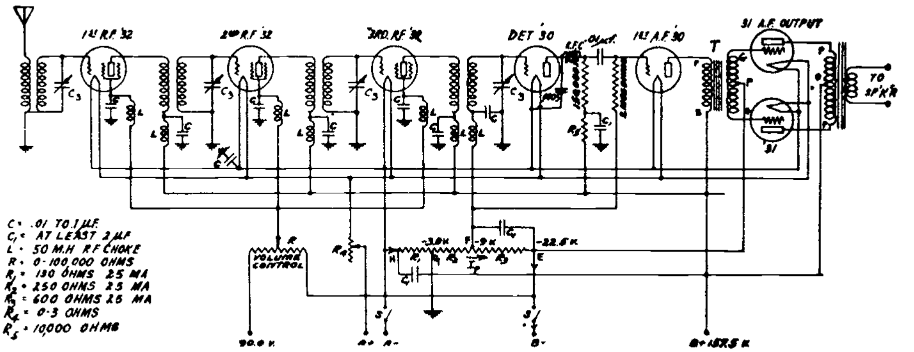


Fig. 366—Typical screen grid t-r-f battery operated receiver with 2-volt type tubes. A tapped resistor is employed for furnishing self-grid bias voltage to the various tubes —thus eliminating the usual "C" batteries. A push-pull output stage is employed. Standard screen grid type tuning coils and tuning condensers may be employed.

the loud speaker through the speaker coupling circuit, where it is converted into sound waves of the same wave-form and frequency. This completes the operation of the receiver. The additional energy added to that of the original incoming signal comes from the "B" batteries.

493. Receiver with self grid-bias: The circuit diagram for a simple battery-operated receiver in which the grid bias voltages are all obtained automatically by utilizing the voltage drops through resistors R_1, R_2 and R_3 of proper value for this particular tube arrangement, is shown in Fig. 366. This circuit differs from that in Fig. 365, in that a 3-electrode tube detector is employed, and a 3-electrode power amplifier tube is used, making the use of two audio stages necessary. the output stage being of the push-pull type. The first a-f stage is resistance-coupled to the detector and the second is transformer-coupled to the first a-f tube.

The combined plate current I_p of all the tubes, flows through resistances R_1, R_2 and R_3 in the direction of the arrows. This makes the potentials of points E, F and G lower than that of H. Since H is connected to the negative filament terminals of the tubes (from which point all grid and plate voltages of a tube are referred), and points E, F and G represent the grid-return points of the power amplifier, detector and first audio, and r-f tubes respectively, it follows that the grids of these tubes are maintained at a definite negative grid bias potential with respect to their filaments. Resistors R_1, R_2 and R_3 are properly proportioned to apply the proper bias voltages to the tubes. Several advantages result from this form of circuit. First, no C batteries are required. Second, correct C bias is furnished to the tubes regardless of the condition of the "B" batteries. As the "B" batteries get older and their voltage drops, proportionately less plate current flows through these resistors and so the grid-bias voltages are correspondingly reduced to the proper value for the particular plate voltages which are being applied to the tubes. Since the grid bias voltage obtained by the voltage drop in the bias resistor, is being subtracted from the applied "B" battery voltage in this circuit arrangement, the effective voltage acting on the plates of the tubes is actually less than the applied "B" battery voltage by this amount. Therefore a higher "B" battery voltage than is ordinarily used must be employed, (157.5 volts instead of 135 volts), to make up for this. This is not necessarily objectionable since the battery connections are greatly simplified (compare with circuit of Fig. 365), and the problem of battery renewal and connection is simpler.

Since 3-electrode type power tubes are used in the last audio stage, they are connected in push-pull in order to provide ample handling capacity for even loud signals. A reduction of second harmonic distortion also results from this connection.

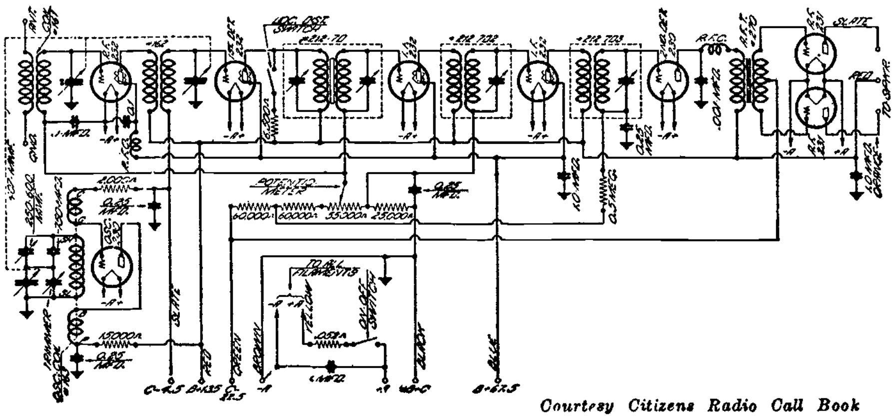
493A. Voltage amplification produced by the receiver: In order to obtain some idea of how much amplification of the weak signal voltage in the antenna circuit is produced by a radio receiver, we may calculate the overall voltage amplification of the receiver as shown in Fig. 366.

The input voltage applied to the first r-f tube is amplified by it, and appears as a larger voltage across its plate circuit load. This is stepped up slightly by the r-f transformer and appears in the secondary winding, where it is applied to the grid circuit of the following tube. This amplifies it in the same way, and so on through to the output terminals of the receiver. Let us suppose a gain of 5 is obtained between the antenna and the input to the first r-f tube. Now although the voltage amplification factor of the '32 type tubes employed as r-f amplifiers in this receiver is found from Fig. 214 to be 440, it is not possible to obtain this much amplification from the tube, because the a-c plate resistance is so high, (800,000 ohms), that the impedance of the r-f transformer primary connected in the plate circuit is small compared to this. Therefore only a small part of the amplification factor of the tube is actually made effective in practice. Let us suppose the actual voltage amplification produced by the detector is 3. We will suppose that the primary winding of the transformer T connected in the plate circuit of the first a-f tube is of high enough impedance so that 90 per cent of the amplification factor (8.8) of the tube is realized. The ratio of this transformer. is 3 to 1. Also suppose that 50 per cent of the amplification factor of 3.5 is realized from each power amplifier tube. Then the amplification produced by the entire receiver is considered as follows:

Between antenna and grid of 1st r-f tube, 5; by first r-f tube and transformer, 30; by second r-f tube and transformer, 30; by third r-f tube and transformer, 30; by detector, 3; by resistance coupling, 0; by first a-f tube, 8.8×.90; by input transformer T, 3; by each push-pull tube, 3.5×0.50. Since the output voltages in the two halves of the primary of the push-pull output transformer combine additively, the total signal voltage appearing across the entire primary is 2 times this value. Therefore, the total amplification is:

$$5\times30\times30\times30\times3\times8.8\times.90\times3\times3.5\times.50\times2=34{,}000{,}000.\text{ approx.}$$

This amplification of approximately 34 million gives some idea of the large total voltage amplification which may be obtained by connecting several amplifier tubes in suitable cascade circuits, so that each tube amplifies the voltage output of the previous one. Suppose that the antenna of this receiver is situated in the field of a transmitting station such that 2



Courtesy Citizens Radio Call Book

Fig. 367—Typical battery-operated superheterodyne receiver employing 1 t-r-f amplifier stage ahead of the first detector, and 2 intermediate-frequency amplifier stages. A single push-pull output audio stage is employed.

microvolts (.000002 volts), is induced in it. Then the voltage appearing across the secondary of the push-pull output transformer would be:

$$.000002\times34{,}000.000=68\text{ volts.}$$

The total voltage amplification produced by any receiver may be calculated in this way.

494. Loud speakers for battery-operated receivers: The possible choice of a suitable form of loud speaker for a battery-operated receiver is narrowed down to the use of either a moving-iron type cone speaker, an inductor type speaker, or one of the permanent magnet moving-coil type. These are described in Chapter 25. All of them are capable of very satisfactory results if they are well designed and constructed. The use of a moving-coil speaker employing an electromagnet type of field is not practical due to the fact that it is not economical to supply the electrical power required by the field, by means of batteries.

495. Superheterodyne battery receiver: A typical circuit diagram of a superheterodyne receiver designed for battery operation is shown in Fig. 367. The special "pad" tuning circuit for the oscillator is necessary to equalize the tuning with that of the r-f and detector circuits in order that single-control tuning may be employed. Two stages of intermediate-frequency amplification are employed, the first stage coil being a sharply tuned band-pass filter. The second detector feeds directly to the push-pull output stage as shown. The filaments are all connected in parallel across the "A" battery supply terminals.

REVIEW QUESTIONS

1. Since electric operation of radio receivers presents so many advantages over battery operation, why are battery operated receivers used at all?
2. Draw the complete circuit diagram of a 5 tube t-r-f battery receiver employing two '32 type tubes for r-f amplification, a '30 type tube as a detector and one as the first a-f amplifier, and a single '31 type tube in the output stage. Both audio stages are to be transformer-coupled. Show the connections for all batteries also.
3. Show by means of a suitable diagram, and explain in detail, just what actions an applied signal voltage causes in the grid and plate circuit of each tube in a 5 tube t-r-f receiver.
4. What would happen if no detector tube were used in the above circuit? Explain in detail.
5. Name the various types of loud speakers with which you are familiar and give your reasons why each one may or may not be desirable for use with a battery-operated receiver for home use.
6. How do run-down "A" or "B" batteries affect the operation of the receiver?
7. How would you determine whether the "B" batteries needed replacement? How would you test the condition of the "A" battery, (a) if it consisted of dry cells; (b) if it was a lead-acid storage battery; (c) if it was an Air-cell battery?
8. A receiver employs three '32 type tubes as r-f amplifiers, one type '30 tube as a detector and two '33 type tubes in push-pull. The detector plate voltage is 45 volts and that applied to the amplifier tubes is 135 volts. Proper grid-bias voltages are applied to each. What is the total current drawn from the "B" batteries? (Use the table in Fig. 214.)
9. What is the total filament current drain of the above receiver?
10. What are the advantages of arranging the circuit of a battery operated receiver so self-gridbias voltage is provided, instead of using dry cell "C" batteries? What are the disadvantages?
11. Why is the total voltage amplification produced in a radio receiver calculated by *multiplying* together the amplifications produced by the individual stages, rather than *adding* them?

CHAPTER 27

THE POWER SUPPLY UNIT

ELIMINATING THE "B" BATTERY — TYPES OF SUPPLY LINES — REQUIREMENTS OF THE B POWER SUPPLY UNIT — B POWER UNIT SYSTEM — POWER TRANSFORMER — RECTIFIERS — HALF-WAVE RECTIFIER — FULL-WAVE RECTIFICATION WITH HALF-WAVE RECTIFIER TUBES — FULL-WAVE RECTIFIER TUBE — MERCURY VAPOR RECTIFIER TUBE — THE FILTER SYSTEM — TUNED CHOKE FILTER SYSTEM — FILTER SYSTEM ARRANGEMENTS — THE CHOKES AND FILTER CONDENSERS — VOLTAGE DIVIDER SYSTEMS — VOLTAGE DIVIDER WITH VARIABLE RESISTORS — VOLTAGE REGULATION — LINE DISTURBANCES — COMPLETE POWER SUPPLY UNIT — "B" POWER SUPPLY UNIT FOR D-C LINES — MEASURING OUTPUT VOLTAGES — REVIEW QUESTIONS.

496. Eliminating the "B" battery: In the battery-operated receivers considered in the previous chapter, common dry cell "B" batteries are used as a source of voltage for maintaining the plate of each tube at a positive potential with respect to its cathode. The filament current is also furnished by a battery. While receivers of this type do have certain fields of application as pointed out, they form a small portion of the receivers in use, because of the troublesome necessity for battery renewal and the fact that the use of sufficient "B" batteries for obtaining the high plate voltages for the proper operation of modern power tubes having adequate handling capacity, is very expensive and impractical. Wherever either a. c. or d. c. electric light service mains are available, it is much more satisfactory and economical to obtain all "A", "B" and "C" power for the operation of the receiver, from the electric light mains. Receivers operating this way are called *electric receivers*.

As has already been pointed out, the purpose of the filament current is merely to heat the cathode to a temperature at which electrons are emitted. Any form of current will heat a filament, so either direct or alternating current may be used for this purpose. The problem of filament current supply in electric receivers is solved satisfactorily by using separate-heater type tubes, whose filaments are heated by either the direct current or raw alternating current of proper voltage from the electric light lines. The problem of plate voltage supply is not so simple, because the plate voltage applied to the tubes must be unidirectional and absolutely steady with no pulsations. Any rapid variations or pulsations in the B supply voltage will cause corresponding variations in the plate currents of the tubes, in exactly the same way that the radio signals do. These, being amplified by each successive tube, will be quite strong at the output of the receiver and will cause objectionable loud hums or other noises to be heard in the loud speaker. Just how important this is, may be seen from the following experiment:

Experiment: Obtain a complete receiver and loudspeaker, which are capable of good low note reproduction. The receiver should preferably be of the battery operated type to facilitate changeover of connections, and a 1 mfd. condenser should be connected in series with the ground lead between the ground terminal on the receiver and the ground connection. Operate it so a station is received loudly and clearly. Now disconnect the B batteries and connect the 110 volt a-c electric light circuit in their place, all the B+ terminals of the set going to one side of the lighting circuit, and the B— terminal going to the other side. Nothing but a loud 60 cycle hum or roar will now be heard. If a d-c electric light circuit is available, this may be used instead of the a-c line, being careful to connect the positive side of the line to the B+ terminals of the receiver. In this case the hum will not be so loud, but it is enough to be objectionable.

This experiment convincingly illustrates the fact that the voltage in the form supplied by the electric light supply line is not suitable for use directly as the plate voltage in the radio receiver. It can be made suitable however, by proper apparatus which we will now study. That for use with a-c electric light lines will be studied first. The apparatus for use with d-c lines is much simpler and will be studied later.

497. Types of supply lines: Current for electric lighting and power purposes is supplied in two forms, *alternating current* and *direct current.* The use of a-c for this purpose is the most common and widespread, although many communities are supplied with d-c. The construction of the "B" power unit depends upon the type of current supplied. This may be ascertained in any particular case by inspecting the nameplate on the watthour meter installed by the electric light company for measuring the amount of power consumed, or by communicating with the local electric light company. We will first consider those "B" power supply units which are designed for operating the plate circuits of radio receivers from the a-c electric light circuit.

498. Requirements of the "B" power supply unit: Before proceeding with the actual study of the operation and construction of the "B" power supply unit, it is well to understand just what must be accomplished by it. We will assume that the electric light circuit is of the ordinary type delivering a voltage of 110 volts alternating at a frequency of 60 cycles. If other voltages or frequencies are supplied, only minor changes in the construction of the parts is necessary, the main system remains essentially the same. The voltages supplied by the unit to the plate circuits of the tubes in the receiver must be steady, non-pulsating, and always in one direction so that the plates of the tubes are always maintained positive with respect to the cathodes. This is necessary for proper tube operation. For this reason, the alternating voltages cannot be applied directly to the receiver, the "B" power unit must "rectify" or change them to direct voltages. The voltages must be non-pulsating, because even a small fluctuation in plate voltage will cause a fluctuation in the plate current of each tube. This will be amplified by the receiver and become large enough to produce an objectionable low-pitched hum from the loud speaker. Therefore the "B" power unit must also smooth out all ripples in the voltage. Since these modern receivers employ at least two types of tubes, (general purpose amplifier tubes and power amplifier tubes) which require different values of plate voltage, it must be capable of delivering the various plate voltage values required. Since these voltages are generally higher than the 110 volts supplied by the electric light line (see Fig. 214), the "B" power unit must also be capable of stepping up the line voltage to the required value, depending on the particular types of tubes employed in the receiver. Also it must be capable of supplying the total plate current required by the various tubes, without undue heating or voltage drop.

499. "B" power unit system: A study of these requirements shows that a "B" power supply system must do several things. It must step up the 110 volt a-c line voltage to the higher "plate" voltages necessary for the

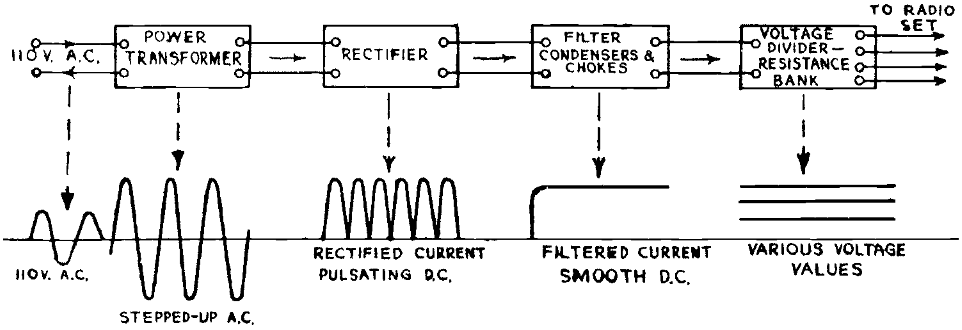


Fig. 368—The main parts of a "B" power supply unit are shown here in the order in which they occur. The changes which the current and voltage undergo and the various forms in which they are present in these parts, are shown by the graphs below.

proper operation of the various tubes used in the receiver, it must rectify the a-c to d-c, it must smooth out the resulting pulsating d-c, and it must provide some means for obtaining several intermediate voltages for the different types of tubes. These functions are performed by the four main parts of the unit, which are as follows:

(1) *Power transformer*: Steps up 110 volts of the line to higher voltage.
(2) *Rectifier*: Changes the a-c from the line to pulsating d-c.
(3) *Filter*: Changes the pulsating d-c output of the rectifier, to smooth d-c.
(4) *Voltage divider*: Enables various voltages to be obtained for the plate circuits of the various tubes in the receiver.

These main parts are shown in the block diagram of Fig. 368, in their proper sequence from left to right. The form of voltage or current which exists in each part is shown graphically in the lower part of the diagram We will now study the operation of each part in order, starting with the voltage step-up in the *power transformer.*

500. The power transformer: The *power transformer* contains a primary winding and several secondary windings—all on a laminated steel core. One secondary winding contains more turns than the primary. Its purpose is to deliver the high voltage which is to be rectified and used for the plate circuits of the tubes. Another low voltage winding of a few turns supplies heating current for the filament of the rectifier tube which will be described. These are the only windings employed for the "B" power pack, but since low-voltage alternating current is also needed for the heating of the filaments of the detector and amplifier tubes in the receiver, this is conveniently obtained by placing one or more additional low voltage windings on the core of the power transformer to supply this current. In this way a single transformer is used to furnish all filament and plate voltage for the filament current supply and another one for plate voltage supply. This reduces the cost and makes the receiver more compact and light. A typical power transformer of this type is shown at the left of Fig. 72. The various windings on the center leg of the core are plainly visible. Typical connections of the various windings may be seen in the circuit diagram of Figs. 282 and 283. The power transformer should be designed with ample copper and iron so that the secondary voltages remain practically constant even though the electric light line voltage varies slightly at different times. It should also be of ample size to supply the required power without undue heating.

501. The rectifier: The next important part of the system is the rectifier tube which changes the high voltage a-c delivered by one secondary winding of the transformer, to pulsating d-c. When an alternating voltage is applied to it, it allows the current to flow in one direction only, by offering a very high resistance to the flow of current in the opposite direction. Rectifiers are divided into two types, half-wave and full-wave. In *half-wave* rectification, only one part of the current wave is utilized, the flow of current being stopped during each half cycle. In *full-wave* rectification the circuit is so arranged that both halves of the waves are utilized. Two half-wave tubes can be connected to form a full-wave rectifier. While there are several types of rectifying devices such as the electrolytic rectifier, the dry plate rectifier, etc., available for the purpose, vacuum tubes are used almost exclusively in B power supply units, on account of their long life, low cost, and general suitability for the purpose. There are two general types of vacuum tube rectifiers. These are, the ***cold cathode*** type and the ***hot cathode*** type. The former is the gaseous type of rectifier, which was very popular at one time, and was marketed under the name of "Raytheon Tube". This employed helium gas. Since these tubes are no longer manufactured in quantity, or used generally, we need not consider them. The hot cathode form of rectifier tube includes the common vacuum type rectifier tube used widely and the mercury-vapor rectifier which presents several advantages over the other types and is used in the high-voltage rectifier systems of public-address equipment, radio transmitters, and also in some broadcast receivers. The different types of rectifiers may be employed according to the requirements of the equipment with which they are to be connected.

502. The half-wave rectifier: Mention was made in a previous chapter of the early form of vacuum tube containing only an electron-emitting filament and a plate. This two-electrode form of tube forms the basis of half-wave rectifier tubes. The '81 type of tube of this form consists of a double V-shaped filament and a single surrounding metallic plate sealed

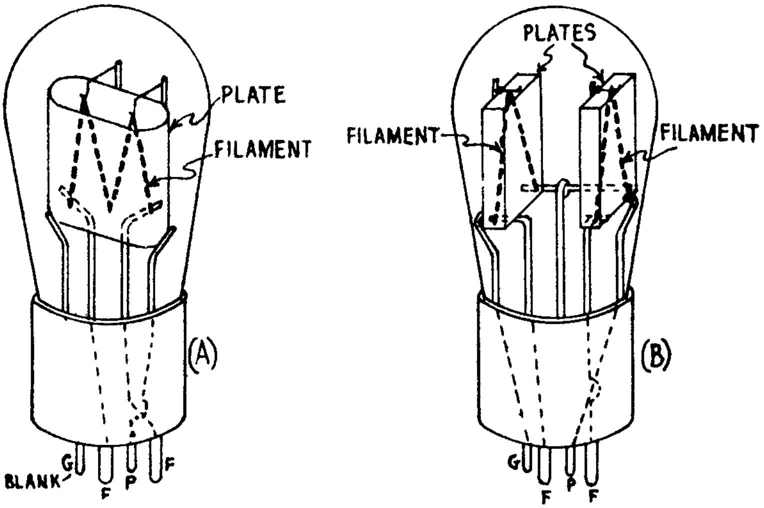
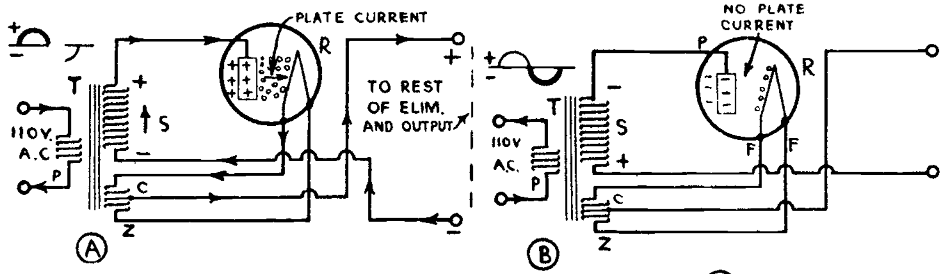


Fig. 369—(A) How the double-hairpin shaped filament and single plate are arranged in the '81 type half-wave rectifier tube.
(B) How the two single hairpin filaments and two plates are arranged in the '80 type full-wave rectifier tube. The two filaments are connected in series inside of the tube.

into a bulb from which the air has been thoroughly pumped out. The filament is of the oxide-coated thick-ribbon type designed to emit a liberal supply of electrons. The arrangement of the elements is shown at (A) of Fig. 369. The two ends of the filament connect to the usual two thick "filament" prongs in the 4-prong base, and the plate connects to the usual "plate" prong. The fourth prong is a dummy—having no connections—and is placed on the tube merely to help hold it firmly against the socket contacts.

The connections of the tube to the power transformer are shown in Fig. 370. The filament is heated by low voltage (7½ volts) alternating current from the secondary winding "Z", so it emits electrons freely. The high plate voltage (about 700 volts effective value for an '81 type tube) is supplied by the winding "S". As the transformer operates on a-c, the polarity of the terminals of the winding S reverses during each half cycle. The diagram at (A) shows the conditions when the top terminal of winding S is positive and the bottom terminal is negative. This makes the plate of the rectifier positive, and it attracts the electrons emitted by the filament. The plate current then flows from plate to filament, through half of winding Z to the center-tap C (or to one end of the winding), and out to the rest of the "B" power unit and the plate circuits of the tubes being operated, back through the minus terminal of the "B" power unit to the lower terminal of S, making a complete circuit. The direction of the current is shown by the arrows.

On the next half cycle as shown at (B), the polarity of S reverses, the top terminal now being negative. As this is connected to the plate it makes the plate negative, thus repelling and stopping the flow of electrons, and no current flows through the rectifier. This half of the wave is thus eliminated. Therefore the current flows in the external circuit in one direction only, one spurt of current getting through the tube during the half of each cycle when the plate is positive. At (C) the half-wave rectifier effect is shown. At the left is the form of the a-c voltage applied to the primary of the power transformer and also that delivered by the secondary winding



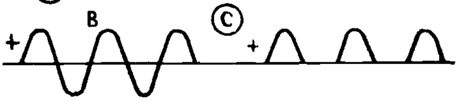


Fig. 370—(A) The operation of the half-wave rectifier. Current flows from the plate to the filament only during each half of the a-c cycle when the plate becomes positive with respect to the filament.
(B) The plate is now negative. It repels the emitted electrons, and therefore no plate current flows.
(C) The a-c line current and the half-wave rectified current.

to the tube. At the right is the pulsating d-c rectified voltage and current appearing in the output circuit of the rectifier tube.

Notice that if a 60 cycle voltage is applied to a half-wave rectifier, since current flows through the rectifier once for each cycle, the output voltage is unidirectional and has 60 pulsations per second.

Notice that this current stops flowing entirely during half of each cycle. This makes it rather difficult to completely filter and smooth the current output of a half-wave rectifier, since the filter must actually store enough current during the peaks of each current flow to be able to keep current flowing in the external circuit during the entire intervals when no current flows through the rectifier. Actually it must store even more than this to completely smooth out the ripples.

For this reason, half-wave rectifiers are not employed extensively in any applications for which a suitable full-wave rectifier tube is available, because the cost of the filter system necessary to completely smooth out the output current of a half-wave rectifier is much greater than that of a filter system designed to smooth out the less pulsating output of a full-wave rectifier tube. Half-wave rectifiers of the '81 type may be built satisfactorily to handle higher voltages than those handled by the '80 full-wave type, so they are particularly useful for supplying the high plate voltages required for the large power tubes of the '50 type, etc., used in public address systems, etc. It is entirely practical and common however, to connect two half-wave rectifier tubes in a suitable circuit to obtain full-wave rectification as we shall now see. In this way all of the advantages of full wave rectification are retained together with the high-voltage handling capabilities of the half-wave rectifier tube.

503. Full-wave rectification with half-wave rectifier tubes: If two half-wave rectifier tubes are connected as shown at (A) of Fig. 371, full-wave rectification is obtained.

The filaments of the two tubes are connected in series across the low voltage heater winding Z, of the power transformer. The high voltage secondary winding S, has its end terminals T and W connected to the plates of the rectifiers as shown.

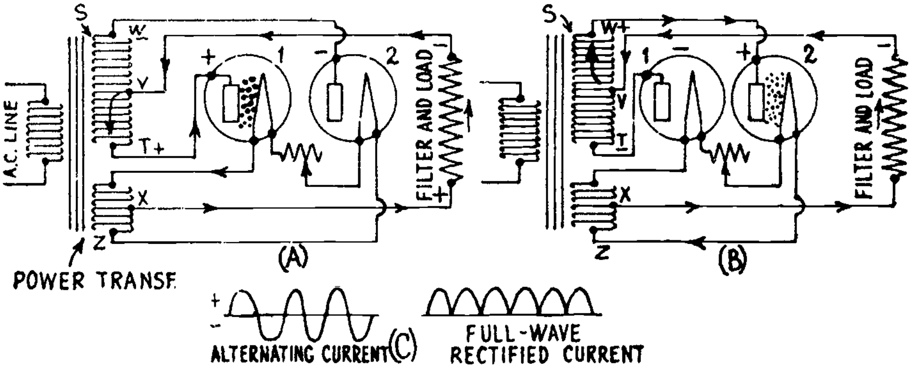


Fig. 371—How two half-wave rectifier tubes may be connected to obtain full-wave rectification. Each tube allows current to flow through it from plate to filament during alternate half cycles. The full-wave rectified current shown at (C) results. This system is used extensively in high voltage power supply units for sound amplifier and public address systems.

It also has a center tap V on the winding, which connects to the filter circuit and load, represented simply by the resistance symbol. This circuit returns to the center tap on the filament heater winding Z. Since an a-c voltage is generated in winding S, the potential of its end terminals alternates during each half cycle. At one instant the bottom terminal T, will be positive with respect to the top terminal W, as shown. The potential of the center tap V is midway between these two, i.e., it is negative with respect to T and positive with respect to W. Therefore since this center tap returns eventually to the filament circuit of the rectifier tubes, at the instant pictured in the diagram, terminal T and the plate of tube No. 1 are positive with respect to the filament of this tube, so the electrons are attracted to the plate and a plate current flows from the plate to the filament, down to point X, and out through the filter system and load in the direction of the arrows, coming back to point V and thus completing the circuit. During this time, terminal W and plate of tube No. 2 are negative with respect to the center tap V and the filament, so no current flows through this tube. On the following half cycle, the polarity of the terminals of winding S reverses, and becomes as shown at (B). Terminal W and the plate of tube No. 2 are now positive with respect to the center tap V and the filament of the tube. Therefore, the plate attracts the electrons from the filament, and a current flows from the plate to point X and around through the circuit in the direction shown by the arrows. Tube No. 1 is now inactive since its plate is negative with respect to the filament. During the following half cycle it becomes active again and the current flows through it, tube No. 2 becoming inactive. The effect then, is for each tube to become operative during one half of each cycle, passing current through from plate to the filament, and around through the external circuit. First one tube operates and then the next. Notice that the current flows through the external load circuit in the same direction no matter which tube is operating, so that the output current is a *direct current*, pulsating as shown at the right of (C).

It is evident that the full-wave rectified current at (C) flows through the external circuit during each half cycle. Comparing this with the half-wave rectified current at (C) of Fig. 370, it is evident that it is much easier to smooth out than the latter, since the filter need only return current back to the line during the short periods when the full-wave rectified current drops to zero value, during each half cycle. Consequently, the filter apparatus is much simpler and cheaper as we shall see later. This is the important advantage of full-wave rectification.

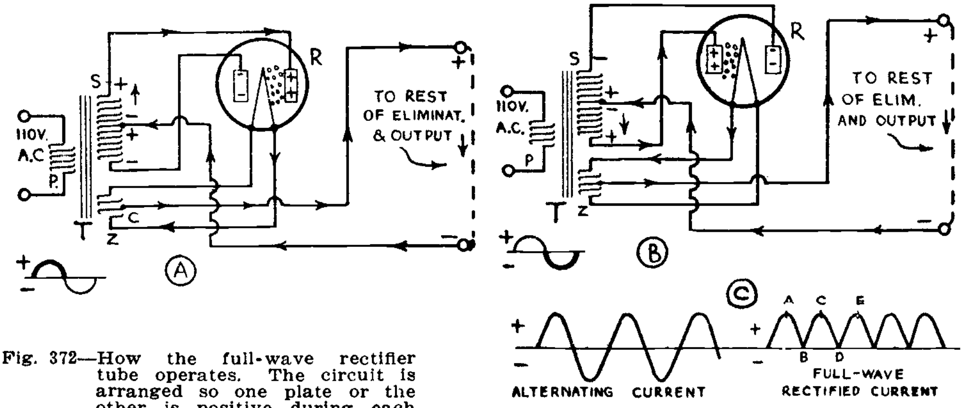


Fig. 372—How the full-wave rectifier tube operates. The circuit is arranged so one plate or the other is positive during each half cycle and is therefore allowing current to flow through to the filament circuit, which becomes the positive side of the output circuit.

504. The full-wave rectifier tube: A single tube which performs the function of full-wave rectification which was accomplished by the two half-wave rectifier tubes in Fig. 371, is known as a *full-wave rectifier tube*. The vacuum type full-wave rectifier tube, consists of two separate plates. Each plate encloses a V-shaped oxide-coated, thick ribbon filament as shown at (B) of Fig. 369. The two filaments are connected in series inside the tube, and in the typical '80 type full-wave rectifier used extensively in electric radio receivers, the entire filament is designed to be heated by a 5 volt source of voltage (see Fig. 214). Since there are two filament terminals and two separate plate terminals, a 4-prong base is employed with the terminal arrangements as shown. The connections of a tube of this type to the power transformer are shown in Fig. 372. The filament is heated by alternating current at 5 volts supplied by the heater winding Z. Each plate is connected to a terminal of the high voltage winding S. The center-tap on this winding connects to the filter and load circuit as shown, the circuit returning to a point in the filament circuit. This point may be either a center-tap on the filament winding as shown, or it may be one end of the winding, no appreciable difference resulting from either connection. The latter is the cheapest arrangement since it eliminates the cost of making the center-tap.

The action of this circuit is exactly similar to that described in Article 503 for the two half-wave rectifier tubes, excepting that the two plates and two filaments are placed together in one tube instead of two separate tubes. This will be now reviewed briefly, referring to the typical full-wave rectifier circuit shown in Fig. 372.

On the positive half of the a-c cycle, the upper terminal of winding S is positive thus making the right-hand plate positive. The lower terminal of S and the left-hand plate are negative. The center tap on S is at a potential half way between these two; it is negative with respect to the upper terminal and positive with respect to the lower terminal. Since the right-hand plate is positive with respect to the center-tap and the filament, it attracts the electrons emitted by the filament. Therefore, a current flows from it to the filament, through half of the filament winding as shown, and out of the center tap to the positive output terminal, through the external filter and load circuit, and back to the negative terminal to the center tap of S. The left-hand plate, being negative, takes no part in the action. Notice that only the upper half of winding S was effective during this period and, therefore, the effective voltage acting on the rectifier tube is half of the total voltage of winding S.

On the next half cycle, the polarity of S reverses and the left-hand plate becomes positive as shown at (B). A current flows from this plate to the filament and around through the circuit as shown. The right-hand plate, being negative, takes no part in the action. Notice that the direction of the current in the external circuit is exactly the same as at (A), so the eliminator delivers a direct current. The wave-form of the applied a-c voltage and that of the rectified output are shown at (C). Notice that both halves of each a-c cycle have been utilized, and the rectified current is much smoother than that produced by a half-wave rectifier and therefore much easier to filter and smooth out completely.

505. Mercury vapor rectifier tube: The development of the hot-cathode type mercury vapor tube rectifier, has been brought about by the demand for a rectifier having a low plate-filament resistance and therefore a low internal voltage drop and high efficiency. The '66 type rectifier (see Fig. 214) is typical of this type of tube. The half-wave type has an oxide-coated filament in inverted "V" form. The plate is suspended horizontally above it and has a disk shape. It connects to a small cap on top of the bulb for external connection. Mercury is introduced into the tube during the time of manufacture. When the filament is heated, a cloud of mercury vapor or free gas atoms of mercury are formed from this. Electrons are also liberated from the heated filament in the usual manner, which, under the influence of a plate potential, collide with the mercury vapor atoms in the space between the filament and plate, to produce ionization of the mercury. This ionization liberates a large number of free electrons from the mercury atoms, in the space between the plate and filament. Since these are immediately attracted by the plate, this increases the current flowing between the plate and filament. Consequently, this type of tube can be built to handle much more current than the ordinary vacuum types. The ionization produced in the tube, produces a characteristic blue glow in it during operation. Due to the presence of the mercury vapor, the resistance of the plate-filament path is low, and is constant over a wide range of load current. This is a true mercury vapor drop, and is generally about 17 volts. Consequently, the loss of energy in the tube itself is very low and the heating of the plate is low. This type of tube is made in several ratings and is capable of handling high voltages and rather large currents, with very little voltage drop and high efficiency. Rectifier tubes are rated on the basis of the peak inverse plate potential and the peak plate current values which they can stand. The maximum *peak inverse plate potential* rating of a rectifier tube is the highest potential the tube will stand in a direction opposite to that in which it is designed to pass current, without danger of internal arcing and short-circuit between the elements. The *maximum peak plate current* of any vacuum tube is the highest peak current that it can stand in the direction in which it is designed to pass current.

In the full-wave type of mercury vapor rectifier tube, two plates and two filaments are used, exactly the same as in the common type '80 vacuum tube rectifier. An idea of the increase in current capacity which is obtained by employing the mercury vapor principle may be gained from the fact that while an '80 vacuum type full-wave rectifier is rated at 400 volts r. m. s. a-c voltage per plate and 120 milliamperes maximum output, a mercury vapor type rectifier of similar construction and size is rated at 500 volts and 300 milliamperes!

506. The filter system: Now that we have seen how the a-c line voltage may be stepped up to any required value by the power transformer, and how the a-c current may be rectified, by either a half-wave or full-wave rectifier of either the vacuum or the mercury vapor type, let us study the operation of the typical filter circuit which smoothes out the pulsating direct current delivered by the rectifier. Examination of (C) of Fig. 372 shows that the output current from the rectifier is a pulsating direct current which increases from zero to maximum value at A, decreases again to zero at B, increases to maximum at C, decreases to zero at D, etc. Any device, which, when connected in the output circuit will store current during the peak-current instants A, C and E, etc., and deliver it back to the circuit during the instants B, D, etc., when the current delivered by the rectifier is low, will serve to smooth out, (*or filter*) the current. Such a device used in a "B" power unit is commonly called the *filter*. Since a condenser has the property of storing electrons or current when a potential difference is applied to its plates, and releases them when the applied potential difference of the circuit becomes less than the potential of the plates, it is natural that condensers should be used for performing this function of smoothing the current flow. They are assisted in their action by iron-core choke or inductance coils (see (C) of Fig. 75) connected properly in the filter circuit. These chokes are wound with a great many turns of wire on steel cores, thus possessing high inductance. They therefore have the characteristic property of an inductance, i.e., they oppose any change in the current flow through them, whether this change be an increase or a decrease in current (Lenz's Law).

A typical full-wave "B" power supply unit circuit with its *brute-force* type filter, is shown in Fig. 373. While several variations of this circuit are possible, it will serve our purposes best for study of the fundamental filter actions, since when its action is understood, the operation of any filter circuits will become clear, because they vary only in minor details. The action is as follows:

The alternating current power transformer steps the 110 volt a-c line voltage up to the high voltage shown at A, which is applied to the plates of the tube. Also, as soon as current is supplied to the primary of the power transformer, the twin filaments in the full-wave rectifier tube heat up. Plate current starts to flow first from one plate to the filament and then from the other, so that the center-tap of the filament-heating winding is always positive with respect to the center-tap of the high-voltage winding. Since the potential difference is being applied across the condenser B, it charges up. Let us start at the instant when the output current and voltage of the rectifier are beginning to increase from zero to maximum (B to C at (C) of Fig. 372). On account of its high inductance (30 henries or so), choke coil F opposes the flow of this increasing current out to the external circuit, and so helps condenser B which is across the circuit, to store a charge of current or electrons into its plates, becoming charged to a potential equal to the peak value. Now the current from the rectifier begins to decrease, (C to D at (C) of Fig. 372). The choke F, by its self- induction action, tends to prevent the current from decreasing (see Article 115), and at the same time, condenser B now being charged to a higher potential difference than that existing across the line, discharges its excess current or electrons. It cannot discharge through the path back through the tube from filament to plate, because current cannot flow in a vacuum tube from filament to plate. It does however, discharge out through choke F and into the external circuit, and so maintains the flow of current through the external circuit even though the rectifier is not supplying much during this time. The result is, that while the current flowing through the rectifier drops to zero during each half cycle as shown at B of Fig. 373, the combined action of the filter condenser and choke keep the current flowing in the external circuit during these instants, as shown by the solid-line curve at C.

The first condenser B can be considered as a voltage regulator insofar as it absorbs each current pulsation in taking a charge from the rectifier output, and feeds the current back to the line when the voltage drops. The charge is absorbed at the peak, thus helping to fill in the valley between the peaks. The first choke coil F opposes the rapid building up of the current as it rises to a peak, by the building up of a counter-electromotive force. As the current reaches its highest value, and begins to decrease, the energy which has been stored in the magnetic field of the coil by the increasing current is now fed back into the circuit. If the current is not smoothed sufficiently by the first choke and condenser of the filter, a second section C-G may be included. In this, the same operation is carried on a second time, but the current on which it operates has had its pulsations smoothed out to a great extent before entering it, and is very much more smooth when it leaves it. The current that passes out of the second choke is usually a very smooth direct current, as shown at D, and the output voltage is sufficiently smooth and steady to be used for the plate circuit supply of a radio receiver.

The third condenser D normally floats across the line in a charged condition, since the voltage across it is practically non-pulsating. However, if a powerful signal or a loud low-frequency note is suddenly received and amplified by the radio receiver, the plate current flowing in the plate circuits of the tubes in the receiver will suddenly increase. Thus increase in the plate current flowing through the circuit of the "B" power supply unit causes the individual I $\times$ R "voltage-drops" in the power transformer windings, rectifier tube, choke-coils, etc., to increase. This would result in a momentary drop in the output voltage of the "B" power supply unit if it were not for the fact that the last condenser D, having been charged to the higher normal voltage, now discharges some of its current back into the line and thus meets the demand for the momentarily increased plate current drain. In this way, this last condenser acts as a reserve current storage device, and keeps the output voltage steady. In some cases, it must be of large capacity (3 to 10 mfd.), if good low-note reproduction is to be obtained. Thus, condenser B controls voltage regulation, C controls hum elimination, and D controls current storage for good quality of low-frequency note reproduction.

It is not always necessary to use two choke coils in the filter system.

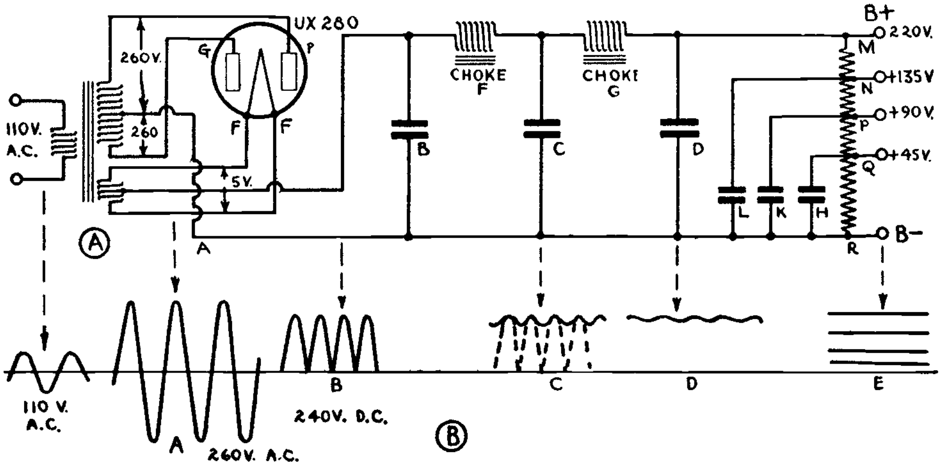


Fig. 373—Complete full-wave "B" power supply unit with 2-section filter. The wave-forms of the currents and voltages existing in the various main parts are shown below. Note that the input is a-c. The output is smooth d-c at various voltages.

In many commercial receivers, the second choke G and condenser D are omitted, the single choke with its two condensers being sufficient to smooth out the current and voltage to the value required for hum-free operation. Also, in many commercial receivers the field coil of the electro-dynamic loud speaker used in the receiver is used as a choke coil in the filter system, as shown at the left of Fig. 344, since it possesses a high inductance. In many cases, especially in midget type receivers, where cost and space are important, the speaker field is the only choke employed. The B current flowing through it serves a useful purpose in energizing the field of the speaker. (Other field connections for the electro-dynamic speakers are shown in Fig. 374). Also, it is not necessary to connect the choke in the positive side of the line as shown in Fig. 373. So far as the filter action is concerned, it may be connected equally as well in the negative side. Many receivers have the choke connected this way, employing the voltage drop in the choke or a part of the choke winding, as a source of C-bias voltage for tubes in the receiver. The receiver circuit of Fig. 282 shows the connection of the field coil (L-11) of the speaker in the negative side of the circuit, as the only choke in the B power supply unit.

Any degree of filtering action may be obtained by using filter condensers of larger capacity and using chokes of larger inductance. However, as the larger chokes and condensers are more expensive, receiver manufacturers use the smallest chokes and the least amount of condenser capacity, that will give satisfactory filter action and even resort to special filter circuit arrangements which improve the filter action so that cheaper chokes and condensers may be used. Although tinfoil-paper type filter condensers are used in filter circuits, (see Articles 138 to 144) the use of dry electrolytic condensers is more widespread on account of their lower cost per mfd., and their more compact form (see Articles 144 to 150). The forms of condensers shown in Fig. 96 are very desirable for this purpose.

507. Filter system arrangements: Several filter system arrangements are used in radio receivers. While the filtering or smoothing action of each is the same, the circuits are arranged somewhat differently in an effort to cheapen the chokes and condensers required. In some systems, the circuit is arranged so as to provide also, the correct C bias voltage for the tubes in the last audio stage of the receiver.

At (A) of Fig. 374, a simple filter in which two chokes or inductances L_1 and L_2, and three filter condensers are employed is shown. In most cases, the field coil of the electro-dynamic loud speaker used with the receiver acts as the second choke L_2, (see Article 460). In this way, it obtains its proper energizing current, and at the same time, serves a useful purpose as a choke in the filter. When a 2-choke system of this kind is used, the plate voltage for the tubes in the last audio stage of the receiver is taken off by tapping the circuit ahead of the last choke, as shown.

This is done to supply a higher voltage to these tubes, since the voltage drop through the last choke is not included. Also, it reduces the direct current flow through the second choke, and thereby lessens the steady field in it. This means that since the tendency of the core to saturate is reduced, the choke may be made smaller and cheaper for a given inductance value. Also, any plate circuit coupling which might exist between the last audio stage and other tubes in the receiver, due to the common heavy plate current flowing through the impedance of the chokes, is reduced, since the second choke is eliminated from the circuit of the last audio tubes by this method. It is true that the plate voltage and current supplied to the last audio tube will not be filtered as well. This is not objectionable, since some plate current ripple can be tolerated here because there are no following tubes to amplify any slight hum voltage which may be set up across the plate load. In general, the plate current supplied to the power output tube in the receiver requires very little filtering, the first a-f and r-f amplifier tubes require more, and the detector tube requires most.

At (B) a filter arrangement in which but a single choke coil and two filter condensers are used, is shown. Usually the electro-dynamic speaker field of the receiver is used as the choke coil. Notice that the first filter condenser is of larger capacitance than the usual first filter condenser used in the 2-choke system. This is necessary in order to secure adequate filtering action. This system is used most in midget-type receivers, since it reduces the cost of the filter, and considerable space is saved in the chassis since no choke other than the speaker field winding is needed. Dry-electrolytic type filter condensers (see Fig. 96) are usually employed on account of their low cost per mf., and small physical dimensions.

At (C) a *tuned choke* filter system is shown. The choke L contains two windings wound or connected so their magnetic fields oppose each other. The inductance L and the condenser C_2, form a resonant circuit of low impedance, which effectively eliminates the ripples in the current, provided the circuit is so designed that resonance is produced at the frequency at which the ripples occur. The advantage of this circuit is that a small low-cost choke and fairly low values of capacitance gives good filtering action.

At (D), the Miessner *tapped-choke system* is shown. Here, the rectifier is connected to the filter choke by a tap at some point near one end,

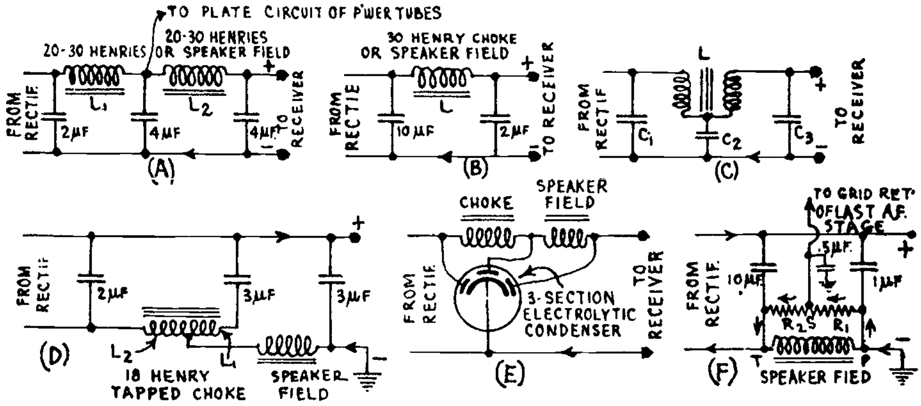


Fig. 374—Various arrangements of chokes and filter condensers used in the filter systems of power supply units in a-c electric receivers.

the filter condensers being connected to the ends of the choke winding. This arrangement reduces the ripple in the current by a factor of five to ten over that obtained with the same choke and condensers connected in the usual manner of (A). Or, conversely, it will provide just as good filtering with considerably smaller values of inductance and capacitance.

The increased filter action is due to a neutralizing effect between the induced a-c components of the two portions of the choke. That is, a rather strong induced a-c component flows through the portion marked L_1, the coupling of which to L_2 neutralizes to a large degree the induced a-c voltage component therein, so that the output pulsations are reduced. A tap located at about 20 per cent from the end (considering the number of turns) is quite effective.

The fact that this system is patented, and is available to receiver manufacturers only on a royalty basis, has perhaps prevented it from being used more extensively, since material savings in the cost of the choke and condensers are obtained by its use. The tapped choke may either be used alone, or another choke (usually the speaker field) may be used with it as shown at (D).

At (E), a common filter circuit with a 3-section electrolytic filter condenser is shown. The common negative terminal of the condenser connects to the negative side of the circuit. Filter condensers of the general type shown at the center of Fig. 96 may be used for this purpose.

At (F), a filter system used in many R. C. A. Victor receivers, is shown. In this the speaker field is used as the choke. Across this are the two resistors R_1 and R_2, properly proportioned so that a negative C-bias voltage of the proper value is obtained by the voltage drop through them. The operation of this interesting arrangement is as follows:

The speaker field acting as a filter choke, is connected in the B- line as shown. The plate-return circuits in the receiver are grounded to the metal chassis which acts as the common B-terminal. The total plate current for the entire receiver returns from the grounded chassis to point P, where it divides in the parallel circuit consisting of the speaker field and resistors R_1 and R_2, as shown by the arrows. The current flowing through each path will be inversely proportional to its resistance. Since current flows from P to S to T, point S is at a lower potential than point P (the grounded chassis) by an amount equal to the voltage drop in resistor R_1. Since the grid return lead of the last audio stage connects to point S, this is thereby maintained at a definite negative potential or grid bias with respect to point P (which connects to the cathode of the tube or tubes in the last audio stage). In this way, by properly proportioning R_1, R_2, and the resistance of the speaker field, the C-bias voltage for the last audio stage is obtained. Resistors R_1 and R_2 may be separate individual units or may simply consist of a single resistor tapped at the proper point.

508. The chokes and filter condensers: The choke coils used in power supply units must have the necessary self-inductance to provide proper filtering in combination with the filter condenser capacities used. The core should be designed with a proper air-gap, to reduce the tendency to saturate due to the steady value of the d-c current flowing through the winding. The use of electro-dynamic speaker fields as choke coils in the filter system is very common. The wire used on the choke should be of sufficient size to safely carry the current continuously without overheating. When the current rating of a choke is exceeded, its inductance decreases rapidly (see Art. 123), and the filtering action is greatly reduced, with consequent increase of hum. The filter condensers may be either of the tinfoil-paper type, (see Figs. 90 to 93), or the electrolytic type. The latter presents the advantages of cheapness, small physical dimensions, and self-healing properties of the dielectric. A single 8 mf. electrolytic condenser and 30 henry choke coil from a B power unit filter system are shown in Fig. 124. These really form a low-pass filter section. An idea of the comparative size of an 8 mf. dry electrolytic condenser and a tinfoil-paper condenser of similar capacitance and voltage rating may be obtained from Fig. 94.

The filter condensers must be built to withstand the *peak* voltages encountered. The condenser nearest the rectifier is subjected to the highest peak voltage. As the voltages at the input of the rectifier and immediately following it are *alternating* and pulsating direct current voltages, respectively, the values usually specified for them are the "*effective values*". The "effective voltage" is the value of voltage which gives exactly the same heating effect as an equal direct current of the same potential. This is the value which an a-c voltmeter indicates. The peak value of an alternating voltage is the maximum value to which the voltage rises during any part of the cycle. Assuming that the output of the rectifier is of sine-wave form, the peak voltage is 1.41 times the effective voltage. As the insulation of the filter condenser immediately following the rectifier must safely stand the peak voltage twice during each cycle, the condenser used must have a voltage rating exceeding the peak voltage, for safety.

(Note: The relation between "peak" voltage and effective voltage is explained in detail in Art. 107.)

509. The voltage divider: If only one value of plate voltage were required by all of the tubes in a radio receiver, the power supply unit would now be complete, but since the various tubes require different plate voltages, provision must be made to supply them. This is the function of the *voltage divider system.* The fundamental principle involved in all voltage divider systems, is that whenever current is made to flow through a resistance connected in the circuit, a certain amount of the e. m. f. applied to the circuit is used up in forcing the current (or electrons) through the resistance.

The common expression applied to this condition is, that there is a *fall of potential* or *voltage drop* in the resistance. The voltage drop resulting in any case, may be calculated by Ohm's law ($E=I\times R$). Keeping the principle in mind, it is evident that all we need to do to obtain various plate voltages, lower than the maximum voltage appearing at the output terminals of the filter in the power supply unit, is to connect resistances of suitable values in the plate circuits of the various tubes, so that a fall of potential occurs in each, due to the flow of the plate current through it.

510. Voltage divider systems: Three general connection arrangements are possible for the voltage divider resistors. These will now be studied by means of receiver circuit diagrams in which all of the parts

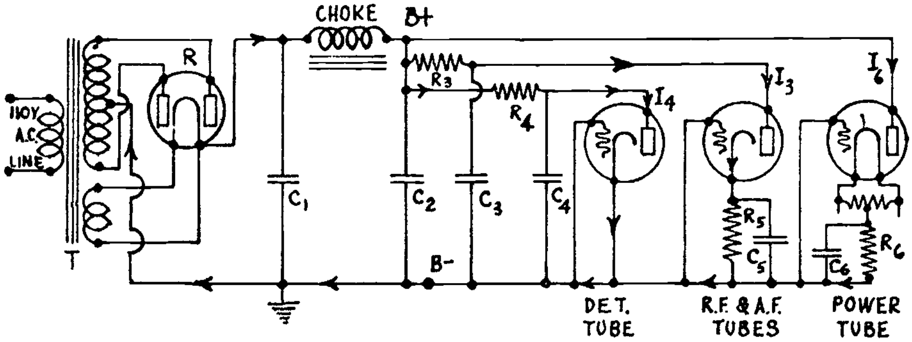


Fig. 375—A typical voltage divider system for power supply units. Various voltages are obtained by making the plate currents of the tubes in the radio receiver (shown at the right) flow thru suitable individual resistors in order to produce voltage drops.

not entering into the operation of the voltage divider system, have been omitted for simplicity. The detector and amplifier tubes in the receiver are shown with their essential plate circuit and grid circuit connections only, all tuning condensers, transformers, tube couplings, etc. being omitted. The path of the plate current of each tube, is indicated by arrows on the diagrams. The filament circuits are also omitted.

A simple form of voltage divider system is shown in Fig. 375. The typical power transformer T, rectifier R, and single-choke filter system are at the left. The plate circuit of the power tube is connected directly to the high-voltage B+ terminal of the filter ouput. The C-bias voltage is obtained by the voltage drop in resistor R_6. The path of the plate current I_6 is from the B+ terminal, through the plate circuit, through R_6, and back to the B— side of the power unit, as shown. The plate current I_3 for first

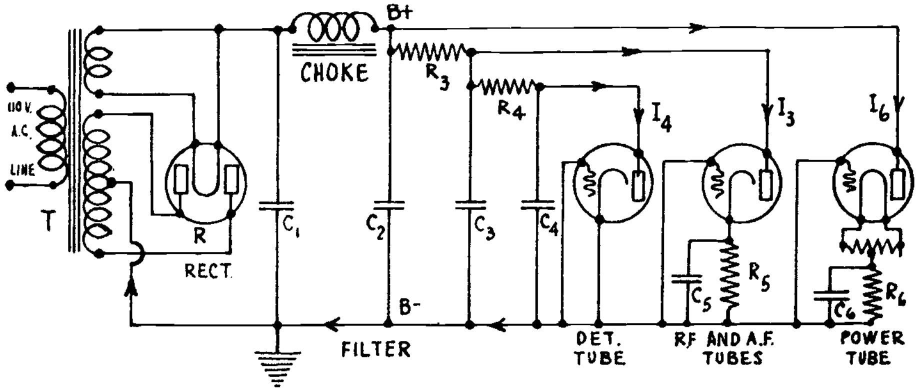


Fig. 376—An improved form of voltage divider system for power supply units. In this, the detector plate current obtains additional filtering to completely smooth it and reduce hum.

a-f tubes, (represented by a single tube in the diagram), flows through resistor R_3 and down through the plate circuit, through C-bias resistor R_6 and back to B—. The plate voltage effective at these tubes, is equal to the maximum voltage output of the power unit minus the I×R voltage drop in resistor R_3. Suppose the former voltage is 300 volts, the total plate current through R_3 is 20 milliamperes, (.020 amperes), and it is desired to supply a plate voltage of 180 volts to these tubes. Then a voltage drop of 300—180=120 volts, must occur in the resistor R_3. Its value must therefore be R=E/I=120/.020=6,000 ohms. In this way, the value of the resistance required to produce any voltage drop may be calculated. By connecting another filter or by-pass condenser C_3 as shown, the resistor R_3 and condenser C_3 act as a resistance-capacity filter, and some additional filtering of the plate current supplied to these tubes, is obtained. The proper plate voltage for the detector tube is obtained by connecting the resistor R_4 in its plate circuit, the actual plate voltage effective on the detector tube being equal to the output voltage of the power unit minus the I×R voltage drop in resistor R_4. By connecting condenser C_4 as shown, additional filtering of the detector plate current is obtained.

Another voltage divider arrangement which possesses some advantages over this one, is shown in Fig. 376.

As before, the plate circuit of the power tube (or tubes) connects directly to the high voltage B+ output terminal of the filter. The plate voltage for the r-f and 1st a.f tubes is reduced by resistor R_3. It obtains additional smoothing or filtering from R_3 and C_3 which really form a filter section. The plate current I_4 for the detector tube flows through R_3 and R_4 in series. The condensers C_3 and C_4 act as filter condensers. Therefore, with this arrangement, the detector plate current is really filtered again by a two-section filter, (R_3, C_3 and R_4, C_4), after leaving the main filter of the power unit. Hence the plate current of the detector is filtered more than that of any other tube in the receiver, and is therefore smoother. This is desirable, since the detector tube is more sensitive to disturbing plate current ripples than any other tube in the receiver. These voltage divider systems can be extended to provide any desired plate voltages on any of the tubes in the receiver.

In Fig. 377 (and in Fig. 373) another voltage divider arrangement is shown.

Here a tapped resistor of the general type shown in Figs. 27, 28 and 378 is connected across the "B" power unit output, between points E and H. The resistor contains taps suitably located at points F and G. These divide it into the resistor sections R_1, R_2 and R_3.

The current through the resistor section G-H is I_1 (not marked on the diagram). The current flowing from point E to F is $I_1+I_4+I_3$. Since current I_3 branches off at F, the current in R_2 is, I_1+I_4. As I_4 branches off at G, the current in R_1 is I_1 alone. The plate current I_6 flows directly to the power tube, without entering the resistor. Since the entire resistor is across the output of the filter, a "bleeder" current will flow steadily through it from the positive to the negative terminal. The condensers C_3 and C_4 assist the filtering action, in the same way as explained for the previous system. In order to produce the proper voltage drops in R_1, R_2 and R_3, so that the voltages at F and G are of the desired values for the proper operation of the tubes, these resistance sections must be proportioned carefully.

The following example will illustrate how such a resistor is designed.

Referring to Fig. 377, let I_3 be 20 milliamperes and I_4 be 5 milliamperes. Let the output voltage of the filter, across points E and H be 300 volts. It is desired to apply plate voltages of 180 and 90 volts to the amplifier and detector tubes, respectively (ne-

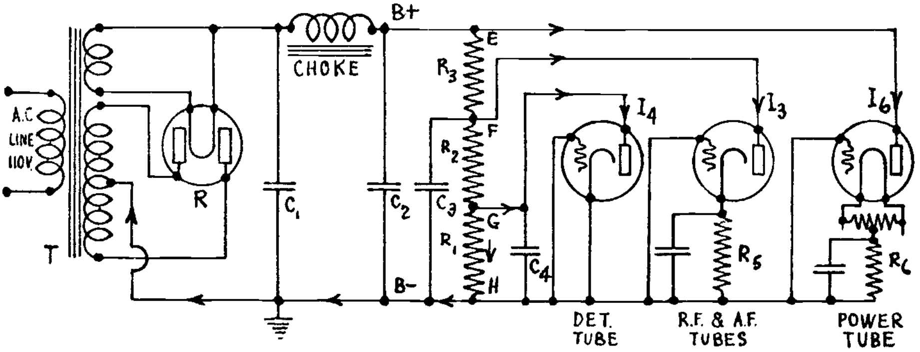


Fig. 377—Voltage divider system of the "bleeder resistor" type.

glecting the voltage drop in R_5 and R_6). The "bleeder" current through the entire resistor must be not over 10 milliamperes (this is equal to current I_1).

Since 10 milliamperes (.010 amperes) flows through R_1, and point G is at a potential 90 volts higher than point H, resistor R_1 is equal to, $R_1=E/I=90/.010=9{,}000$ ohms. The difference of potential between points F and G is $180-90=90$ volts. This is equal to the fall of potential through R_2. The total current through R_2 is equal to $I_1+I_4=10+5=15$ m.a. Therefore, $R_2=90/.015=6{,}000$ ohms. The difference of potential between point E and F, (voltage drop in R_3), is 300—180=120 volts. The total current in R_3 is equal to $I_1+I_4+I_3=10+5+20=35$ m.a. Therefore $R_3=120/.035=3{,}400$ ohms. (Approximately.)

It is evident that if exact plate voltages are to be obtained, the voltage divider system in any receiver must be designed especially for the particular number and types of tubes to be operated and the voltages to be applied. Examination of Figs. 376 and 377 shows that the voltage divider in the latter is really the same as in the former, with the exception of R_1. This resistor is called the *bleeder resistor* since it allows the small *bleeder* current to flow through it to the B— minus terminal and back to the rectifier circuit, steadily.

This has one advantage in that it places a small load on the power supply unit almost as soon as the receiver is turned on, since the filament of the rectifier tube heats and begins to emit electrons almost immediately. The separate-heater amplifier tubes do not heat so rapidly, and they may not begin to pass plate current for several seconds. Placing the load on the rectifier immediately, prevents the high-voltage surge produced by the self-inductance action of the high voltage secondary of the power transformer, which would otherwise act on the filter condensers. This therefore lengthens their life. The disadvantage of course, is that the bleeder current flows continuously and places an additional load on the rectifier and the filter. However, by making the resistors of high enough value it may be kept down to a fairly unobjectionable value of 10 or 20 milliamperes.

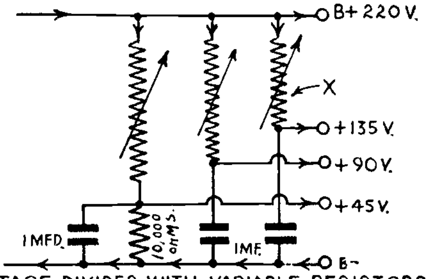
Although the voltage divider resistors are usually placed near the amplifier tubes in order to shorten the wiring in the receiver, they are properly considered as part of the "B" power unit. The resistors are usually either of the wire-wound type or the solid compressed-carbon type. Several wire-wound resistors suitable for this purpose are shown in Fig. 28. At the left of Fig. 378 is a tapped wire-wound voltage divider resistor of the vit-

Courtesy Ward Leonard Elect. Co. *Courtesy Aerovox Wireless Corp.*

Fig. 378—Left: Tapped, wire-wound voltage divider resistor for medium-voltage power supply units.
Right: 2-section tapped wire-wound voltage divider resistor for high-voltage power supply units.

reous enameled type designed for use in power packs delivering medium values of voltage. Its total resistance is approximately 12,000 ohms. At the right is a 2-section tapped, wire-wound resistor used in high voltage power units for public-address systems, etc., in which '81 type rectifier tubes are employed. Its total resistance is about 41,000 ohms. The resistors used should be of proper wattage rating, (I^2R), to safely carry whatever current must flow through them, without undue temperature rise. They should be mounted where they will receive continuous ventilation so that the heat will be carried away as fast as it is developed.

511. Voltage divider with variable resistors: In experimental work, it is often convenient to have a power supply unit having variable resistors in the voltage divider. They may be arranged somewhat as shown at the left of Fig. 379. The 10,000 ohm fixed bleeder resistor is at the bottom. The voltages marked at the taps give some idea of the values which may be obtained from a small unit. Of course, the voltage



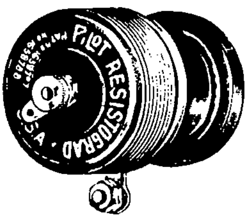
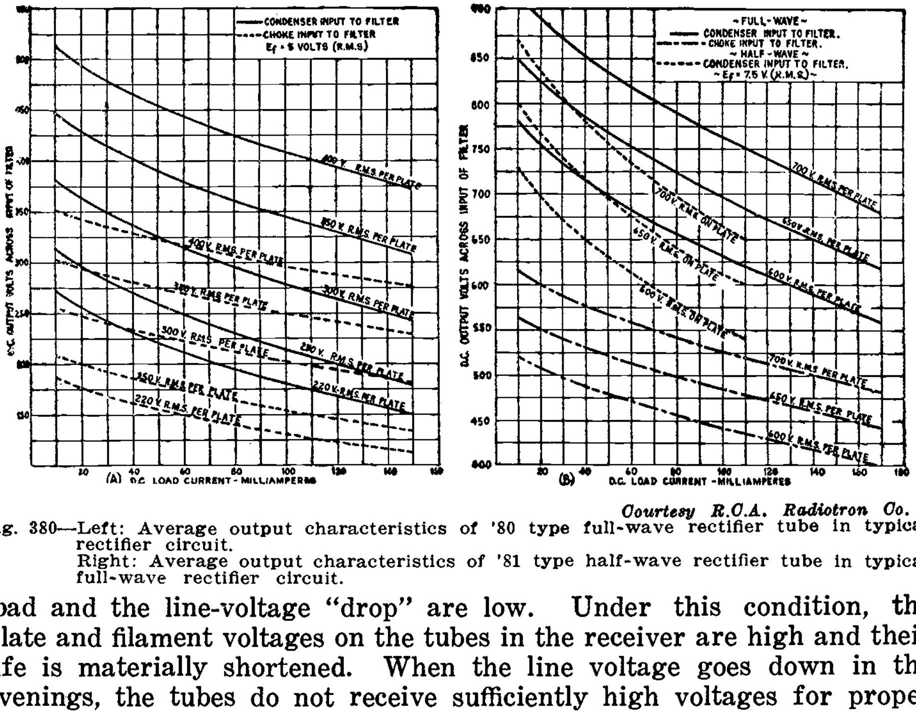


Fig. 379—Left: Voltage divider system with variable resistors. The voltage at each tap may easily be raised or lowered.
Right: A typical powdered-graphite flaked-mica type heavy-duty variable compression resistor for use in the type of voltage divider shown at the left. Its resistance range is from 40 to 10,000,000 ohms.

at each tap may be varied above or below the value marked, simply by varying the resistor in its circuit. A form of heavy-duty variable resistor suitable for this purpose is shown at the right. This is of the powdered-graphite flaked-mica compression type. The case is of metal, with circular cooling-fins to increase the radiation and conduction of the heat developed by the passage of the current through the resistance material.

512. Output-voltage regulation: The current delivered by a "B" power supply unit must flow through the resistance of the high-voltage secondary winding of the power transformer, through the plate-to-filament resistance of the rectifier tube, through the resistances of the chokes, and through the voltage divider resistances. A voltage drop occurs in each of these resistances, proportional to the current flowing. Therefore, the output voltage will not be constant for various values of current drawn from the unit. Of course, no general statement can be made regarding all of these voltage drops since the values of the resistances of the various parts are different in different power units. The voltage drop in the standard types of rectifier tubes can be studied however, by means of the curves shown in Fig. 380. The curves show the voltages existing across the input of the filter for various d-c load currents, when certain fixed values of voltage are applied to the plates of the rectifier tube. The curves at the left are for the '80 type full-wave rectifier tube. Those at the right are for two conditions; one (solid lines), where two '81 type half-wave tubes are connected up in a full-wave rectifier circuit as in Fig. 371; the other (dotted lines), is for a single tube in a half-wave circuit. The curves are drawn both for the type of circuit in which the rectifier connects directly to the choke coil without any filter condenser between, and for the usual arrangement where the first filter condenser follows the rectifier. Notice, that in all cases, the available output voltage drops as the load is increased.

512A. Line-voltage regulation: In all of those localities where the electric light circuit line-voltages vary considerably from hour to hour, or day to day, the output voltages of the "B" power unit may also vary. In such districts, the voltage is high in the mornings and afternoons when the



Courtesy R.C.A. Radiotron Co.

Fig. 380—Left: Average output characteristics of '80 type full-wave rectifier tube in typical rectifier circuit.
Right: Average output characteristics of '81 type half-wave rectifier tube in typical full-wave rectifier circuit.

load and the line-voltage "drop" are low. Under this condition, the plate and filament voltages on the tubes in the receiver are high and their life is materially shortened. When the line voltage goes down in the evenings, the tubes do not receive sufficiently high voltages for proper operation. Several devices to reduce this difficulty have been used.

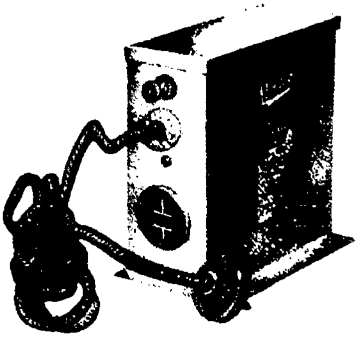
The use of a resistor connected in series with one side of the lighting circuit line has been used extensively because of its simplicity and cheapness.

Typical units of this type, are made in the form shown at the left of Fig. 381. The resistance element is enclosed by the ventilated metal protecting case. The lower end plugs into the lighting circuit socket. The plug from the power supply unit of the radio receiver plugs into the top end. This automatically connects the resistance in series with one side of the line. Some units of this type are made with the resistance easily adjustable to adapt it to the particular requirements of any particular installation. Line-voltage regulators of this type, are only able to reduce the voltage applied to the receiver, down to a certain required value. They are not able to boost the voltage up to this value if the line voltage should fall below normal value.

Gas-filled ballast tube voltage regulators, and glow tubes of various kinds, have also been developed for protecting the receiver from harmful rises in line voltage. The ballast lamp is connected in series with the primary of the power transformer, and consists of an iron filament wire having a high temperature coefficient of resistance, through which the current for the receiver flows.

The filament is enclosed in a glass bulb which contains hydrogen gas. When the line voltage varies, the voltage drop across the tube varies due to its change in resistance, and the voltage effective across the primary of the power transformer remains practically constant. One objection to this form of regulation is that a voltage drop of 40 volts or more occurs in it, and a considerable amount of electrical power is wasted in it in the form of heat. Also, the primary of the power transformer must be wound specially for the 60 or more volts which exist across it, and on which it must operate.

The "glow tube" type of regulator typified by the UX874 type (see Fig. 214) is connected across the 90 volt tap of the voltage divider. It is gas-filled and possesses



Courtesy Ward Leonard Elect. Co. *Courtesy Aerovox Wireless Corp.*

Fig. 381—Left: A resistance type of line voltage regulator which is plugged in between the receiver power-input plug and the electric light supply socket.
Right: Typical electric light line "interference eliminator" containing two by-pass condensers having their common junction connected to ground. This connects between the lighting circuit socket and the radio receiver plug.

the characteristic such that the voltage across it remains practically constant at 90 volts for all current from 10 to 50 milliamperes.

Several special forms of voltage regulators which operate by magnetic action, have been perfected for keeping the voltage at the receiver terminals constant regardless of whether the line voltage drops or raises above the normal value. While this is the ideal form of voltage regulator, these devices have not found general application in medium priced radio receivers on account of their additional cost. They are used extensively however, in other fields of application where cost is not so important.

513. Line disturbances: In many electric receiver installations, electrical disturbances originate in the electric light supply lines. These enter the power supply unit via the power transformer primary and are transferred to the secondary circuit and thus to the plate supply of the amplifier tubes in the receivers. The reader must have observed the "click" produced in an electric radio receiver, when an electric light switch is turned on or off in the house, and has probably heard the hum produced when a small household motor is turned on. Interference of this kind may become very serious, especially in apartment houses in cities where many electrical devices are being operated on the same lines. No general remedy for this condition can be given, since there are so many possible sources and types of interference.

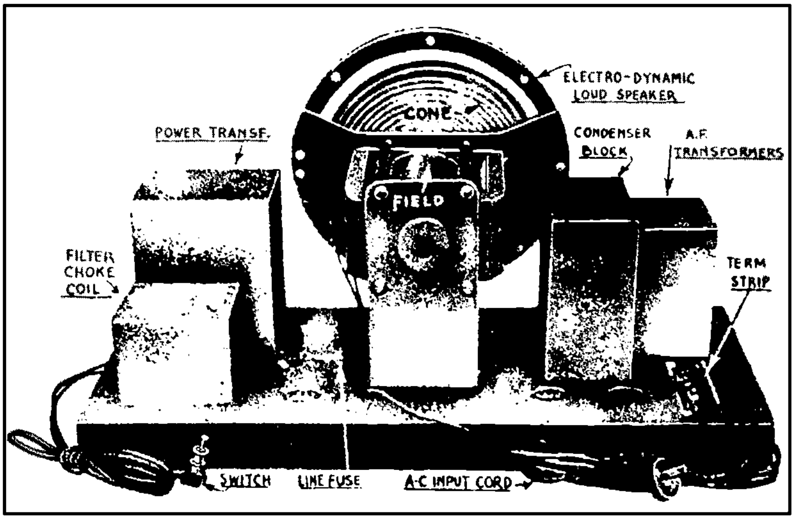
Sometimes two 1 mfd. condensers connected in series with each other and *across* the electric light circuit, are very effective. The junction of the two condensers should be connected to ground. A commercial interference eliminator unit of this type, is shown at the right of Fig. 381. In some cases, it is necessary to connect an r-f choke coil in series with each side of the line, ahead of these condensers. The chokes must be wound with wire of sufficient current-carrying capacity to safely carry the full current taken by the receiver. In some power supply units, an r-f choke coil of about 85 millihenries inductance is connected in the positive lead between the filament circuit of the rectifier tube and the first filter condenser to prevent any r-f disturbances from reaching the r-f amplier in the receiver, via the plate circuits. This may be small in size, and wound with wire of small current carrying capacity, since only a small current flows through this circuit.

It must be remembered, that all electrical disturbances in electric receivers may not be picked up through the electric light circuit. In many cases, the antenna lead-in wire is acted on by the fields created by the disturbances. In such cases, it is necessary to shield the lead-in wire with a copper braid shielding connected to ground. Special shielded, or lead covered wire, is made for this purpose. The entire antenna wire should not be shielded of course, for then it would no longer be acted upon by the fields of the transmitting stations and the signals from the stations would not be received. To test for the source of disturbance, operate the receiver with the noise coming in loudly. Now, disconnect both the antenna and ground wires from the receiver. If the interfering noises stop, it indicates that they were coming in via the antenna circuit. If they continue, they are originating in the power supply line. Shielded lead-ins are discussed in Art. 613 and shown in (A) of Fig. 464.

514. Complete "B" power supply unit: Now that we have studied the operation, construction and circuit arrangement of the various parts in an a-c receiver "B" power supply unit, we are prepared to study a typical complete unit of this type. In midget type receivers, the power supply equipment is built on the same chassis with the amplifier and detector portions, since the entire receiver must be built in a single unit, and as compact as possible. This construction may be seen from an inspection of the illustration of the midget receiver chassis in Fig. 286, and that in Fig. 298. In Fig. 298 the shield on the power unit has been removed to show the arrangements of the main parts. U is the power transformer and V is the filter choke. The condenser block is mounted underneath. The rectifier tube is directly in front of the filter choke. The voltage divider resistors are not visible in the illustration.

In the larger receivers which are designed to be installed in console cabinets, the power supply unit, the loud speaker, and the last audio stage, are usually mounted on a chassis separate from that of the amplifier and detector portion. A typical power unit and last audio stage speaker, assembly of this type is shown in Fig. 382. This is sometimes referred to as a "power amplifier". This arrangement results in several advantages. First, when the weight of the power supply unit is included on the receiver chassis, there is a possibility that the receiver cabinet shelf will warp and that the stresses caused by shipping will tend to strain the chassis to an extent which may affect the alignment of the plates in the gang tuning condenser. Another advantage is that the assembly and the later testing and servicing of the power supply unit are made easy. Also the vibration caused by the loud speaker is not communicated directly to the detector tubes, and therefore less tendency toward howling due to vibration of the tube elements results.

The exact circuit diagrams and arrangements of the types of complete power supply units applied in a-c electric radio receivers, phonograph



Courtesy R.C.A. Victor Co.

Fig. 382—A typical power supply unit, loud speaker, and last audio stage chassis assembly for an a-c electric receiver. The various parts are enclosed in metal protecting cases, and are mounted on a rigid steel base.

amplifiers and public-address systems, will be studied in the later chapters dealing with these devices.

515. "B" power supply unit for d-c lines: While the voltage appearing across direct current electric light circuits is always in one direction, it is not an absolutely steady, smooth voltage. The reason for this becomes apparent if we refer back to Article 106, and Fig. 68.

It will be remembered, that each d.c. generator used in the power house for generating the direct current voltage, is constructed with a commutator for rectifying the a.c. voltages which are actually generated in the coils of the armature. The resulting voltage is really a rectified a.c. voltage and contains slight ripples or pulsations as shown at (C) of Fig. 68. This condition is similar to that existing in the output circuit of the rectifier tube in the power supply units designed to operate from a.c. lines, only the pulsations are not quite so prominent. If a voltage of this kind is applied to the plates of the amplifier and detector tubes in a radio receiver, every slight change in value of the voltage will cause a corresponding change in the plate current and this being amplified by each tube appears as quite a large ripple in the output current or voltage. The diaphragm of the loud speaker will vibrate in accordance with this ripple in the plate current, and an objectionable low-frequency hum results.

Obviously, in order to make this line voltage suitable for B-supply, the pulsations or "ripples" must be removed. This can be accomplished satisfactorily by means of a filter system similar to that used in the "B" power supply units already described for a-c circuits, excepting that since the voltage ripples in d-c lighting circuits are not as pronounced as those which appear in the output circuit of a vacuum tube rectifier, a comparitively small amount of filtering is required. Usually a single 30-henry choke connected in series with the line, together with two 2-mfd. filter condensers across the line (one on either side of the choke), are sufficient. In some lines, such as those fed by small d-c electric light systems in rural communities, where the armature on the generator does not contain a great many coils of wire, the ripple in the voltage may be pronounced. In this case two choke coils and larger condensers may be required. These may be

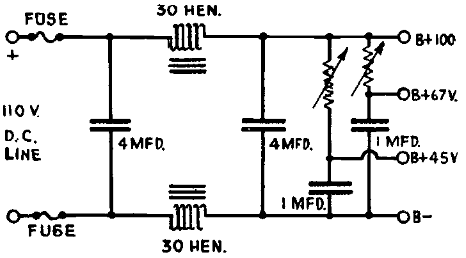
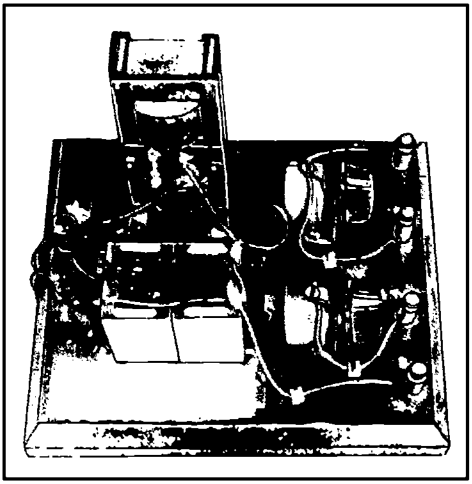


Fig. 383 — Left: circuit diagram of a B-power supply unit for operation from the 110 v. d-c electric light circuit. In most cases, only one of the chokes is required, and 2-mf. condensers may be used.



Right: A unit built from the diagram shown at the left. This is constructed in "bread board" style for laboratory use.

connected as shown at the left of Fig. 383. The output-voltage divider system is of simple form, consisting either of a tapped fixed resistor across the output circuit, or variable resistors as shown. Proper by-pass condensers are shunted across the taps as shown, to prevent interstage coupling due to the common plate circuit impedance in the eliminator. They assist the filtering action of course. If these by-pass condensers are already incorporated in the receiver, they may be eliminated from the power pack. An actual laboratory form of B-power supply unit of this type for d-c circuits is shown at the right. Notice the simplicity of the unit, as compared with the a-c type in which the power transformer, rectifier, etc., are required. The double choke is at the rear, in front of this are the two filter condensers, and at the right are the variable resistors.

One disadvantage of operation from d-c lighting circuits, is that the voltage cannot be stepped up by any simple device such as a transformer, etc., because transformers will not operate on direct circuits. Therefore the maximum voltage available from the B-power supply unit does not exceed that of the electric light circuit. Actually it is a few volts less, due to the I $\times$ R voltage-drop in the resistance of the filter chokes. The circuit arrangement of a complete receiver designed for operation from the d-c electric light line, will be studied in the next chapter.

516. Measuring the output voltages: When measuring the output voltages delivered by a "B" power supply unit, a high-resistance type voltmeter having a resistance of at least 1000 ohms-per-volt (see Art. 205) should always be employed instead of using an ordinary type of voltmeter. The full-scale range should be adequate for the voltages delivered by the unit.

The ordinary type of voltmeter has a resistance such that the meter draws quite some current from the circuit being measured, for its operation. This amount of current is required to operate the meter. When measuring the voltage of an ordinary low-resistance circuit, this is not objectionable, but when measuring the voltage across a circuit having apparatus of fairly high resistance connected in it, this current drawn by the meter must flow through the resistance of this apparatus, thus causing a "voltage-drop" in each piece of apparatus. Consequently as soon as the meter is connected across the circuit, it causes the voltage existing across the circuit to drop. The voltage reading indicated on the meter is therefore *lower* than that actually existing across the circuit when the meter not connected, so that the *true* voltage reading is not obtained.

The moving-coil element of the high resistance type voltmeter is built so sensitive that it requires only 1 milliampere of current through it to make the needle deflect over full scale (in a 1000 ohms-per-volt meter). Therefore since it draws but a small current from the source, it does not cause the voltage to drop appreciably. Consequently, it gives a reading which is the *true* voltage existing across the circuit. For this reason, a high-resistance type voltmeter should always be used when measuring the output voltage of a "B" power supply unit (see Art. 205).

REVIEW QUESTIONS

1. State three advantages of operation of a radio receiver with a B-power supply unit operating from the a-c electric light circuit, over operation with "B" batteries.
2. Show by diagrams and explain in detail why the voltage from an a-c electric light circuit cannot be used directly for plate voltage supply in a radio receiver.
3. Name the four principle parts of a "B" power supply unit and describe the function of each. Draw a block diagram showing the units connected in proper sequence.
4. Explain the operation of the half-wave rectifier tube.
5. Explain and show by diagrams, how two half-wave rectifier tubes may be connected to form a full-wave rectifier circuit.
6. Explain the operation of the full-wave rectifier tube.
7. What advantages does the mercury vapor rectifier tube possess over the vacuum type? What feature of its construction is responsible for this?
8. Draw a circuit diagram of a complete "B" power supply unit for operation from the a-c line. A full-wave rectifier tube is employed, and the filter contains a 30 henry choke and the field

of an electro-dynamic loud speaker. The unit is to supply 300, 180 and 45 volts to the plate circuits of the tubes in the receiver. Explain the operation of each part in the unit.

9. Draw the circuit diagram for four filter system arrangements. Explain the operation and advantages of each.
10. What are the requirements of (a) a satisfactory choke coil; (b) a satisfactory filter condenser, in a filter system.
11. Which condenser in a two-section filter is called upon to withstand the highest voltage? Why?
12. Draw the circuit diagram of a "B" power supply unit arranged to provide the "C" bias voltage for the push-pull tubes in the last audio amplifier stage of the receiver.
13. It is desired to obtain a plate voltage of 135 volts for an amplifier tube whose plate current is 5 milliamperes. A voltage source of 300 volts is available. Show by a diagram, how this may be arranged, and calculate the values of the parts required.
14. The potential of the high-voltage line in a radio receiver is 300 volts. It is desired to operate four '27 type amplifier tubes, and two '47 type pentode tubes in push pull, at their maximum rated plate voltages, from this line. Draw the circuit diagram showing all connections, and calculate the values of all resistors required to supply proper plate and grid voltages for the tubes. (See Fig. 214.)
15. Why should a "high-resistance" voltmeter be used for all voltage measurements in "B" power supply units?
16. Draw the circuit diagram for a "B" power supply unit designed to operate from the 110-volt d-c electric light circuit. The voltage divider is to be of the fixed-resistor type and is to be designed to supply 15 m.a. at 90 volts, 5 m.a. at 45 volts, and 5 m.a. at 22½ volts. The maximum output voltage available is 100 volts.
17. Why is it necessary to use a filter in a unit of this kind? Is more, or less, filtering required than in the case of a power supply unit operating from an a-c line? How does this affect the size of the chokes and condensers, and their cost?
18. What will happen in a "B" power supply unit operating from an a-c line, if the paper dielectric in one of the filter condensers becomes punctured? How does this affect the operation of the receiver? What would happen if electrolytic type filter condensers were used?
19. What will happen if the windings in one of the filter chokes becomes; (a) short-circuited; (b) open-circuited?
20. What happens if an open-circuit occurs in one of the voltage divider resistances, if the system shown in Fig. 375 is used?
21. Explain what happens when the rectifier tube gets old and its electron emission diminishes greatly.

CHAPTER 28

ELECTRIC RECEIVERS

ELECTRIC RECEIVERS — D-C ELECTRIC RECEIVERS — SERIES FILAMENT CIRCUIT — TYPICAL D-C ELECTRIC RECEIVER — A-C TUBE ELECTRIC RECEIVERS — TYPICAL T-R-F A-C ELECTRIC RECEIVER — TYPICAL SUPERHETERODYNE A-C ELECTRIC RECEIVER — TYPICAL MIDGET SUPERHETERODYNE RECEIVERS — GENERAL CONSIDERATION OF A-C RECEIVER DESIGN — HUM IN ELECTRIC RECEIVERS — REVIEW QUESTIONS.

517. Electric receivers: In Chapter 27, various types of practical "B" power supply units, for supplying unvarying, smooth, direct current voltages to the plate circuits of radio receiving equipment were described. These take their power from the electric light socket, one form being used with a-c lighting circuits and another form being used with d-c lighting circuits. The problem of supplying the current for heating the filaments of the tubes in the receiver, is solved by using tubes of the indirect-heater type, in which the electron-emitting cathode is heated by a heater-filament electrically insulated from it.

Before proceeding further with the study of electric receivers, it will be well to become familiar with the nomenclature which has originated in connection with this subject. It is obvious that various combinations of electrical operation methods can be resorted to in any set. Thus a receiver may use a "B" power supply unit operated from the electric light line, but use a storage "A" battery for filament supply. Such a set is not a true electrically-operated receiver.

The following standard definitions adopted by the Radio Manufacturers Association will be used in this book.

(1) *"Battery-Operated Receiver"*: A radio receiver designed to operate from primary batteries and (or) storage batteries.

(2) *"Electric Receiver"*: A radio receiver operating from the electric light line without using batteries.

(3) *"A-C Tube Electric Receiver"*: A radio receiver employing tubes which obtain their filament or heater currents from an a.c. electric light line without the use of rectifying devices, and with a built-in rectifier for the plate and grid-biasing potentials.

(4) *"D-C Tube Electric Receiver"*: A radio receiver employing tubes which obtain their filament or heater current from a direct current electric light line, without the use of rectifying devices, and with a built-in power supply for the plate and grid biasing potentials.

It is evident from these definitions that a true electric receiver does not use batteries of any kind, all filament, plate, and grid voltages being obtained entirely from the power taken from the electric light circuit. Since there are two forms of current, (a-c and d-c), furnished by electric light circuits, the two types of electric receivers defined in (3) and (4) will now be studied.

518. D-C electric receivers: In many localities, *direct current* is furnished by the electric light and power company, for electric lighting. The electric radio receivers to be used in these places, must be designed to operate with this direct current as a source of power. As outlined in Article 515, the voltage and current in a commercial d-c electric light

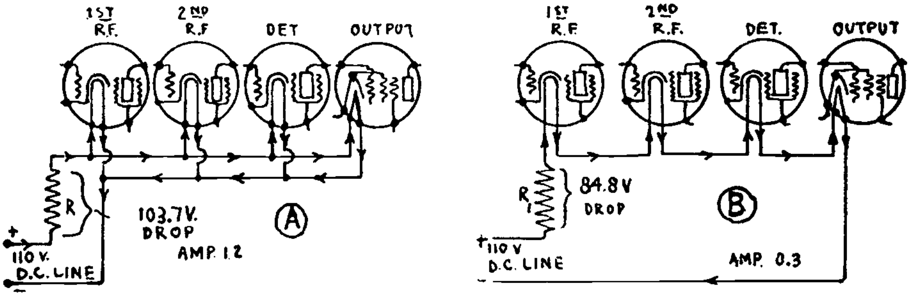


Fig. 384—(A) All of the tube filaments connected in parallel.
(B) All of the filaments connected in series in a d-c electric receiver.

circuit is not absolutely smooth and unvarying, but contains pulsations or "ripples" due to the action of the commutator on the d-c generator. A satisfactory filter system for smoothing the voltage and current for the plate circuits of the tubes in the receiver was described in Article 515. This solves the problem of d-c electric operation insofar as the plate circuits are concerned. It is not practical to filter the filament-heating current for the tubes, because the cost of such a filter would be unreasonably great. It is really not necessary to filter this current anyway. If tubes such as the '12A type, or the later '36, '37 and '38 types, are employed in the receiver, no objectionable hum results if the unfiltered current from the line is used for heating the filaments. While good d-c electric receivers have been constructed using '12A type tubes, the development of the separate-heater type tubes referred to above, makes possible the construction of d-c electric receivers whose operating characteristics are very much superior. We will consider the use of these separate-heater type tubes only.

519. Series-filament circuit: Since the filaments of the d-c electric receiver are to be operated from the 110 volt electric light circuit, two filament circuit arrangements are possible. These are, the parallel arrangement, and the series arrangement. If we consider the use of separate-heater type tubes such as the '36, '37 and '38 which were developed especially for service of this kind, we find from Fig. 214, that they require a filament voltage of 6.3 volts and take a filament current of 0.3 ampere each.

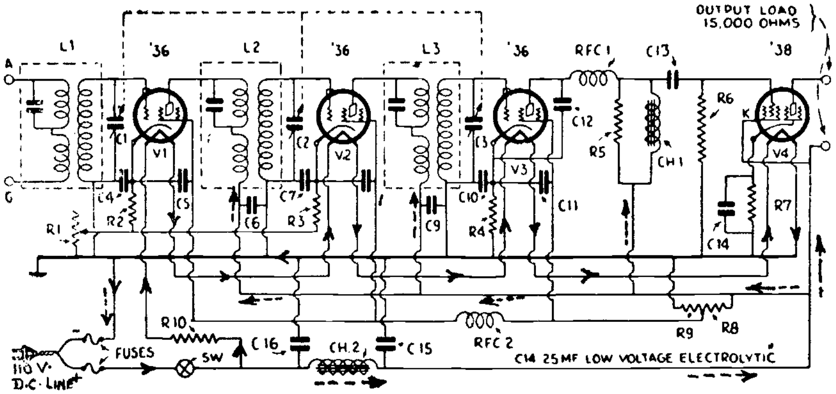
Let us consider the simple four-tube d-c electric receiver, whose circuit is shown in Fig. 385, and in which these types of tubes are employed. If the filaments of the tubes were connected in parallel, as shown at (A) of Fig. 384, a resistor R would have to be connected in series with them to drop the line voltage of 110 volts, to 6.3 volts for the filaments. The total filament current, $0.3 \times 4 = 1.2$ amperes would flow through this resistor. The voltage drop required in it, would be $110 - 6.3 = 103.7$ volts. Therefore its resistance would have to be equal to $R = E/I = 103.7/1.2 = 86.4$ ohms. The power dissipated in the resistor would be equal to $W = I^2R = 1.2 \times 1.2 \times 86.4 = 124.4$ watts. This is quite a large amount of electrical power to be dissipating in the resistor in the form of useless heat, just to drop the voltage down to the proper value. The total power taken from the line for the entire filament circuit will be, $W = E \times I = 110 \times 1.2 = 132$ watts. Let us see what happens if we connect the filaments in series, as shown at (B). The total current in the circuit is now equal to 0.3 ampere—the same as that for one tube. The total voltage to be applied to all of the filaments in series is $6.3 \times 4 = 25.2$ volts. Therefore a series resistor R_1 must be connected in the circuit as shown, to drop the voltage to the proper value. The voltage drop in R_1 must be equal to $110 - 25.2 = 84.8$ volts. The resistance required to produce this voltage drop is equal to $R = E/I = 84.8 \div 0.3 = 282$ ohms. The power dissipated in this resistance will then be equal to, $W = I^2R = 0.3 \times 0.3 \times 282 = 25.4$ watts. The total power taken from the line for the entire filament circuit is $W = E \times I = 110 \times 0.3 = 33$ watts.

The advantage of the series-filament connection for receivers of this type is evident. In the first place, since the voltage-dropping resistor must dissipate less power in the form of heat in the series arrangement, it can be constructed smaller and more cheaply. In the second place, a large saving in the power taken from the electric light circuit results. In this case, it is 132 watts for the parallel arrangement, and only 33 watts, (¼ as much) for the series arrangement. A large amount of the power is wasted in the series resistor in the parallel arrangement. The advantages of the series arrangement are apparent. Insofar as the heating of the filaments is concerned, one circuit is just as effective as the other.

520. Typical d-c electric receiver: The complete circuit diagram of a 110 volt d-c electric receiver employing the series-filament connection, is shown in Fig. 385. Four separate-heater tubes are employed. Due to the separate-heater construction, the filament current need not be filtered, since the ripples in it do not affect the emission of electrons from the cathode. The filament current flows from the positive side of the 110 volt d-c lighting circuit through the "on-off" switch, up through the 282 ohm resistor R_{10}, through filaments V_1, V_2, V_3 and V_4, and back to the negative side of the line, as shown by the solid arrows.

An ordinary 40 watt, 110 volt incandescent lamp bulb could be used as resistance R_{10}, since it has a resistance of approximately 300 ohms and would allow about 0.29 amperes to flow through the filament circuit when the line voltage was 110 volts. The tubes would operate satisfactorily with this current, and some margin of safety would be secured in the event of the line voltage rising to 115 volts or more at times.

The receiver employs two stages of tuned r-f amplification using screen grid tubes, a screen grid power detector, and a power pentode output tube. The r-f coils L_1, L_2 and L_3, are of the special resonated primary type, (see (3) of Fig. 290A), for uniform r-f amplification. Tuning condensers C_1, C_2 and C_3 are the sections of a 3-gang condenser, for singe-dial tuning control. The grid-bias voltages for the tubes are obtained by means of the voltage drops in the resistors R_2, R_3, R_4 and R_7 respectively, connected in the cathode circuits. By-pass condensers of suitable values shunt these resistors. The volume control resistor R_1 in the common cathode return circuit, varies the grid bias on the two r-f tubes. The filter system for the plate voltage supply consists of 30 henry choke CH_2 connected in series with the positive side of the line, and filter condensers C_{15} and C_{16} connected across the line. The paths of the plate currents of the various tubes, are shown by the dotted arrows. The proper screen grid voltage is obtained from potentiometer R_8 connected from B— to the B+ line. The r-f choke RFC_2 and by-pass condensers C_5 and C_{11} in the screen grid circuits prevent interstage coupling which might otherwise be caused by the



L_1=Shielded Antenna Coil
L_2, L_3=Shielded R.F. Coils
R.F.C.$_1$—R.F.C.$_2$=85 M.H. R-F Chokes
CH_1=A-F Transformer Secondary
CH_2=30 Henry Choke
R_2, R_3=800 Ohms
R_1=50,000 Ohm Volume Control
R_4=10,000 Ohms Bias Res.
R_5, R_6=.5 Meg.
R_9=5000 Ohms

C_1, C_2, C_3=3 Gang Variable Cond.
C_4, C_5, C_6, C_7, C_8, C_9, C_{13} .01-μF. By-pass Cond.
C_{10}, C_{11}=1μF By-pass Cond.
C_{12}=.001 μF By-pass Cond.
C_{14}=25 μF Low-voltage, Dry-electrolytic Cond.
C_{15}, C_{16}=200 v. Filter Cond. (One 2μF, One 4μF)
R_7=1200 Ohm Bias Res.

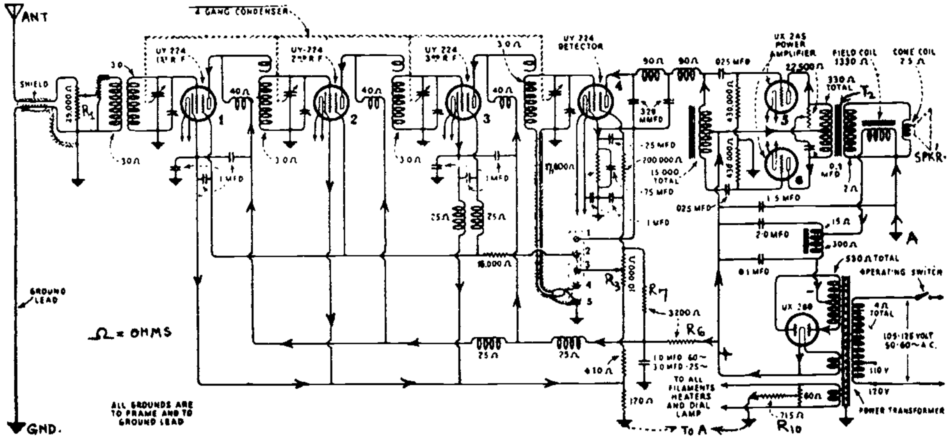
Courtesy Radio Craft Magazine

Fig. 385—A typical modern 4-tube receiver designed to operate from the 110-volt d-c electric light line. It employs two screen grid t-r-f. amplifier stages, a screen grid detector, and a power pentode output tube—all being of the separate-heater type.

common impedance in the circuit. Since grid-bias resistor R_7 has a resistance of only 1200 ohms, a rather large value of by-pass capacity C_{14} must be connected across it to prevent serious degenerative effects in the pentode circuit due to the varying plate current flowing through R_7. A low-voltage type electrolytic condenser is suitable for this.

It should be remembered that the line plug for any d-c electric receiver must be inserted properly in the receptacle so that the "positive" side of the line connects to the "plate" side of the circuit. If the plug is reversed, the plates of the tubes have a negative potential applied to them, and the receiver will not function.

521. A-C tube electric receivers: The construction of a-c electric receivers embodies the many principles which we have studied in previous chapters. In general, there are three main circuit arrangements employed in receivers of this type. The first, is the ordinary t-r-f receiver which employs several stages of tuned radio-frequency amplification. The second is the band-pass selector type receiver, in which the tuning is accomplished in a band-pass selector preceeding the amplifier tubes, as shown in Fig. 258. Then the wanted signal is amplified by several stages of untuned r-f amplification. The third is the superheterodyne circuit. Of course, each of these employs a detector and at least one audio stage. The r-f amplifiers of modern receivers employ screen-grid type tubes on account of their many advantages. The detector tubes may either be of



Courtesy R.C.A. Victor Co.

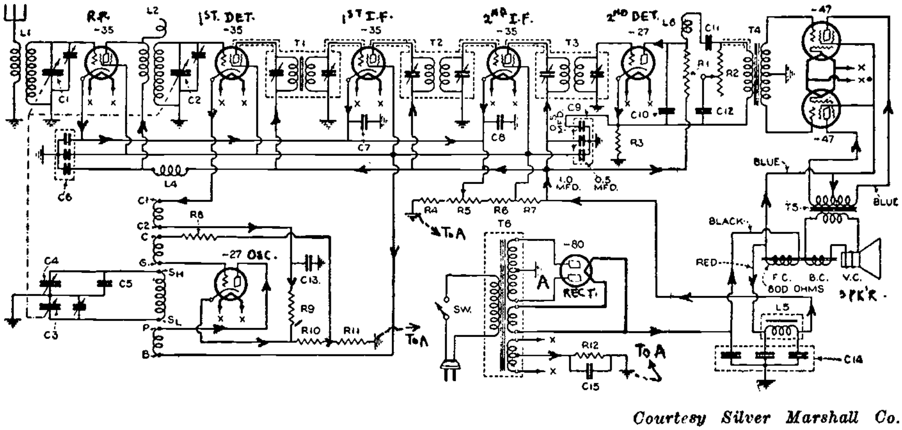
Fig. 386—Typical a-c electric screen grid t-r-f. receiver employing 3 stages of t-r-f. amplification, screen grid detector, and single stage push-pull a-f amplifier. The arrows show the directions of flow of the plate currents of the various tubes.

the screen-grid, the 3-electrode, or the power pentode types. All a-c electric receivers contain a rectifier, filter, and voltage divider system for making the a-c line voltage suitable for use in the plate circuits of the tubes. Separate-heater type tubes, heated by raw a-c current obtained from low-voltage windings on the power transformer, are commonly employed, with the exception of the power amplifier tubes, which are usually of the direct-heater, thick-filament type. Grid-bias voltages are obtained by utilizing the voltage drops occurring in resistors of proper values connected properly in the circuit for this purpose.

522. Typical t-r-f a-c tube electric receiver: The circuit diagram of a typical t-r-f a-c electric receiver is shown in Fig. 386. This employs three stages of tuned screen-grid r-f amplification, a screen-grid power detector, and a single push-pull audio stage using '45 type power amplifier tubes. An analysis of this circuit follows:

The four tuning condensers are constructed in gang form for single-dial tuning control. The r-f coils have a "capacity winding" shown at the top, to equalize the r-f amplification over the broadcast band (see (2) of Fig. 290A). A dual-type volume control consisting of potentiometer R_1 in the antenna circuit and R_3 in the screen grid circuits of the r-f tubes is employed. Tone control is obtained by means of the 22,500 ohm resistor and 0.1 mf. condenser, across the primary of the push-pull output transformer. All of the filaments of the tubes are connected in parallel across the 2.5 volt heater winding on the power transformer. A full-wave rectifier tube is employed and the rectifier filter system is of the Miessner type, with a tapped filter choke in the negative side of the circuit. The field of the loud speaker connected in series with this, also acts as a filter choke. The proper plate voltage for the r-f tubes is obtained by means of the voltage-dropping resistor R_6. The direction of the plate current flow of each tube is shown by the arrows. Resistor R_7 drops the voltage to the proper value for the screen grids. The grid bias voltage for the power amplifier tubes is obtained by the voltage drop across resistor R_{10} connected in the plate current return circuit of these tubes. The resistance of the plate circuits of the power amplifier tubes in push-pull is matched to the low impedance of the speaker voice-coil by means of the special output transformer T_2.

523. Typical superheterodyne a-c tube electric receiver: The complete circuit diagram of a typical superheterodyne a-c electric receiver is shown in Fig. 387. This employs a stage of t-r-f amplification ahead of the first detector, using a variable-mu type tube. Two stages of intermediate-frequency amplification are employed, with band-pass tuner interstage coupling transformers T_1, T_2 and T_3, each having a tuned primary and a tuned secondary. The second detector is of the 3-electrode power type, and feeds into a push-pull power pentode amplifier stage. The pair of '47 type pentode tubes in push-pull are capable of handling from



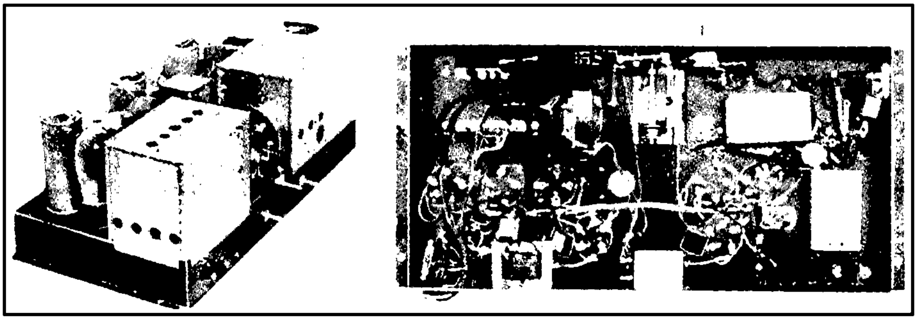
Courtesy Silver Marshall Co.

Fig. 387—Circuit diagram of a typical a-c tube electric superheterodyne receiver employing variable-mu and power pentode tubes. The arrows show the paths of the plate currents. The actual receiver is shown in Fig. 388.

6 to $7\frac{1}{2}$ watts of power—which is ample for home requirements. Excellent volume control is obtained by means of resistors R_4 and R_5, which vary the grid bias applied to the variable-mu amplifier tubes. Due to the fact that these tubes can handle large values of signal voltage without rectification, cross modulation effects are not troublesome, and no preselector is required ahead of the first r-f tube. The oscillator tuning cir-

cuit is of the "padded" type designed to be tuned in synchronism with the r-f and detector tuning circuits.

The plate current of the second detector tube is brought through resistor R_1 and is isolated from the primary of the audio transformer T_4 by condenser C_{11}, the combination of R_1, C_{11}, and the primary of T_4 making up the Clough system of tuned a-f amplification. This is designed to produce slight over-amplification of the audio fre-



Courtesy Silver Marshall Co.

Fig. 388—Top and bottom views of the a-c superheterodyne receiver shown in Fg. 387. Note the sturdy metal chassis, and the simplified wiring which results from a careful design and proper layout of all parts and wiring.

quencies between 50 and 100 cycles, to compensate for the deficiencies of the loud speaker on these frequencies (see Arts. 431, 451 and 485). The tone control circuit consists of rheostat R_2 of 500,000 ohms resistance, and condenser C_{12} of .025 mf. capacity.

The power supply unit utilizes a full-wave rectifier tube, with power transformer T_6 supplying all filament and plate voltages. Winding X-X supplies the low voltage a-c current for the parallel-connected filaments of the tubes in the receiver. Resistor R_{12} is the C-bias resistor for the power pentode tubes. The filter circuit utilizes one choke coil L_5, and the 800-ohm speaker field F.C., together with three 4-mf. dry electrolytic condensers C_{14}, and in addition, the filtration effect provided by the hum-bucking coil B.C. in the speaker voice-coil circuit and the additional by-pass condensers in the plate circuits. The plate voltage for the power pentodes is taken off from the point between the two chokes. The voltage divider consists of resistors R_7, R_6, R_5 and R_4 connected between the high voltage side and B—. The high voltage is supplied direct to the plates of the amplifier and detector tubes. The paths of the plate currents through the receiver are shown by arrows on the diagram. It will be very instructive for the reader to trace these paths through the receiver. Resistor R_7 drops the voltage to the proper value for the screen grids and the plate of the oscillator tube. Resistor R_4 and the portion of R_5 included between this end and the movable arm determine the control-grid bias voltage of the r-f and i-f tubes, this being employed as the volume control. Resistor R_4 is used to assure that at least a certain value of grid-bias potential will be applied to the amplifier tubes even when the arm of the volume control resistor R_5 is set at its extreme left position.

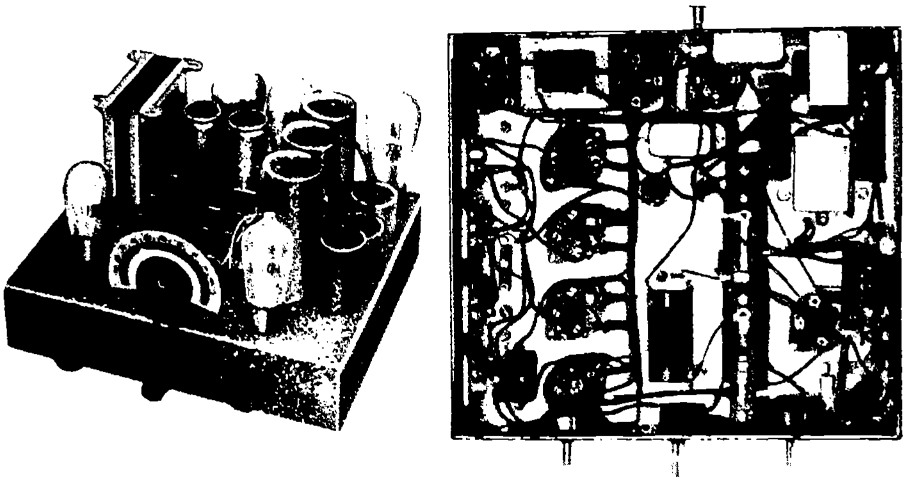
The loud speaker is designed especially for over-accentuation of the high audio frequency note reproduction, to compensate for the suppression of the upper side band frequencies in the r-f and i-f amplifiers in an attempt to secure exceedingly sharp tuning in these circuits. The proper combination of low-frequency compensation in the audio amplifier, and high-frequency compensation in the loud speaker, (see Article 485), gives an overall frequency-response which provides satisfactory reproduction, considering that the 10 kc channel basis, on which stations are allowed to transmit, permit them to transmit only those audio frequencies up to about 5,000 cycles. The tone control provides an adjustment of the high-frequency response to suit the taste of the individual listener.

The sensitivity of this receiver is such, that an actual signal voltage of 2.84 to 1.85 microvolts (depending on the frequency of the station) applied in the antenna circuit (standard 4 meter effective height) will produce the standard output of 50 milliwatts in the output circuit. These figures divided by 4, give a sensitivity of from .71 to about .46 microvolts-per-meter (see Art. 347). Sensitivities of this order are really higher than can be utilized in practice in most locations because of static, electrical disturbances, etc., and are high enough to receive any signal sufficiently above the prevailing noise level, to be intelligible.

A top view of this receiver showing the simplified construction, is shown at the left of Fig. 388. The power supply unit is contained in the ventilated shield at the front left. The gang tuning condenser and oscillator tube are at the right. At the rear are the various tubes, shielded from each other. The rectifier and power amplifier tubes are shown at the lower left. The illustration at the right shows the arrangement of the wiring and the smaller parts such as tube sockets, audio transformers, plate and C-bias resistors, by-pass condensers, volume and tone control resistors, etc., under the chassis. Notice that while the circuit diagram of Fig. 387 looks fairly complicated, the actual construction and wiring of the receiver itself is also simple, as a result of the great care observed in laying out the parts and wiring.

524. Typical midget superheterodyne receivers: The so-called *midget type* receivers, have attained a definite status in the low-price radio receiver field. They are constructed in very compact form, and are enclosed, together with the electro-dynamic loud speaker, in very compact cabinets which may be placed on a suitable table, and readily be transported. While it is true that midget type receivers are not able to reproduce the lower audio frequencies down to anywhere near 40 cycles, due to the fact that the loud speaker baffle which is formed by the receiver cabinet is necessarily very small, fairly pleasing reproduction is obtained by properly suppressing the high-note reproduction so the tone appears low to the ear. Of course this is not true undistorted reproduction. From the standpoint of amplification, the midget type receiver may be constructed to have practically as high a value of sensitivity as the larger receivers, provided a reasonable amount of cabinet space is available for the parts. The results accomplished by receiver designers in this field, are little short of marvelous. Of course, the development of the high-amplification screen-grid and variable-mu tubes, the high power sensitivity pentode tubes, the development of the compact form of dry electrolytic filter condensers, and the compact form of electro-dynamic loud speaker have all assisted materially in making this form of receiver possible. A typical midget receiver chassis and loudspeaker is shown in Fig. 286. An idea of the relative size and spacing of the parts may be obtained, when it is realized that this entire chassis is just 12 inches wide. A sensitivity of 6 to 10 microvolts-per-meter is obtained. Another midget superheterodyne receiver whose chassis measures only 12 inches long, 10¾ inches deep and 8 inches high overall, is shown in Fig. 389. Notice the compact arrangement of the parts and the simplified wiring under the chassis.

Both the t-r-f and the superheterodyne circuits have been used extensively in receivers of this type. Of course, screen-grid type tubes, and power-pentode output tubes (either singly or in push-pull), are employed almost exclusively, since less stages of amplification are required when they are employed. The circuit diagram of a typical t-r-f midget receiver is shown in Fig. 390. This contains two stages of tuned radio-frequency amplification employing variable-mu tubes, a screen grid power detector



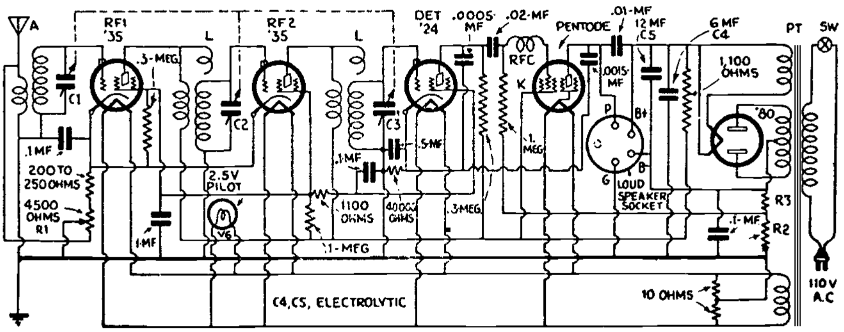
Courtesy Radio News Magazine

Fig. 389—Top and bottom views of a typical midget superheterodyne chassis which measures only 12x10¾ inches. This contains two stages of i-f amplification, first and second detectors, and a push-pull audio output stage—8 tubes in all, including the rectifier.

and a single power-pentode output tube. The r-f transformers employ the small capacity coupling winding to equalize the sensitivity throughout the tuning range. The power detector is resistance-capacity coupled to the output '47 type pentode tube. The full-wave rectifier circuit employs two electrolytic filter condensers, and the field coil of the loud speaker, (which connects between G and B in the loud speaker plug socket shown) acts as a filter choke in the B— lead. The reader should trace and study the various features of circuits such as these, as much valuable practice and knowledge will thereby be obtained.

Fig. 391 shows the rear view of a typical midget receiver chassis with electro-dynamic loud speaker, in a small midget cabinet. Notice the loud speaker, mounted against the top of the front face of the cabinet. The chassis is suspended in the floating rubber suspensions shown at the sides of the cabinet, to reduce the vibration which would otherwise be communicated directly from the loud speaker to the tubes, by the cabinet.

525. General consideration of a-c receiver design: It is obviously impossible because of space limitations, to present and discuss in a text of this kind, a large number of circuit diagrams of commercial receivers being manufactured. The author does not feel that it would be desirable to include these anyway, for the details of vacuum tube and radio receiver designs are constantly being improved and changed from



Courtesy Crosley Radio Corp.

Fig. 390—Circuit diagram of an a-c electric midget type receiver employing two stages of screen-grid t-r-f amplification, power detector, and a single power pentode audio output tube.

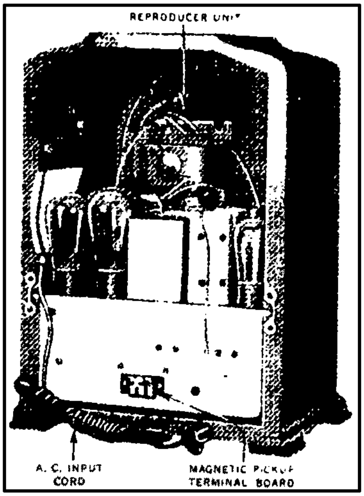
season to season. It is felt that the typical circuits presented here will enable the reader to understand the general circuit arrangements employed in the various types of receivers. It will be found, that as a rule, receivers marketed by various manufacturers differ only in minor circuit details, structural design of the parts and mechanical arrangement. The student who is well grounded in the fundamentals concerning vacuum tubes and the theory of receiving systems should have no difficulty in analyzing the circuit of any particular receiver in which he may be interested, at any time. In fact, it is strongly urged that he develop the habit of studying and analyzing the latest receiving circuits which are published in the popular radio magazines and circuit diagram manuals. A little experience in doing this, will enable him to quickly analyze the important features of any receiver circuit in but a few minutes.

Receiver design has progressed so rapidly in the United States that it is difficult to see where any radical improvement in operating characteristics can be made—under present broadcasting conditions. Medium priced receivers are available, which have as much sensitivity as it is possible to employ in practice on account of the "noise level" resulting from all sorts of extraneous electrical disturbances such as "static", disturbances set up by electrical machinery and appliances, etc. Tone quality in many of the larger receivers employing satisfactory baffling for the loud speaker, has been improved to a point where the average listener would not notice any further improvement. It would seem that any further radical improvements which may be effected will be along the lines of even further simplification and reduction of size and cost of the receiver, rather than in marked improvements in operating characteristics.

525A. Hum and noises in electric receivers: An electric receiver should operate without objectionable hum or other extraneous noises due to the electric operation. Absolutely silent operation is difficult to obtain in receivers which reproduce the audio frequencies down to 60 cycles. However, in well designed receivers, the hum is reduced to a value where it does not cause objectionable disturbance, and is practically unnoticeable.

One frequent cause of a-c hum in a receiver, is the interaction between the magnetic fields of the parts in the power supply unit and those in the audio amplifier. As shown in Fig. 391A, the power transformer used in the power unit, as well as the filter chokes, and the audio transformers used in the receiver, have magnetic fields which spread out to a considerable distance in their vicinity. If these parts are placed close to each other so that the fields and windings interact, alternating voltages will be induced in the chokes and the audio-frequency amplifier transformer coils, and will be amplified along with the signals, producing a bad hum in the loudspeaker. Any slight a-f voltage induced in the first audio transformer is especially liable to cause troublesome hum, as this voltage is amplified several hundred-fold by the audio amplifier. The use of a resistance coupled first audio stage eliminates this, since a resistance coupling unit does not have coils to pick up induction effects. The use of a resistance-coupled audio stage following the detector in a-c tube electric receivers has become very popular for these reasons.

The power transformer, the chokes, and the audio transformers (especially the first stage one) must be kept a suitable distance apart to avoid this trouble. Thus distance is best determined by experiment with the particular units used, by shifting the parts around. This trouble can also be reduced effectively by locating the parts in such relation to each other that the magnetic fields are at right angles to each other. Also keep all grid and plate leads as short as possible, and away from all circuits carrying alternating current. The wires carrying a-c should be twisted to prevent magnetic induction effects (see Art. 124). Faulty a-c tubes or faulty rectifier tubes are also a frequent cause of hum in a set. They can be detected by plugging new tubes in their places while the receiver is operating.



Courtesy R.C.A. Victor Co.

Fig. 391—Rear view showing position of chassis and loud speaker in a typical midget type receiver. Notice the compact construction.

Noisy sets usually present quite a problem, as it is usually difficult to locate the source of the trouble. To locate the cause of noises, first find out if the scratchy noises are coming from the aerial circuit or from the set, tubes, power unit, or batteries. To do this, first operate the set so the scratchy noises come in loudly. Now disconnect both the aerial and ground from the set and short the "Ant" and "gnd" terminals of the receiver with a short piece of wire. If the noises stop, it indicates that they have been caused by some outside electrical disturbance sending the electrical impulses to the aerial. In this case, you will have to try to locate the cause of the trouble and eliminate it.

If the noises continue when the aerial is disconnected, it indicates that they originate in the equipment. Check over every connection to make sure it is made tightly. Now try a new tube in each socket at a time to find out if one of the regular tubes is causing the noises.

Hum or howling is sometimes caused by one or more microphonic tubes in the set. To locate a microphonic tube, operate the set so that the hum or howl comes in very loud. Now press your hand firmly down on each one of the tubes in the set in turn. When you do this to the microphonic tube, the hum will decrease in strength or disappear altogether. It should either be replaced with a new tube, or one of the weighted "howl-arresters" made for this purpose should be placed on it. They can

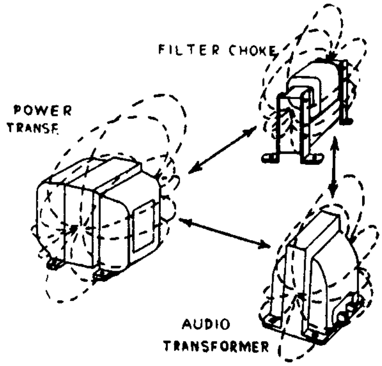


Fig. 391A—How the external or "stray" varying magnetic fields existing in the space around the power transformer and filter choke coils in a power supply unit may act on the windings of an audio transformer and induce 60 or 120-cycle a-c voltages in these windings. These induced hum-voltages will be amplified greatly by the a-f amplifier in the receiver and will result in an objectionable 60 or 120-cycle hum from the loud speaker. To prevent this, the a-f transformer should be mounted at some distance away, and with its core at right angles with those of the other units.

be purchased at radio stores for a nominal sum. Placing the speaker too close to the set sometimes causes a hum or howl due to the strong sound waves from the speaker setting up a mechanical vibration of the tubes. When the tube elements vibrate (at the audio frequency), the distance between them changes, resulting in corresponding audio-frequency plate current changes which are amplified by the audio amplifier, resulting in a hum or a bad howl. The remedy for this is to mount the speaker at some distance from the set, or use weighted rubber "howl-arresters" on the sensitive tubes located by the above tests.

REVIEW QUESTIONS

1. Show by an actual example, why it is more satisfactory and economical to operate the filaments of the tubes in a d-c electric receiver in series, than in parallel.
2. A d-c electric receiver is to be constructed with six tubes having their filaments connected in series across a 110 volt line. Each filament is rated at 5 volts and 0.25 ampere. What must be the resistance value and wattage rating of the resistor which must be connected in series with the filament circuit? Draw a diagram showing the complete filament circuit only.
3. Describe briefly what must be done to the current from the d-c electric light line before it can be applied in the plate circuits of the receiver.
4. Draw a diagram showing the "B" supply circuits and filter for the receiver in question 2.
5. Explain why it is not possible to use "raw" a-c applied directly to the plate and grid circuits of an a-c electric receiver.
6. Draw a circuit diagram showing the "B" and "C" circuits of an ordinary 5 tube t-r-f a-c electric receiver, complete with the "B"

power supply unit in which the speaker field and an additional 30 henry choke coil are used in the filter.

7. What is the advantage of using screen-grid tubes of the variable-mu type instead of the 3-electrode type, in the r-f or i-f amplifier circuits of a receiver?
8. What are the advantages of using power pentode tubes instead of 3-electrode power tubes in the output stage?
9. What are the relative advantages of a-c and d-c current supply for the operation of electric receivers?
10. Draw the complete circuit diagram, with all filament, plate, and grid-bias voltage supply circuits, of a three-stage tuned r-f a-c electric r-f amplifier, using variable-mu type tubes. Use your own ideas regarding volume control, etc.
11. Add a screen-grid power detector to the circuit in the previous question.
12. Add a push-pull audio output stage using pentode tubes, to this diagram. Draw the loud speaker connections and a tone control in the circuit, using your own ideas, as to their proper arrangement. Now explain the main features of the entire circuit.
13. Repeat questions 10, 11, 12 for a superheterodyne type receiver.
14. Explain why separate-heater type tubes are used in a-c electric receivers.
15. What improvements in radio reception would result, if each broadcasting station were allowed to transmit a band of frequencies 20 kc wide instead of the 10 kc band now employed? What changes in present receiver design would be necessary to enable the benefits resulting from such a change to be realized at the receiving end?
16. Describe the construction of a 3-electrode separate-heater type amplifier tube, and explain how filament operation with a-c current is possible without resulting in objectionable hum.
17. Explain two advantages of using resistance coupling between the detector and first audio stage in an a-c tube electric receiver using a power detector.
18. Explain in detail how you would proceed to determine whether "scratchy", "crashing" noises issuing from the loud speaker of an electrically-operated radio receiver are due to electrical disturbances reaching the set by way of the antenna-ground circuit, or reaching it by way of the electric light supply line.
19. If your test in question 18 indicates that the disturbances are reaching the set via the antenna-ground circuit, and further tests show them to be induced in the antenna lead-in wire only, how could you eliminate them? Explain!
20. If the disturbances are reaching the set via the electric light supply line, how would you prevent them from reaching the set? Explain, with diagram!

Chapter 29

AUTOMOBILE AND AIRCRAFT RECEIVERS

RADIO RECEIVERS IN AUTOMOBILES — SELECTION OF THE TUBES — THE RECEIVER — THE LOUD SPEAKER — THE "B" BATTERIES — TUNING CONTROL — THE ANTENNA AND GROUND SYSTEM — IGNITION SYSTEM INTERFERENCE — AIRCRAFT RADIO RECEIVER REQUIREMENTS — ENGINE IGNITION INTERFERENCE — SHIELDING THE IGNITION SYSTEM — THE ANTENNA SYSTEM — RADIO EQUIPMENT — RADIO BEACONS — REVIEW QUESTIONS.

526. Radio receivers in automobiles: The use of radio receivers installed in automobiles, either for entertainment purposes, or for general police signal work, etc., presents some special design and installation problems which are not encountered with home receivers. These problems arise from the special operating conditions which exist in automobiles.

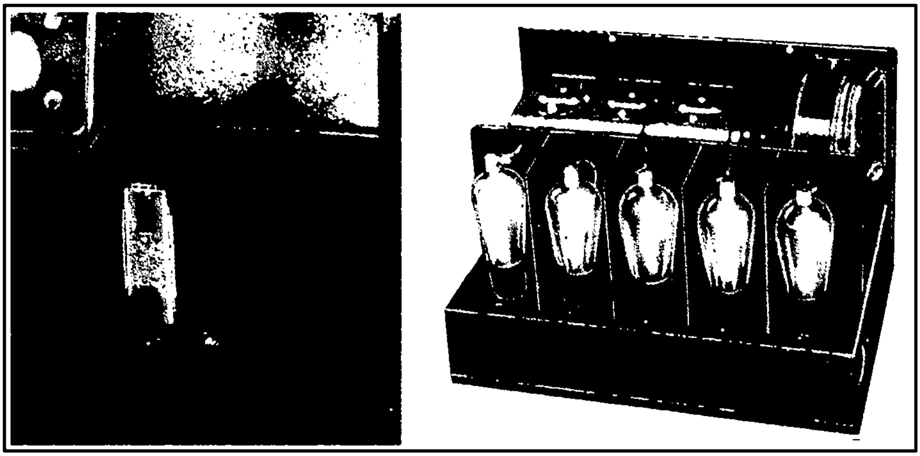
The most important of these special operating conditions is the fact that the auomobile radio receiver must obtain all filament, plate and C-bias voltages for the operation of its tubes either directly (or indirectly) from the same storage battery (usually 6 or 12 volts) which is used for the starting, lighting and ignition system of the automobile. Therefore, it should not require large filament or plate currents, for this would impose an excessive current drain on the car battery. A heavy current drain is especially objectionable in cold weather, when it is necessary to maintain the storage battery in fully-charged condition at all times in order to facilitate the operation of the self-starter motor when the engine is cold and the lubricating oil is stiff.

The "filament" current for automobile radio receivers is usually obtained directly from the car storage battery. The "plate" and "C-bias" voltages may be supplied by dry-cell batteries (see Arts. 62-64), but it is more common to employ specially-designed mechanical-vibrator and transformer arrangements, dynamotors, etc., for producing the high "plate" and "C"-bias voltages required. These devices also take their operating current from the storage battery of the car.

Since only a short antenna may be erected on the automobile, the signal pickup is rather weak (a few microvolts at best) and a very sensitive receiver is required. Also, the electrical, interference created by the ignition system of the automobile must be eliminated. Finally, the problem of providing satisfactorily tuning and volume controls within easy reach of the driver, must be considered.

527. Selection of the tubes: The filament current for the tubes is usually obtained from the same storage battery which is used for the ignition and lighting system of the car. Since the tubes used in receivers of this type must be able to withstand the continuous vibration of the car without shattering, they must be of rigid construction. Also, since the output voltage of the charging generator connected across the battery is a pulsating current, the filament current will also be pulsating while the engine is running. For these reasons, tubes of the separate-heater type are desirable on account of the rigidity of their heaters and the freedom from electron emission variations. While both 6 and 12-volt types of batteries are used on automobiles, the 6-volt type is most common in American automobiles. Special separate-heater type tubes have been developed to operate satisfactorily from this source of filament voltage supply. Among these, are the '36 type screen-grid amplifier tube, the '37 type general-purpose tube, and the '38 type power output pentode tube, (see Fig. 214) which all operate with a filament voltage of 6.3 volts and a filament current of 0.3 amperes.

All are of the high-vacuum type, and they employ coated cathodes, indirectly heated. The cathodes, which are the same for all three tubes, have been carefully designed to insure uniform heating over as wide a range of heater voltage as possible, in order that the tubes will perform satisfactorily under the normal voltage variations of automobile batteries during charge and discharge. This feature, together with that



Courtesy The National Co.

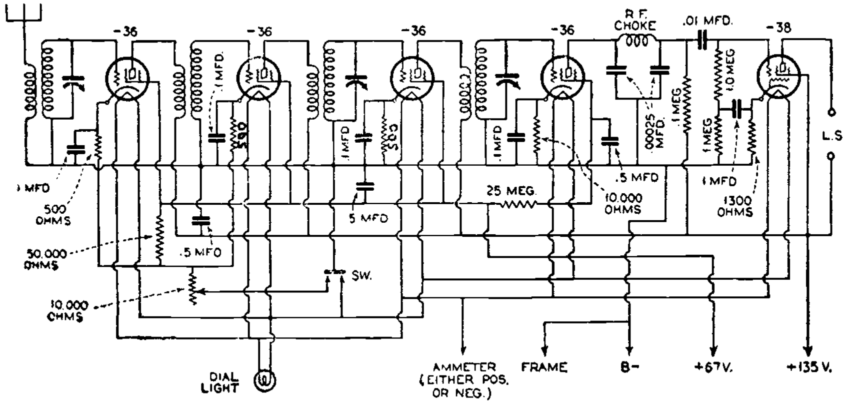
Fig. 392—Five tube t-r-f receiver designed for automobile installation. The receiver is shown mounted in place under the instrument board of the car, at the left. It is enclosed in a dust-proof metal case. A tuning dial is provided directly on the receiver. The circuit diagram is shown in Fig. 393.

of the general freedom from microphonic and battery circuit disturbances of the separate-heater type, make these tubes particularly well suited for use in automobile receivers. The '36 type screen grid tube may be used either as radio-frequency amplifier or detector. The heater voltage, which is obtained directly from the car battery, may vary between 5.5 and 8.5 volts during the charge and discharge cycles of the battery, without appreciably affecting the performance or serviceability of tubes. No resistor in the heater circuit is required when operated from a 6-volt car battery. If a battery of higher voltage is installed in the car, the voltage may be dropped to the proper amount by connecting a resistor in series with the circuit, its value being calculated by Ohm's Law ($R=E/I$).

528. The receiver: Since the signal pickup of the short, low antennas which must be used on automobiles is very small (being only a few microvolts at best), the receiver must be designed to be very sensitive, a sensitivity, such that the receiver will deliver a signal output of 80 milliwatts when a signal voltage of about 20 microvolts is applied to it, being considered satisfactory for most ordinary requirements. This performance must be obtained with economy of space, weight, and batteries.

Construction must be dust-proof, and sufficiently rigid to stand up well under the vibration existing in the car. Both superheterodyne, and t-r-f circuits are suitable for receivers of this type. A typical 5-tube t-r-f receiver designed especially for automobile installation is shown in Fig. 392. The installation of the receiver unit under the instrument board of the car is shown at the left. The "on-off" switch, tuning knob and volume control are plainly visible. This particular unit is constructed so it slides out of the container cabinet by unfastening four screws on the front panel. This facilitates tube replacements or testing. At the right, the chassis is shown removed from the container. The tubes, 3-gang tuning condenser, and dial are plainly visible. The circuit diagram of this receiver is shown in Fig. 393.

The receiver contains three stages of screen-grid tuned r-f amplification, a screen-grid power detector, and a power output pentode tube. The filaments are all

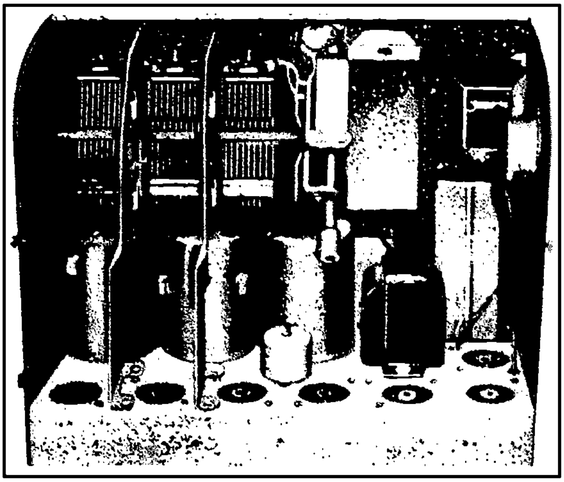
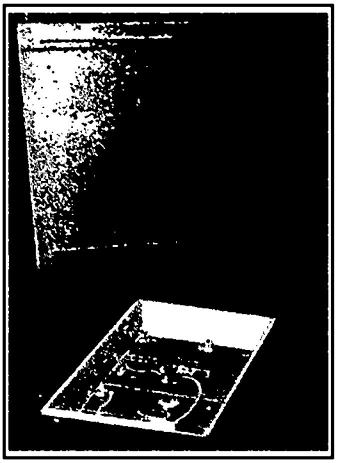


Courtesy Radio News Magazine

Fig. 393—The circuit diagram of the automobile radio receiver which is shown in Fig. 392. It is a 5-tube screen grid t-r-f receiver using a power pentode output tube. All tubes are of the 6.3 volt filament separate-heater type.

connected in parallel, one terminal going to the terminal of the ammeter on the instrument board of the car, and the other one connecting to the frame of the car, which is grounded to one side of the storage battery which is ordinarily used for ignition, starting and lighting current supply. Whether the positive, or the negative, terminal of the car battery is grounded to the frame does not matter. Grid bias voltages for the various tubes are obtained by the voltage drop through the various grid bias resistors connected in the cathode circuits as shown. The detector is resistance-capacity coupled to the '38 type pentode output tube. The use of the power pentode tube has the advantage that large output is obtained with relatively small signal voltage input to the grid. Only three leads run to the B batteries, one for the B— connection, one for the +67 volts for the screen grid circuits and one for the 135 volts for the plates. A 3-gang tuning condenser is employed, for single-dial tuning control. A double contact "on-off" switch which opens both the filament circuit and the main "B" or "plate" circuit is provided.

529. The loud speaker: From 2 to 2.5 watts of power are necessary for satisfactory reproduction in automobiles. Three types of loud speakers are suitable. They are, the "balanced-armature", the "inductor", and the "moving-coil" types. Cone diaphragms with a metal protecting case are usually employed. The moving-coil type may have a field magnet of either the permanent magnet or electromagnet type. The field coil on the latter must be wound either to operate from the 6-volt storage battery of the car or to act as a filter-choke in the "B" power supply unit. Since only a small volume of sound is required in an automobile, the speaker really need not be of the types designed to handle large volume. The location of the loud speaker in the car has considerable effect on the resultant tone quality, and before definitely mounting the speaker in position it should be tried in several different locations. The location under the dash, commonly used in many installations, is one of the poorest places from an acoustic point of view, in which to place the speaker.

Courtesy Radio News Magazine

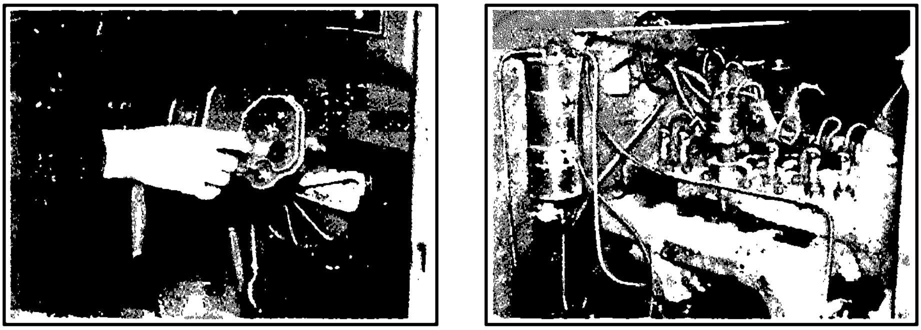
Fig. 394—Left: Interior view of the chassis of an automobile receiver designed for remote tuning control: The shaft and coupling at the center, attach to the tuning-control drive-shaft.
Right: A "B" battery compartment consisting of a sponge-rubber lined metal box sunk into the floor at the rear of the automobile. "B" batteries need not be employed, for satisfactory "B"-power supply units operating from the car storage battery are available.

Mounting it under the roof of the car, at the center is preferable, but this requires a speaker of pleasing appearance and fairly flat construction.

530. The "B" batteries: When "B" batteries are employed, they are usually mounted in a suitable metal box, lined with sponge rubber at least ½ inch thick for protection against jolts. In touring cars and sedans, this box may be built into the floor at the rear; on the side of the car opposite that on which the exhaust pipe and muffler are located, for heat deteriorates "B" batteries. An installation of this kind is shown at the right of Fig. 394. In roadsters and coupes, there is generally ample space for the "B" battery box in the luggage compartment in the rear.

In making battery connections to the receiver, armored cable or miniature BX especially made for automobile wiring purposes, should be employed, and this metal covering should be grounded. Not only does this shielding of the battery wires reduce the ignition disturbances picked up, but it greatly decreases any possibility of short circuits due to damaged insulation caused by shifting and rubbing of the wires, and consequent grounding of either the plate or filament circuits. Due to the use of the heater-type tubes throughout, polarity of the connections to the storage battery is of no consequence. A connecting plug into which the leads from the "A" and "B" batteries are terminated, is usually plugged into a socket provided at the side of the receiver box.

531. Tuning control: Two types of tuning controls may be used. One is the direct type shown on the receiver of Fig. 392, in which the tuning dial is mounted directly on the receiver cabinet. The other type, shown in the installation at the left of Fig. 395 employs a flexible drive



Courtesy Radio News Magazine

Fig. 395—Left: Remote tuning control mounted on the instrument board of the automobile. The receiver and loud speaker are underneath.
Right: Spark plug resistors in place on the spark plugs of a 6-cylinder automobile engine to suppress interference from the ignition system.

member between the tuning control, which is placed in a location most convenient to the driver, and the tuning condenser drive on the receiver. This flexible drive member may consist of link-connected rods, a flexible cable or spring drive system, etc. This remote-control tuning provision enables the receiver to be mounted in the most suitable location, away from the tuning control if necessary, but adds to the cost of the outfit. In the receiver shown at the left of Fig. 394, and at the left of Fig. 395, a remote tuning drive is provided, the receiver controls being mounted on the instrument board, and the receiver and loud speaker being mounted out of the way under the cowl, as shown.

532. The antenna and ground system: Two types of antenna installation are in common use.

In one type, the antenna system consists of two flat metal plates about 8 $\times$ 30 inches each, which are mounted by insulators, beneath the running boards of the car. These two plates are connected together to the "antenna" terminal of the receiver. The "ground" connection is made to the metal frame of the car, this acting as a "counterpoise ground" (see Art. 615). This type of antenna has the important advantage of reduced ignition circuit interference pickup, since it is fairly well shielded from the disturbances radiated from the ignition system, but the radio-signal pickup is also rather law.

In the other antenna system, the antenna is installed in the roof of the car, above the roof upholstery. It may consist of a cloth-covered copper screen, "chicken-wire" metal screening, or a coiled loop of insulated flexible wire. A shielded lead-in wire is usually brought down through one of the hollow front posts of the car body, for connecting the antenna to the radio receiver.

Many cars are equipped with built-in antennas in the factories, when they are assembled. Generally, these antennas consist of metal screen-mesh located above the upholstery in the roof of the car. While it is not an impossible task for anyone to remove the roofing material and install such an antenna, a much simpler method in a used car, is to obtain a large darning needle and some fine flexible wire and thread the wire through the roof upholstery forming a coiled-wire antenna.

In roadsters and touring cars, a flexible wire may be stitched into a piece of cloth, to form a horizontal coil. This unit is then stitched to the pads which support the "top" material at each side. A lining of the same material as the top, is stretched beneath to conceal it from view. In such an installation, the top may be folded back, as the lead-in wire is brought down from the rear of the top, and along the body-sill to the cowl. The set may be operated with the top up or down, although better reception is of course had with the top up. Measurements of these screen-type antennas show, for sedan models, a capacity of about 200 $\mu\mu$f. and a resistance of about 1.5 ohms at 1,000 kc. The inductance is negligible. This capacity compares favorably with that of a good broadcast antenna, but the effective height averages but .4 meter, which means that the signal voltage pickup is very weak (a few microvolts at best), and a very sensitive receiver is required.

533. Ignition system interference: Unless suitable precautions are taken in the design and installation of automobile radio equipment, objectionable noises due to electrical interference from the ignition system of the engine, will result.

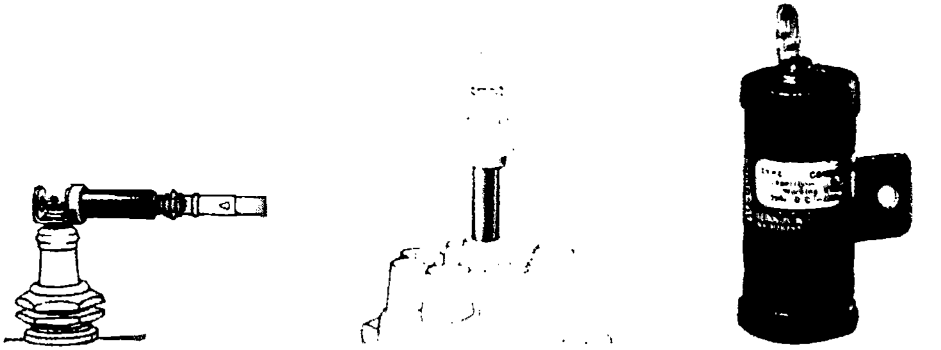
The high-tension ignition wires of a gasoline engine may be considered as miniature antennas, grounded at the spark-plug end and oscillating at a frequency dependent upon their distributed inductance and capacity, practically determined by their length. The passage of the spark at the plug, excites these miniature antennas, and as their radiation efficiency is high, a considerable amount of power is radiated. Owing to the high radiation resistance, damping in these circuits is also high and the energy thus radiated in highly damped trains impacts the antenna used for the radio receiver. Each time a spark plug fires, a clicking noise sounds in the radio receiver. The resultant interference is similar to that experienced by broadcast receivers from 600-meter spark transmitters of high decrement. In the car however, the interfering damped train from the ignition system has a frequency lying between 10 and 60 megacycles, in some cases higher. Also, coupling is much closer. The spark plug wires could be shielded by a grounded metallic shielding, but this would materially complicate the ignition system, and is not really necessary. The oscillatory character of the currents in the ignition wires may be destroyed by connecting sufficient resistance in each oscillatory circuit so as to make it aperiodic. Each spark current then becomes a single pulse instead of a train of damped waves. In practice it is customary to connect a resistor of from 10,000 to 25,000 ohms directly in series with each spark plug lead (at the plug), to accomplish this. The introduction of resistance, even in the order of several thousand ohms, in series with the very high resistance of the spark gap before rupture does not appreciably affect the *total* resistance of the circuit and will have no effect on the spark. It will however, rapidly dissipate the energy fed to the circuit by the spark coil after the rupture has occurred, thus dissipating this energy as heat, rather than radiating it at radio frequencies.

Suitable carbon-type resistors designed especially for connection to each spark plug are employed. A typical resistor of this type, fastened to the spark plug terminal, is shown at the left of Fig. 396. The installation of the resistors on the spark plugs in an actual engine, is shown at the right of Fig. 395. Spark plugs of special construction, in which the resistance element is already included in the center of the usual porcelain insulator are also available and are used extensively.

In a gasoline engine, the wires directly associated with the spark plugs are not the only source of radio-frequency disturbances.

These wires terminate at the distributor, which is in reality a rotary switch. The center rotor of the distributor is fed from the high-tension terminal of the spark coil. This "rotor" is separated from the various contacts by a definite gap, and this gap is important, being placed there for a particular purpose. If a plug is "fouled" because of carbon deposits, the resistance of the circuit in the plug can no longer be considered infinite, but assumes a high value, generally several megohms. The high-potential current induced in the coil secondary would leak thru this resistance rather than rupture the gap in the plug. The purpose of the distributor rotor clearance, then, is to permit the secondary current to build up to a fairly high potential before passage to the spark-plug, thus insuring a spark even though the plug be partially shorted by the resistance due to fouling. A resistor must therefore be inserted in series with the lead to the distributor brush, in order to destroy such oscillation as may occur in this lead. A resistor for this purpose, which plugs directly into the middle terminal of the distributor cap, is shown at the center of Fig. 396.

With the elimination of the high-tension circuit interference, the major source of trouble is overcome. However, electrical interference may still be present, caused by



Courtesy Allen Bradley Co. *Courtesy Aerovox Wireless Corp.*

Fig. 396—Left: A resistor in series with the spark plug for suppressing the oscillations in the spark plug circuit.
Center: A resistor in series with the high tension lead of the distributor for the same purpose.
Right: A special heat-resisting by-pass condenser for use in ignition interference suppression systems on automobile radio receiver installations.

various elements of the low-tension circuit. The primary of the ignition coil still causes trouble, owing to the oscillatory nature of the break at the timer points.

The frequency of these disturbances is rather low, seldom higher than about 2,500 cycles, but it can find its way to the audio system of the receiver via the filament circuit. This may be overcome to a great extent by connecting a condenser of 1 to 2 mf. capacity between the battery side of the coil, and the ground, so as to provide a short low-impedance by-pass path for these oscillations. It also prevents any r-f impulses which may be developed at the breaker points, from travelling back through the primary wiring of the car to the storage battery and to the filament circuit of the receiver.

Electrical disturbance from the generator is often very noticeable. A 1 or 2 mf. condenser connected directly across its brushes, will clear up any but the most perverse ripples. If this is insufficient, the generator must need attention. A dirty commutator, badly-fitting brushes, or open bars will cause brush sparking which is noticeable in the radio receiver. The radio receiver thus serves as an excellent check on the condition and operation of the generator.

A simplified schematic diagram of a complete automobile ignition system for a four-cylinder engine is shown in Fig. 397. The location of the various "suppressor" resistors and the generator by-pass condenser are indicated on the diagram. Since the generator by-pass condenser must be able to withstand the rather high temperature existing under the engine hood, it should be impregnated with a wax of high melting point. A special metal-enclosed condenser of this type designed to withstand temperatures up to 160 degrees F. is shown at the right of Fig. 396.

534. Aircraft radio receiver requirements: Two-way communication between aircraft and ground stations is becoming a very important essential to safe flying. The value of such equipment for the purpose of obtaining reliable weather reports, landing field condition reports, radio beacon signals, and for emergency work, cannot be too strongly realized. The requirements of radio equipment to be used on aircraft are rather severe.

The dominating requirements are, of course, light weight and small size. Not only must the set be small and light, but the accessories, such as batteries, must be compact and light, too. The airplane receiving set must be made so that it can be placed anywhere on the "ship," in some cases with remote controls to operate it. It also must have great sensitivity variation because it is changed in location so rapidly, from nearness to the sending station to a distance from it. In open-cockpit planes, the tuning controls must be such as to permit operation with heavy gloves on, at times. A locking device is frequently necessary to prevent "creeping of tuning", due to vibration of the plane, especially for beacon work. The apparatus must be able to withstand the unusual climate, humidity, and temperature changes encountered during any kind of flight, and must stand up under the continuous vibration caused by the engines.

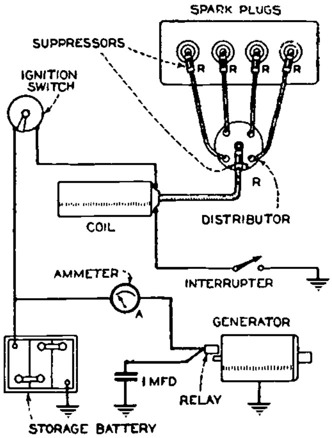


Fig. 397—Simple schematic diagram of the main parts of an automobile ignition system showing how the spark plug and distributor "suppressor" resistors, and the generator 1-mfd by-pass condenser are connected to eliminate interference in the radio receiver.

535. Engine ignition interference: As aircraft engines use ignition systems with spark plugs, such as are employed in automobiles, the receiver itself must be thoroughly shielded and proper steps must be taken to eliminate the radiation of radio-frequency fields from the ignition wiring and the magnetos which are commonly used as the source of e.m.f. for the ignition system. Since very sensitive receivers are generally used in aircraft, it has been found necessary in most cases, to employ elaborate shielding harnesses for both the spark plugs and the high-tension wiring, and to bond all the bracing wires and cables in the ship in order to prevent discharges of static electricity generated by metal parts rubbing on other surfaces. All wires in the ship are either shielded with copper braid or else run in conduit. The latter method is preferable, where possible. When the ship is equipped with a high-frequency transmitter, all wiring is generally completely enclosed in grounded shielding, to prevent it from absorbing the radiated energy from the transmitter.

536. Shielding the ignition system: The shielding of the entire magneto is a relatively simple matter. A typical shield for this purpose is shown in Fig. 398*. It consists of two aluminum sheets bolted to the magneto, and a band of spring bronze which covers the gap between the plates. A removable block with the wire outlet tube, fits in front. All of the ignition wiring is also shielded, a complete harness being made up for this purpose, as shown in Fig. 399.

Ordinary braided shielding alone over the wires is not effective, because when oil soaks into the braid, it insulates each strand from its neighbor enough to impair the

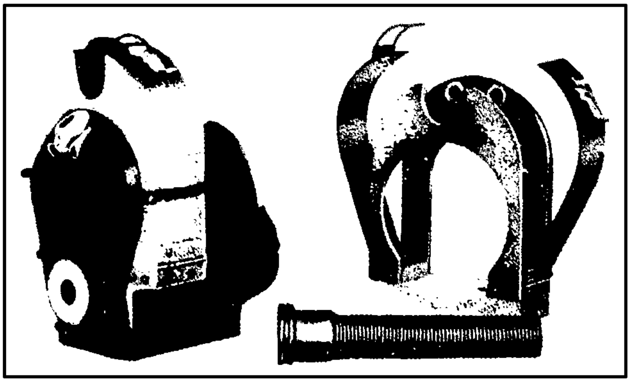


Fig. 398 — Magneto shield developed for confining the r-f radiations set up by the magnetos on aircraft engines. At the left, the shield is in place on the magneto. At the right, it is removed and opened. The high-tension ignition wires are led out through the metal tube shown at the bottom.

Courtesy Mr. R. H. Freeman and Aeronautical Eng. Magazine

effectiveness of the shielding. The shielding harness consists of two main tubular aluminum rings in which the wiring is placed. One ring carries the wires for the front spark plugs, and the other one placed at the rear of the motor carries the wires for the rear plugs. Branching off from these rings are flexible oil-proof shielded leads running to the spark plugs, and large flexible tubing to the magnetos. The in-

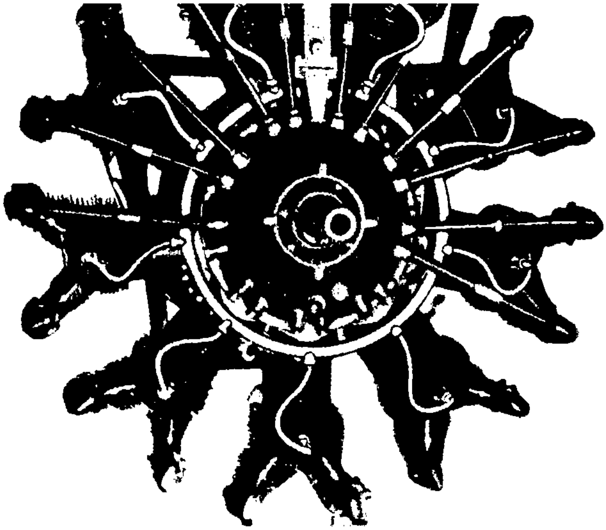


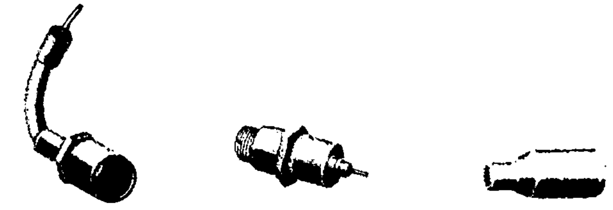
Fig. 399 — Complete "harness" for shielding the ignition wires running to the front spark plugs of an aircraft engine. All of the wires run inside of it. A similar harness is at the rear of the engine for the wiring to the rear spark plugs. Notice the short flexible leads from the tubular ring to the individual spark plugs.

Courtesy Mr. R. H. Freeman and Aeronautical Eng. Magazine

*From an article on Commercial Aircraft Radiophone Communication by Robert Freeman, in Vol. 3, No. 2 issue of Aeronautical Engineering Magazine.

sulated ignition wires run inside of the shielding. A typical complete harness mounted on a radial aircraft engine is shown in Fig. 399. Each spark plug is shielded by a metal shield cap with prongs which fit down over the plug sleeves and clamp into the groove at the base of the nut by spring action. At the top of the cap there is a gooseneck which reverses the direction of the wire in rather a short arc and leads it back toward the direction of the harness. Inside the cap there is placed an insulating sleeve which fits down over the center electrode of the plug, inside of the nut sleeving. This forms a long path for the electrical energy to jump across or leak through. A small spring and screw in the top of the insulator, connect the top of the plug to the wire entering the cap. The shielded spark plug, gooseneck and insulator of this type are

Fig. 400—From left to right are shown the gooseneck and metal shield cap, shielded spark plug, spring, and special hollow insulating sleeve which are used in the shielding arrangement of Fig. 399.

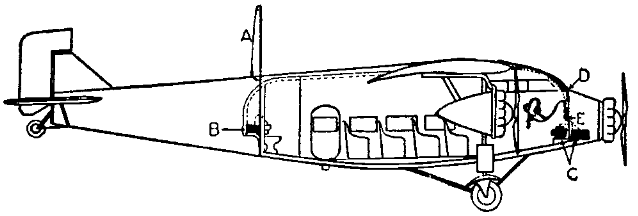


Courtesy Mr. R. H. Freeman and Aeronautical Eng. Magazine

shown in Fig. 400. In this way a complete covering of metal for the ignition system is provided, which suppresses the interference to a point where it is not audible in the receivers.

537. The antenna system: The trailing-wire type of antenna, which has been used until very recently for both the dirigible type of airship and the heavier-than-air type of craft, has several distinct advantages as well as disadvantages. Its use is confined largely to the lower frequencies, and it is comparatively satisfactory around 300 kc.

It is possible with this type of antenna to communicate over comparatively long distances with a minimum of power. However, it is necessary to reel it out when



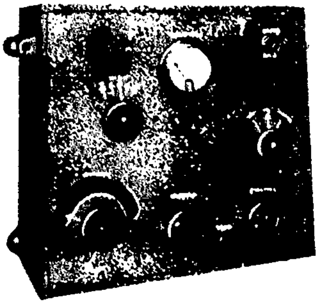
Courtesy Radio Craft Magazine

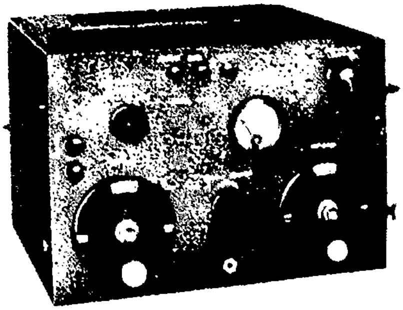
Fig. 401—Arrangement of radio transmitting and receiving equipment on a large passenger plane. The receiving antenna "A" comprises a length of wire supported on a streamlined strut; "B" is the radio receiving set; "C" is the dynamotor and battery; "D" is the remote tuning control dials at the pilot's seat; "E" is the remote volume control, and "F" indicates the headphones.

communication is desired and to reel it in when communication is finished. The maintenance cost of this type is large, and the hazards encountered when flying at low altitude make it undesirable. It is also impossible to use it when a forced landing must be made. Its air resistance increases the drag on the ship and materially reduces its speed. It is impractical for military use, as a plane cannot be stunted with it. A short vertical "rod" or "strut" antenna is commonly used instead. This consists of a streamlined duraluminum vertical antenna rod A about 6 feet in height, mounted vertically on top of the fuselage, away from the direct radiation field of the ignition wiring as shown in Fig. 401. In those cases where radiation is required for transmission, two wires may be run from the front-wing spar on either side to the top of the mast and then back to the vertical tail fin. With this antenna, transmission can also be carried on while the plane is on the ground. The engine frame and the bonded bracing wires in the wings and fuselage act as the counterpoise ground.

538. Radio equipment: The type of transmitter used in aircraft depends upon many factors. The transmitters are built compactly, and of light weight.

A range of at least 100 miles of consistent communication is acceptable for commercial aircraft flying along standard airways, since stations are located every 200 miles, and beacon marker stations with auxiliary





Courtesy Allen D. Cardwell Mfg. Co.

Fig. 402—Left: U.S. Signal Corps aircraft code and phone transmitter. Right: U.S. Navy aircraft receiver.

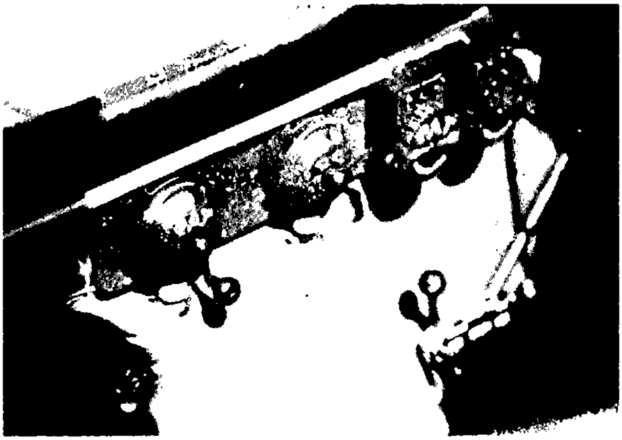
equipment every 100 miles. A combined CW and radiophone transmitter seems to be the desirable thing, because few pilots have the time or patience to learn the code sufficiently for expert operation of a straight CW transmitter. Special microphones designed to eliminate outside noises are employed. These fasten to the helmet of the pilot, together with the light-weight earphones built into the helmet.

The matter of filament and plate power supply for radio transmitters and receivers seems to be very much an open question. Batteries are heavy and a sufficient number cannot be carried for transmission purposes. A dynamotor, which is in reality a motor-generator, is very inefficient because the current that is used must first be supplied at low voltage by a storage battery and translated from electrical to mechanical energy and back again at a higher voltage in the dynamotor. There is an extra loss of efficiency in going through the dynamotor which can and does add both weight and power to the equipment that is needed. A wind-driven generator cannot be used, because its driving propeller becomes unbalanced with a coating of ice in winter often tearing the generator loose from its mounting. The double-voltage generator which converts mechanical energy directly into the two voltages needed for filament and plate supply seems to be the proper answer. A clutch and a third winding on the armature will permit its being used as a dynamotor on forced landings for power supply when the motor is dead. It may then be operated from a small emergency battery. It is true that there are still some mechanical difficulties with the double-voltage generator, but it is felt that these can be eliminated. It is the lightest combination available that will provide the necessary power for the radio transmitter. A special voltage regulator which is provided, keeps the output constant.

A typical aircraft transmitter for both code or radiophone transmission is shown at the left of Fig. 402. This is used by the U. S. Signal

Corps. A form of aircraft receiver used by the U. S. Navy is shown at the right. In large passenger and mail planes, the transmitter and receiver are installed usually in the tail end of the fuselage or in a compartment directly behind the main passenger compartment. Flexible shafts connect the tuning condens·· shafts of the receivers with remote control dials in the pilot's cockpit The arrangement of the remote tuning and volume controls at the lef· side of the open cockpit on a mail plane are shown in Fig. 403.

539. Radio beacons: The radio beacon for guiding aircraft, has been perfected so that it is as practical and perfect as the ordinary mag-



Courtesy Mr. R. H. Freeman and Aeronautical Eng. Magazine

Fig. 403—Remote tuning and volume controls for the radio equipment on a mail plane. These are mounted at the left side of the cockpit within easy reach of the pilot. Notice the lever-type controls to permit of easy handling by the pilot even though he may be wearing thick, heavy gloves.

netic compass. The loop or coil form of antenna has the peculiar property of directional reception and transmission which makes it invaluable in radio beacon work.

In directions toward which it points, reception is good. At right angles to its plane, reception is practically zero. When a loop antenna is used for transmitting, a similar effect is noticed. The radio range beacons in service in American airways rely upon this principle. However, two loop-type transmitting aerials are used at the airport, at right angles, or at different angles with each other in accordance with the nature of the course. A remarkably ingenious system is used to enable the pilot to maintain his direction. One loop aerial is continuously sending out a certain radio code signal by a mechanical device, say a dash and a dot, and because of the characteristics of the loop aerial, this particular combination goes out in the general direction of North and South or East and West, as the special position of the course requires. The other loop aerial is sending out another complimentary combination of dots and dashes which exactly fit in between those of the first aerial. The plane has a separate receiving loop antenna mounted on the end of each wing. Therefore, when the plane is headed directly along its proper course toward the transmitting station, its receiving loops receive an equal amount of energy from each of the transmitter loops. Since the signals transmitted by the two transmitter loops are complimentary, the fact that they are received with equal loudness causes them to fit in with one another so that the pilot is unable to distinguish either the dot-dash combination or the dash-dot combination, and instead, he hears only a continuous dash or sound, as long as his plane is headed properly along the course.

This condition of equal loudness occurs only along a very restricted path pointing straight toward the beacon, so narrow in fact, that at a distance of 100 miles, the path over which the two signals blend perfectly is only 6 miles wide. As the pilot flies toward the beacon he is able to correct his course constantly, for if the plane gets off to one side, his radio set picks up the signals from that side with greater volume than from the other side and he instantly knows which way to turn. As he gets nearer to the beacon, the course narrows greatly, guiding him directly to the airport.

The radio beacons use frequencies in the band from 285 to 350 kilocycles (corresponding to about 857 to 1,052 meters). Originally, different groups of dots and dashes were used, but it was found that the pilots got better results with the N and A (dash-dot and dot-dash) combinations. To identify which station is being received aboard the plane, a number of combinations forming a single group (with a pause between each group) is employed. In addition. every 15 minutes the station switches over to a microphone and an announcer gives the call letters and name of the station, and also weather and wind conditions and forecasts.

REVIEW QUESTIONS

1. How do the operating conditions for radio receivers operated in automobiles differ from those in home receivers?
2. Explain the requirements as regards sensitivity, size, weight, battery current consumption, etc., which a satisfactory automobile radio receiver must meet.
3. Explain how it is possible to operate a radio receiver in an automobile in which no connection is made to the earth, since the rubber tires on the automobile insulate the chassis from the earth.
4. Describe two forms of antenna installations in automobiles.
5. Explain how the high-tension circuits in the ignition system of a gasoline engine, create interfering electric disturbances which radiate from it. How may these disturbances be reduced effectively in automobile radio installations?
6. Explain how the low-tension circuits in the ignition system create interference, and how this may be prevented.
7. Explain how the battery-charging generator on the car may cause interference and how this may be prevented.
8. Why is it desirable to run all battery wiring in an auto-radio receiver installation in metal conduit grounded to the frame of the car?
9. Why is the signal pick-up of the average antenna installed in an automobile very small? Of what importance is this?
10. If the filament-current drain of the receiver were causing the storage battery to operate in a discharged condition most of the time, would increasing the charging rate of the generator help any? Explain!
11. Explain the advantages obtained by using, (a) separate-heater type tubes; (b) screen-grid amplifier type tubes; and (c) power pentode output tubes, in automobile radio receivers.

12. How is the electrical interference from the ignition system of aircraft engines effectively suppressed, to permit satisfactory operation of extremely sensitive radio receivers? Why are these extreme precautionary measures not usually necessary in automobile radio installations?
13. Describe the elements and operation of the radio-beacon system used for guiding the flight of aircraft.
14. Why must aircraft receivers and transmitters be designed ruggedly, and of lighter weight and greater dependability than similar equipment used on the ground?
15. How is it possible to receive radio signals in an airplane, when the earth may be several thousand feet below it, and no "ground" connection to the earth is possible?

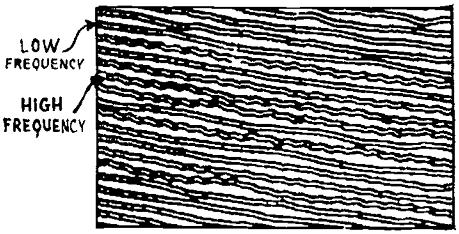
CHAPTER 30

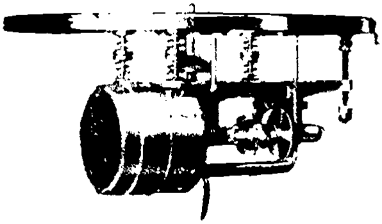
PHONOGRAPH PICKUPS AND SOUND AMPLIFIER SYSTEMS

PHONOGRAPH RECORDS — THE ELECTRICAL PHONOGRAPH PICKUP SYSTEM — THE ELECTRICAL PHONO-PICKUP UNIT — THE OIL DAMPED PICKUP — VOLUME CONTROL — SCRATCH FILTER — CONNECTION TO RADIO RECEIVER — HIGH IMPEDANCE AND LOW IMPEDANCE PICKUPS — SOUND AMPLIFIER SYSTEMS — THE AMPLIFIER — MICROPHONES — MIXING PANEL — THE LOUD SPEAKERS — HOME RECORDING — REVIEW QUESTIONS.

540. Phonograph records: The popular phonograph record of today is made by recording sound vibrations on a circular disc of suitable material. The disc contains a continuous spiral groove in which the needle of the reproducer unit runs while the record revolves. In records for home use, the reproducer is started at the outside edge and runs toward the inside of the disc. In records used in sound picture work, the reproducer starts at the inside and moves toward the outside edge of the disc. The spiral groove contains little waves or ripples all along it, whose wave-form corresponds to the wave-form of the sound recorded. In the *laterally-cut* type record which is used almost entirely nowadays, the spiral groove is of practically constant depth and cross-section, having a spacing between adjacent turns or spirals of the groove, of about 1/100 of an inch. However, the groove has little horizontal wiggles or waves in it, whose wave-form corresponds to that of the original sound, and whose frequency at any instant (provided the record is rotated at the proper speed) corresponds to the frequency of the sound. If we were to look at the grooves of a phonograph record under a powerful magnifying glass, they would appear somewhat as shown at the left of Fig. 404. Notice that the grooves are all of constant width. For a high-frequency note recording, the groove has many short wiggles following each other closely. For a low-frequency note recording, the wiggles are long and not so frequent. The student is urged to inspect with an ordinary reading glass or other magnifying glass, the grooves in a phonograph record containing low-frequency recordings. It is evident that any device which is placed in, and made to follow, the groove while the record is revolved at the proper speed, will be forced to vibrate back and forth sideways, as it follows the waves or wiggles in the groove. The *amplitude* of its vibration will correspond to the amplitude of the wiggles, and the *frequency* of its vibration will correspond to the number of the wiggles (in the groove), which come past the device every second. Of course, this depends on the speed at which the disc is rotated, so that if the sounds are to be reproduced at their proper frequency, the record must be rotated at the proper speed. The usual phonograph disc record is designed to be revolved at 78 revolutions per minute. The 12-inch record plays for four minutes, while the 10-inch record plays but 2½ minutes. The 16 inch records used in sound picture work, in sound amplifier systems, and for broadcasting purposes (electrical transcriptions) revolve at 33⅓ r.p.m. and play for about 14 minutes.

Experiment: Play a phonograph record at its proper speed. Now slow up the disc gradually by pressing your hand against the turntable. Notice that the tone becomes lower and lower, since the wiggles in the groove are not going past the needle in the reproducer as fast as they should, and therefore the needle is not vibrated as fast is it should be. Now place a small strip of paper under the record so its end projects out and is visible. Set the record in motion, and count the number of revolu-





Courtesy Pacent Elect. Co.

Fig. 404—Left: How the wiggles in the grooves of a portion of a phonograph record appear when observed under a magnifying class. The needle-point running in the groove, vibrates from side to side due to these wiggles. A high-frequency recording consists of short wiggles close together. In a low-frequency, recording the wiggles are long and far apart, as shown.
Right: A side view of a typical induction type a-c elctric spring mounted phonograph motor and the turntable.

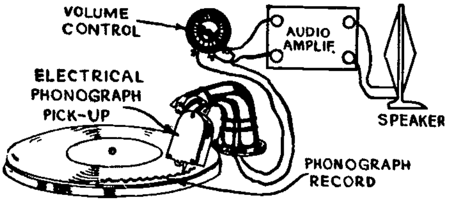
tions it makes in one minute, by noticing the seconds hand on a watch. The regulation on the motor may be adjusted until the disc rotates at the proper speed in accordance with the figures given above. Now place the end of your thumb-nail, or the corner of a piece of thin stiff paper, in the groove while the disc rotates. Notice that the music is reproduced faintly by the vibrations of the nail or paper caused by the wiggles in the groove.

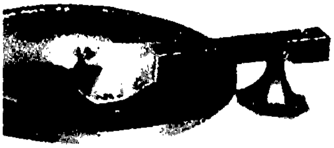
Phonograph records may be rotated either by the old-fashioned mechanical spring-type motor, or by the more modern electric motor drive which does not need to be re-wound after playing a record. A spring-mounted motor of this type with the turntable, is shown at the right of Fig. 404. Units of this type usually consist of an induction type a-c electric motor and a turntable, equipped with an automatic trip-stop and having a brake and switch arranged for either manual or automatic operation. The motor is provided with a simple speed regulation adjustment. Induction type motors are employed almost exclusively, since they have no brushes or commutator, and therefore do not cause electrical disturbances which might affect the radio receiver.

541. The electrical phonograph pickup system: In the old mechanical type of phonograph, the reproducer head was arranged so that the sharp point of the needle, following the wiggles in the spiral grooves of the record, transmitted its vibrations to a flat diaphragm which produced corresponding vibrations (sound waves) of the air in the "sound box".

In the usual form of *electrical phonograph pickup unit* as shown at the right of Fig. 405, the vibrations of the needle are made to generate an e.m.f., whose value varies in exact accordance with the amplitude and frequency of the wiggles of the groove which go past the needle point. This induced e.m.f. is fed to the input terminals of an audio-frequency amplifier. This amplifies the audio-frequency variations of this e.m.f. until they are of sufficient strength to operate one or more loud speakers. In this way, the sound may be amplified to almost any intensity desired, and splendid reproduction is possible. The audio amplifier and loud speaker employed, may be a separate amplifier and speaker as shown at the left of Fig. 405, or the ordinary a-f amplifier and speaker which are already present in the home radio receiver. In the latter case, suitable provision is made, either by a switching arrangement or an adapter plugging into the detector tube socket, for connecting the a-f amplifier either to the phono-pickup unit or to the r-f amplifier and detector for either phonograph or radio reproduction. Most modern radio receivers are provided with suitable terminals for connecting the phono-pickup unit to the audio amplifier.

542. The electrical phono-pickup unit: A *phonograph pickup unit* may be defined as an electromechanical device actuated by the phono-





Courtesy Pacent Elect. Co.

Fig. 405—Left. Electric phonograph-reproducing system. The variations in the e.m.f. generated in the pick-up are amplified by the a-f amplifier, and reproduced as sound waves by the loud speaker.
Right: A typical magnetic type of phonograph pick-up unit with the needle in place in the groove of the record. The arm and head are counterbalanced by the weight at the right.

graph record and delivering power to an electrical system, the wave-form of the voltage or power delivered to the electrical system corresponding to the wave-form existing in the grooves of the phonograph record. Phono-pickups operating on several different principles have been developed. Among these are the condenser type, the carbon resistance type, and the magnetic type. The latter is used almost exclusively, on account of its commercial practicability due to its high voltage output, comparative freedom from extraneous noises and simple mechanical construction, and the fact that its frequency-response characteristics may easily be modified to compensate for those of the record or amplifier systems so as to produce a satisfactory overall response. The magnetic pickups are of two types: *rubber-damped* and *oil-damped.*

The construction and operation of the simple reed-type rubber-damped magnetic pickup may be seen from Fig. 406. As shown at (B) and (C), a strong magnetic field is provided by a small permanent horseshoe magnet, having pole pieces of suitable shape fastened to it. Fitting between these pole pieces is a small coil containing several thousand turns of very fine enameled copper wire. Attached to the needle which runs in the record groove, is a small iron reed or armature which is pivoted, and placed within the hollow center of the coil between the pole-pieces, as shown. The pickup is placed over the phonograph record, in such a direction that the wiggles in the record groove cause the needle point to vibrate rapidly from side to side as shown by the dotted line positions at (A). On account of its large inertia, the pickup head itself does not vibrate. The amplitude and frequency of the movements of the needle point, depends on the amplitude and frequency of the wiggles in the groove.

Just how this motion causes an e.m.f. to be induced in the coil may be seen from Fig. 407. Here the gap between the pole pieces has been drawn exaggerated, and the rubber damping blocks are not shown. The iron armature serves as a good magnetic path for the lines of force to travel through between the pole pieces. Remember that it is placed inside of the coil of wire, so any lines of force through the armature are

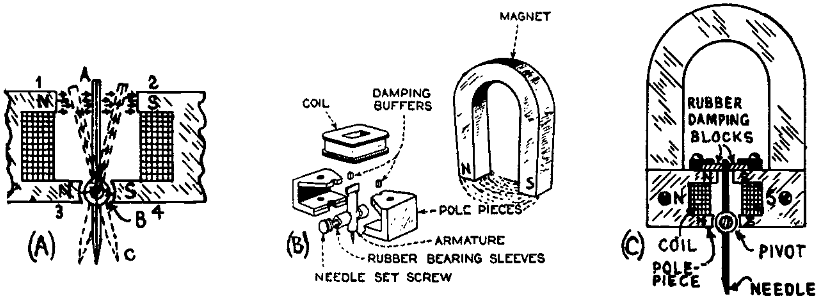


Fig. 406—The arrangement of the various parts in a typical magnetic type phonograph pick-up with rubber damping. (A), Various positions which the needle and armature take during the playing of a record. (B), The parts of a phono-pickup unit separated. (C), The parts all assembled together.

really threading through the coil. When the armature is in the extreme position shown at (A), some of the lines of force of the permanent magnet are diverted from their normal path straight across the gap, and go from pole piece No. 1, *down* through the armature to pole-piece 4 and around through the magnet. They take this path because the iron armature presents a better magnetic path than the air gap across from 1 to 2. If the armature now returns to its vertical position as shown at (B), the air gap from 1 to A is increased. Therefore the field through the armature down to 4 weakens, and a greater part of the field goes directly across to 2. The main point to remember is that movement of the armature from the position at (A) to that at (B) has weakened the field through it, i.e., has changed the number of lines of force threading through the center of the coil. Therefore according to the laws of electro-magnetic induction, an e.m.f. is induced in the coil. When the armature moves to

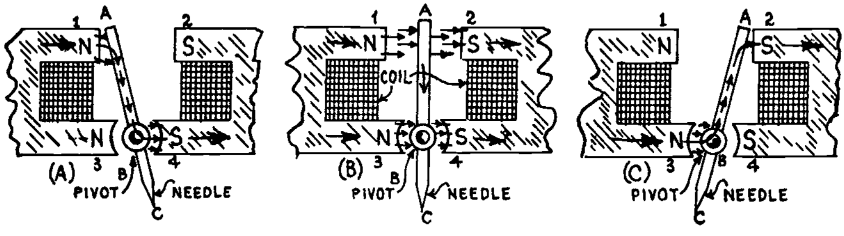


Fig. 407—The movement of the needle and iron reed or "armature" in the phonograph pick-up unit, varies the magnetic flux through the coil and so induces an e.m.f in it. The path of the magnetic lines of force is shown here for three positions of the needle and armature.

the extreme position at (C) the lines of force through it actually reverse in direction, now going up through it from the N pole piece No. 3 to the S pole piece No. 2 as shown. This causes another change in the flux, and since the flux through the coil is now in the reverse direction, the e.m.f. induced by it is also reversed. Consequently a complete vibration of the armature, such as might be caused by say a sine-wave wiggle in the record groove, would cause an e.m.f. of the same sine-wave form and frequency to be induced in the coil. When the record is being played, the armature is vibrating back and forth rapidly as shown at (A) of Fig. 406, and the induced e.m.f. is varying likewise. The two terminals of the coil are led out to the input terminals, of the audio amplifier which amplifies the a-f voltage variations. The output voltage of the coil differs in pick-ups of different manufacture, being anywhere from a half volt to over 5 volts. The types delivering the higher voltages are especially suitable for operation with the single-stage audio amplifiers being employed in modern electric receivers, the single audio stage amplifying the output of the phonograph-pickup sufficiently to bring it up to good loudspeaker volume.

In most pickup units the weight of the pickup head, which contains the somewhat heavy permanent magnet, pole pieces, and the coil and armature, is partly counterbalanced by a weight at the other end of the arm (on the far side of the arm swivel), so the needle does not press down too heavily on the record and cause excessive wear of both the record and the needle. The vertical unit pressure between the needle point and the record is astoundingly great, due to the fact that the weight rests on the very small area of the needle point. Assuming the diameter of the needle point bearing surface to be .003 inch, and the needle pressure 5 oz., the resulting vertical unit pressure is roughly 44,000 lbs. per square inch. The counterbalancing weight may be seen at the right end of the pickup in Fig. 405. It is not desirable to completely counterbalance the weight of the pickup head and arm, for some weight must act on the needle in order to keep it from jumping out of the groove when loud low-frequency notes are played. As a consequence, records must be made of hard material, and they must be abrasive enough to grind the needle down a bit during the first few revolutions, in order to reduce the unit pressure at the needle point.

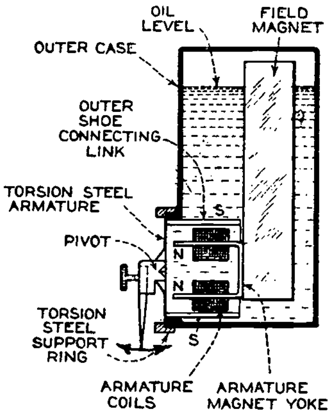


Fig. 409—Left: Interior view of rubber-damped magnetic pick-up unit with cover removed. The horseshoe magnet, pole pieces, armature, and coil are plainly visible. Right: Cross-sectional view of a typical oil-damped pick up, showing the relative arrangement of the parts.

The frequency characteristics of a pickup are almost wholly dependent on the character of the reed or armature, which makes up, with the needle, its simple vibrating system. A reed set in motion manifests a certain resonance frequency. In the best modern pickups, this resonance point usually lies between frequencies of 3000 and 4000 or over. In order to prevent an excessive response at these frequencies, it is necessary to damp the system. This is usually accomplished by means of rubber buffers applied to the free end of the armature. These buffers serve also to center the armature in the magnetic air-gap.

543. The oil-damped pickup: The oil-damped pickup, a cross-section view of which is shown at the right of Fig. 409, possesses frequency-response characteristics which are superior to those of the common rubber-damped type just described, and is used extensively in sound-picture reproduction, and in high grade sound amplifier systems.

As shown at the right of Fig. 409, a horseshoe field magnet (shown in side view) is arranged with an outer shoe and an armature magnet yoke with two windings on its leg. If the former is a S pole, the latter is a N pole as shown. Mounted near the poles is a thin steel armature fastened to the needle and pivoted at the center. Movement of the needle point causes torsional movement of this armature, thus varying the air-gap between it and the N poles, and consequently varying the magnetic flux threading through the armature magnet yoke and the coils. This induces a varying voltage in the coils. The case is nearly filled with oil which acts as the damper against the armature, and so damps the motion. Since the construction of this form of pickup is more complicated than that of the rubber-damped type, it is more expensive.

544. Volume control: The output voltage at the terminals of the pickup can be controlled smoothly by means of a potentiometer of about 50,000 ohms resistance connected across it. The two ends of the full resistance are connected across the pick-up coil. The output terminals connect between the arm and one end of the potentiometer, as shown at (B), (C), and (D) of Fig. 410. In this way, any fraction of the total voltage generated in the coil may be made available at the terminals of the pickup and applied to the input terminals of the audio amplifier. Most pickups are constructed with the volume control potentiometer built into the base.

545. Scratch filter: Due to the fact that the sides of the wavy grooves in a phonograph record are not cut absolutely clean and smooth, little microscopic rough edges are present. These affect the motion of the needle as they go past it, and are responsible for the generation of audio-frequency voltages of around 4,500 cycles. These are reproduced by the loud-speaker as "scratchy" sounds. This is commonly called "needle scratch". These voltages can be effectively by-passed by means of a series wave trap tuned to about this frequency, and connected directly across the pickup coil. An inductance of about 200 millihenries connected in series with a fixed condenser of .004 to .006 mfd. will be in resonance at the scratch frequency and will effectively suppress it. This forms a *scratch filter*.

Most of the better pickups are so designed as to eliminate most of the scratch. Others have a suitable scratch filter built into them. Scratchy sounds coming directly from the record and needle, due to the rubbing or scraping effect of the needle on the record, will be found to come direct from the phonograph cabinet, and can be stopped by closing the cover each time the phonograph is played. While the electrical method of playing phonograph records will work with the older form of records, the reproduction is not as good as when the new Orthophonic type (electrically cut) records are used. In former years, records were made mechanically by a machine which had many defects, and their frequency-range was very limited. Thus, many of the musical instruments in an orchestra were never heard at all, because they were not recorded on the record. Now the records are cut by an electrical recorder which has a wider frequency-range, and produces records which are far superior, both in accuracy in cutting of the groove, and wider frequency-response limits. Practically the entire useful frequency-range of musical instruments is recorded, and all of the instruments in the orchestra are heard (see Art. 9).

545A. Connection to radio receiver: If the phonograph pick-up is to be used with the radio receiver in the home, it can be connected in several ways, as shown in Fig. 410, provided it is of the high-impedance type.

At (A), a double circuit phone jack is wired into the detector plate circuit of the receiver, as shown. The pickup is plugged into this jack and feeds into the primary of the 1st a-f transformer in the receiver. A more common method, which enables the pickup to be connected permanently to the receiver, is shown at (B). One side is permanently connected to the B+ side of the a-f transformer. A single-pole

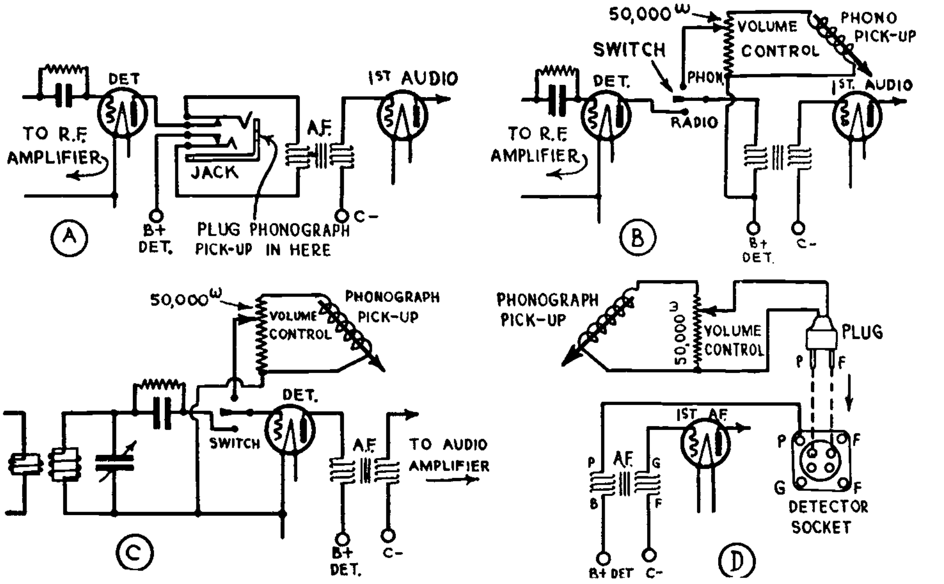


Fig. 410—Various circuit arrangements which may be employed for feeding the output voltage of a phonograph pickup to the audio amplifier of a radio receiver for amplification.

double-throw switch, which may be mounted on the front panel of the receiver or on the tuning dial, enables the top terminal of the transformer to be connected either to the plate of the detector tube in the receiver for radio reception, or to the phonograph pickup for phonograph music. At (C), the pickup is connected to the input of the detector tube by the switch as shown. As the grid leak and condenser are put out of the circuit, the detector tube acts as an amplifier when the pickup is connected in. Thus the additional amplification of the detector tube is made use of in this connection. This method of connection is used extensively in receivers which employ only one stage of audio amplification, since the additional amplification of the detector tube (which now operates as an amplifier) helps to increase the volume. When it is applied in the circuit of a grid-bias detector tube, a slightly different arrangement must be employed. The pickup may be switched in series with the by-pass condenser which is normally across the detector grid-bias resistor. This puts the pickup and the by-pass condenser in series, and the combination is *across* the grid bias resistor. The varying voltage output of the pickup is therefore impressed across the resistor and so causes the grid potential of the tube to vary correspondingly. At the same time, a suitable resistor must be introduced across the detector grid-bias resistor, so as to reduce the grid bias voltage and cause the tube to operate on the "straight" portion of its characteristic curve instead of over the lower "bend" (detector condition).

Some pickup units are provided with an adapter for plugging into the detector tube socket. This adapter has the P and F pins connected to the pickup, and when it is plugged into the detector tube socket, the pickup becomes connected to the input of the audio amplifier as shown at (D). For a-c electric receivers, the pickup connects between the "plate" (P) and "cathode" (C) terminals.

546. High-impedance and low-impedance pickups: When the connecting wires from the phonograph pickup unit to the amplifier are fairly short, the pickup is usually made of the high-impedance type. In this type, the coil contains several thousand turns of wire, and the pickup may have a d-c resistance of about 2,000 ohms, and an impedance something like 20,000 ohms at 5,000 cycles. A pickup of this kind delivers a rather high output voltage, (1 to 5 volts or more), and since its impedance is fairly high, it may be connected directly to the grid circuit of an amplifier tube without any impedance-matching transformer in between. This is known as the *"high-impedance"* type of pickup.

Where the pickup is located some distance from the amplifier or is to be connected to it by long wiring, the distributed capacity of the leads may be appreciable, and acts as a by-pass condenser across the pickup coil. The effect is the same as if a condenser is deliberately connected across the pickup. The higher-frequency audio voltages are materially by-passed, and the high-note reproduction suffers. This trouble may be overcome by constructing the pickup with a low-impedance coil, having fewer turns. Although this does not eliminate the self-capacity of the long extension wires, it removes the undesirable effect of it, since the proportion of the *impedance* of this shunting capacity to that of the pickup coil is now greater, and so proportionately less shunting results. Since the *low-impedance* pickups have less turns of wire on their coils, their voltage output is much less than from the high-impedance type.

Where long leads are used, it may also be desirable to employ a low impedance pickup, to avoid feed-back and the picking up of line noises. It is standard practice in theater and public address system to use either 200 ohm or 500 ohm lines, the latter being more common. When a low-impedance pickup is to be connected to the amplifier by such a line, for proper energy transfer, its impedance must be matched to that of the line by a suitable impedance-adjusting transformer. For instance, a low-impedance pickup wound to 100 ohms should be connected to a 500 ohm line through an impedance-adjusting transformer having an impedance-ratio of 100 ohms primary to 500 ohms secondary. The turns-ratio of such a transformer is equal to the square root of the impedance-ratio required (see Art. 445).

Since the net result of connecting a low-impedance pickup to the grid circuit of the first tube in the amplifier, through a proper impedance-matching transformer, is that a voltage step-up is obtained in the transformer, the disadvantage of the low output voltage is partly overcome.

547. Sound amplifier systems: Sound amplifier systems are used primarily for the amplification and reproduction on a large scale, of programs picked up, (1) directly from microphones, (2) by radio, or (3) from phonograph or film records; and many installations provide for all three. Sound amplifier systems do not amplify sound waves directly. They amplify the varying audio signal voltages applied to them, which are converted into sound waves by the loud speakers. The system may be designed to reproduce the sound in a single place, such as a large auditorium, an athletic or aviation field, a stadium, etc., or it may be used to supply the sound program to many individual places, such as the individual rooms in a large hotel, apartment house, etc. While it is obviously impossible in a book of this character, to present a detailed study of all the various types and arrangements of commercial sound amplifier systems which may be employed, some idea of the typical apparatus which is used in this work will be considered here. Since an ordinary radio tuner and

Courtesy Electrad Inc.

Fig. 411 — A typical 2-stage direct-coupled audio amplifier with an output capacity of 10 watts and a 60 DB gain. Its circuit arrangement is shown in Fig. 412.

detector system must also be used if radio programs are also to be received, the sound amplifier apparatus proper consists of audio amplifier equipment capable of high amplification and large power output, proper loud speaker equipment, and proper input, output and control circuits.

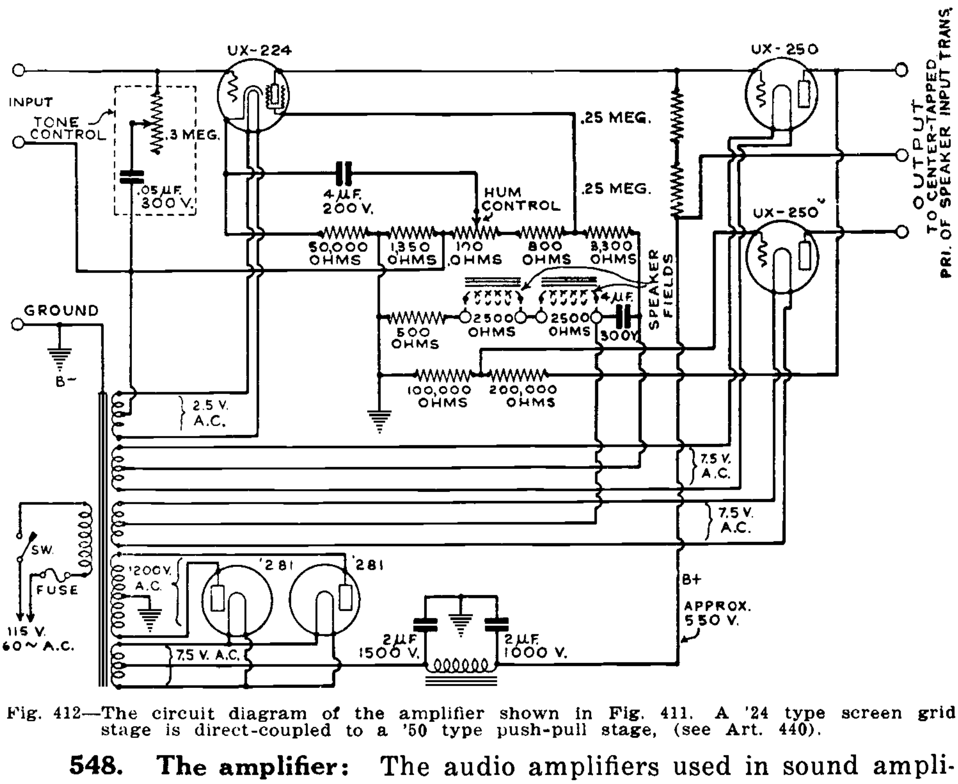
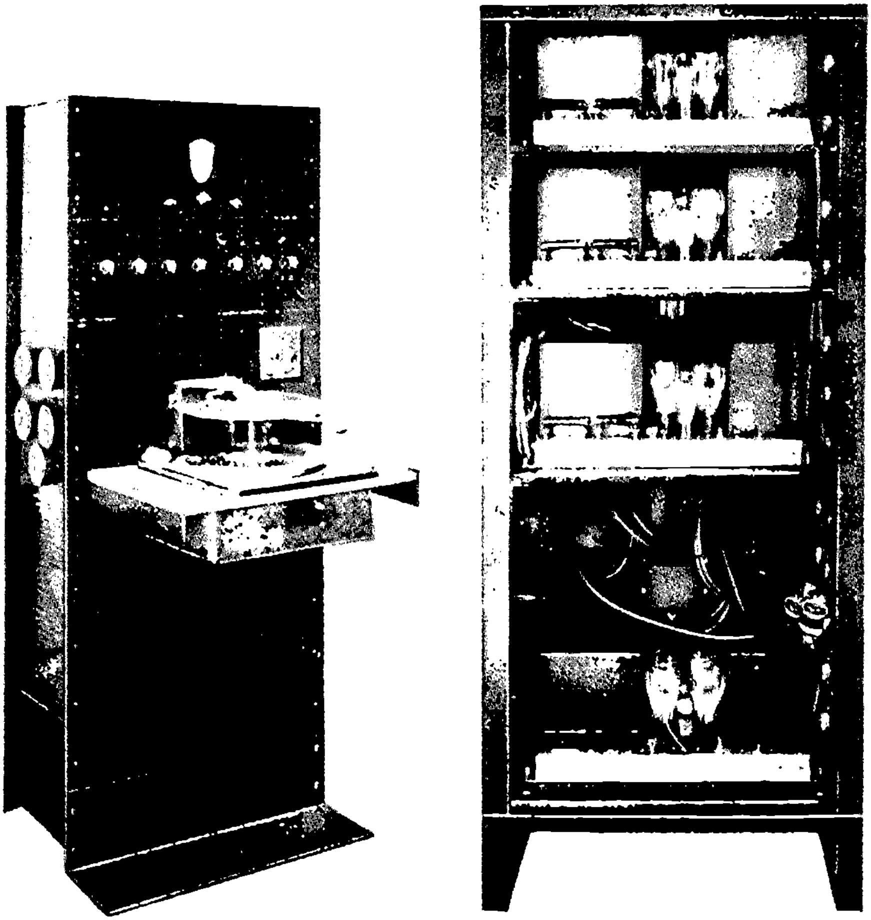


Fig. 412—The circuit diagram of the amplifier shown in Fig. 411. A '24 type screen grid stage is direct-coupled to a '50 type push-pull stage, (see Art. 440).

548. The amplifier: The audio amplifiers used in sound amplifier systems range from small, 2-stage audio amplifiers employing power output tubes of medium power handling capacity, to large 3 or 4-stage amplifiers constructed in switchboard fashion on racks and panels and capable of handling outputs of several hundred watts. The power output capacity of the amplifier employed, depends upon the number and the power input requirements of the loud speakers used, which in turn



Courtesy Electrad Inc.

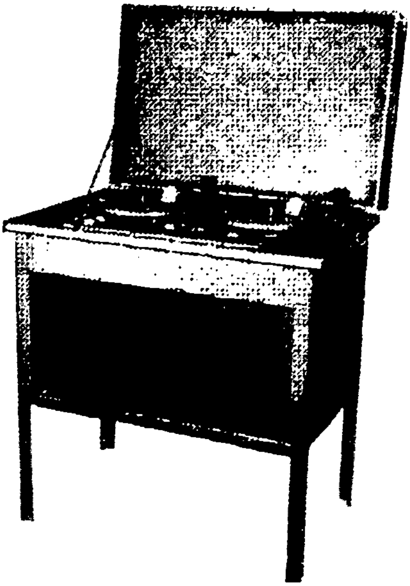
Fig. 413—Left: Front view of a 4-channel amplifier capable of outputting 10.3 watts of undistorted power to each channel. Provision is made for either automatic playing of phonograph records by the automatic record changer at the front; for radio reception; and for microphone pickup of speech or music.
Right: A rear view of this amplifier, showing the four separate amplifier units—one for each channel.

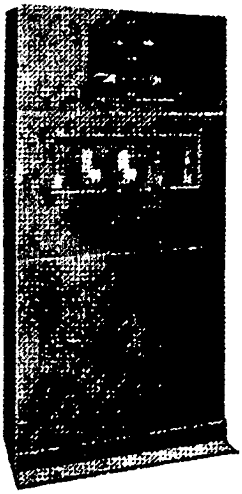
depends upon the area to be served by the system if it is used for outdoor work, or the cubical contents of the room or auditorium if it is to be used for indoor work. Since practically every installation presents different requirements in this respect, no definite figures can be given here. Specifications for the sound amplifier equipment required for any particular installation should always be obtained from the manufacturer of the equipment to be used, in order to assure satisfactory results.

For auditoriums of medium size, or outdoor work over a limited area, two-stage amplifiers of the typical form shown in Fig. 411 are common. This is a two-stage direct-coupled amplifier of the Loftin-White type, (see Art. 440).

The circuit diagram is shown in Fig. 412. It will be seen that two stages of amplification are employed, a '24 type screen grid tube in the first stage feeding to two '50 type tubes in push pull. Two half-wave rectifier tubes connected in a full-wave rectifier circuit are employed. A tone control is included at the input. This particular amplifier produces a gain of 60DB, and with an input voltage of 0.3 volts produces its maximum undistorted output of apparently 10 watts. This particular amplifier can be used with either a phonograph pickup, microphone, or radio tuner connected to its input through a suitable transformer and switching arrangement.

A typical *rack-and-panel* type amplifier unit designed to supply four different programs at one time by means of four separate output circuits





Courtesy Amplion Products Corp.

Fig. 415—Left: A double-turntable phonograph cabinet for a sound amplifier system used in skating rinks, dance halls, hotels, etc.
Right: A 50-watt amplifier for a large sound amplifier system. Note the rack-and-panel construction.

or *channels* is shown in Fig. 413. This can be used for high-power reproduction of radio programs, phonograph music or microphone pickup of music and voice. In rack-and-panel construction, the amplifier system is divided into interchangeable units mounted on separate metal panels which are fastened to a sturdy channel-iron frame. This saves floor space since the panels are mounted vertically, results in a rigid construction, and offers great flexibility because amplifier systems of any desired arrangement and power can be built up from standard amplifier and control units and may be added to at any time. The view showing the automatic record changer and phonograph pickup is at the left.

The top panel contains a three-stage screen-grid tuner and detector whose output can be applied to any one or all of the four audio amplifiers, and thus feed to any of the four channels. Below this is the mixer panel containing the knobs for controlling pickup, individual channel output volume, and microphone volume. It is possible to use the radio, phonograph pickup, or microphone independently, or to mix them all, by simply operating a single switch. Thus, a speaker may have a musical background to color his speech, if desired. The automatic record changer which changes 10 records and provides 50 minutes of record reproduction, is shown together with the phonograph pickup unit on the projecting shelf at the front. A rear view of this amplifier is shown at the right. A separate amplifier unit is provided for each channel supplied.

Another high power sound amplifier system with a separate double-turntable phonograph cabinet is shown in Fig. 415. The amplifier shown at the right, has a power output of 50 watts and amplifies over an audio range of 60 to 10,000 cycles with a 65 DB gain. The control knobs are shown on the top panel, with the tubes beneath. Amplifiers of this large output capacity are used for dance halls, skating rinks, stadiums, etc. Either radio reproduction, phonograph music, or microphone pickup of

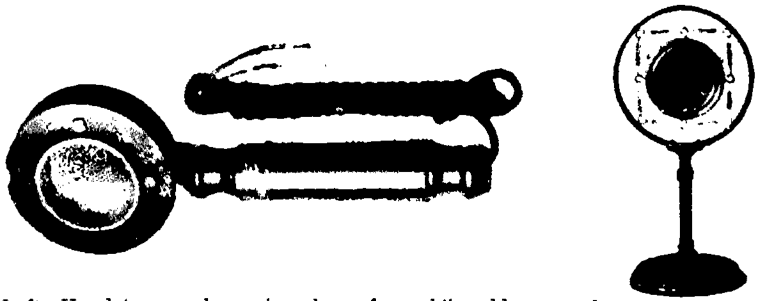


Fig. 416—Left: Hand-type carbon microphone for public address work. Right: Desk-type carbon microphone. Notice the spring mounting for the microphone at the center.

speech or music may be supplied. A large rack-and-panel amplifier used in sound picture work in theatres is shown in Fig. 492.

549. Microphones: Microphones used for public address work are usually of the carbon type, although condenser-type microphones are sometimes employed for high-quality pickup. The construction and operation of the carbon-type microphone has already been discussed in connection with the radio broadcasting station equipment in Article 235. A cross-section view of a carbon microphone is shown in Fig. 169.

Fig. 416 shows two typical forms of carbon microphones used in public address work. That at the left is designed to be held in the hand of the speaker, that at the right is a desk type. The microphone may also be mounted on a tall stand of adjustable height, so it reaches the level of the speaker's mouth. In general, the microphones used for speech only are constructed with a higher sensitivity but smaller frequency range than those intended to cover the complete range of speech and music frequencies. The microphone unit is suspended by springs to take up shocks and vibrations.

The battery current sent through this type of microphone should never be allowed to exceed the value specified by the manufacturer.

The construction and assembly of the various parts of a condenser-type microphone or "transmitter" is shown in the cross-section view of Fig. 417.

It consists essentially of a thin duraluminum diaphragm under tension, separated by a very small distance from a plane metal plate, the plate and the diaphragm forming the two plates of a condenser, from which the microphone derives its name. The thickness of the diaphragm is of the order of .001 inch, and the spacing between the diaphragm and the back plate is about the same distance. For broadcast purposes, the diaphragm is usually stretched to a natural vibration frequency of 8,000 cycles per second to avoid resonance effects in the a-f range normally transmitted. In use, the condenser microphone is normally "polarized" by having 180 volts connected across it, as shown in the connection diagram of Fig. 418. Sound waves striking the diaphragm cause it to vibrate very slightly. This changes the distance between it and the back plate, which changes the capacitance, causing a tiny flow of charging current to flow back and forth around from one plate through the circuit to the other. This current must flow through the 20 megohm resistor, thus setting up a varying voltage across it. This varying voltage whose wave-form is the same as that of the sound waves, is applied to the grid circuit of an amplifying tube, the same as in any ordinary resistance-coupled amplifier.

Since the capacitance of the condenser transmitter is very small, the capacity between the leads from it to the grid of the first amplifying tube must also be kept

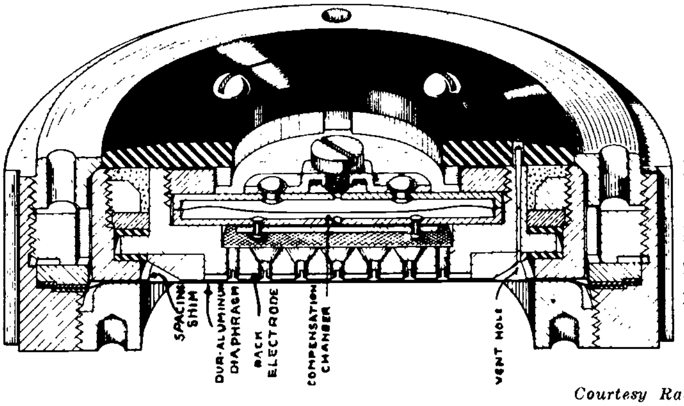


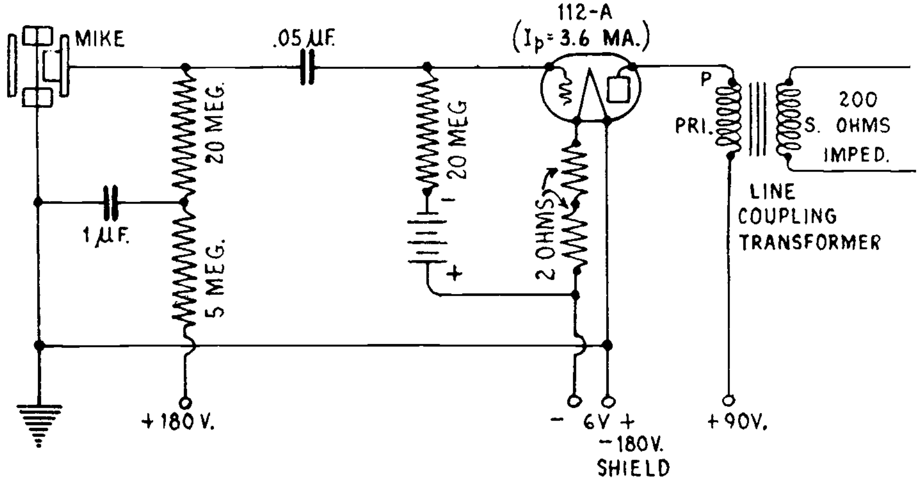
Fig. 417 — Cross-section view of a condenser-type microphone, showing the back plate and the diaphragm. The sound waves striking the diaphragm cause it to vibrate, thus varying the distance and capacitance between it and the back plate.

Courtesy Radio Engineering Magazine

very small or it will represent an appreciable percentage of the total capacitance of the circuit. It is general practice, therefore, to build the microphone and the first stage or two of amplification as a unit. This keeps the leads very short. A typical amplifier stage for use with a condenser transmitter is shown in Fig. 418. A line-coupling transformer for coupling this to a 200-ohm line is included in the output. The amplifier unit is built in with the microphone.

The signal available from the condenser microphone is very small, so little, in fact, that two stages of amplification are usually required to bring the signal level up to that which would be produced by a carbon-grain microphone. However, absence of the usual hiss that is so objectionable in the carbon type of microphone, much better frequency characteristics, and ruggedness make the condenser "mike" the preferable of the two types where undistorted output is essential.

550. Mixing panel: Since the sound amplifier systems are commonly designed to amplify the output of either a radio signal tuner and detector, phonograph pickup, or microphone, provision must be made at the input circuit of the amplifier, to quickly throw over from one to the other and to control the input voltage smoothly. This is the function of the *mixer circuit.* While mixer circuits may be very complicated if several microphones and phonograph pickups are to be employed, the simple system shown in Fig. 419 will serve to illustrate the general principles which are involved in them in most cases.



Courtesy Jenkins and Adair Inc.

Fig. 418—The circuit arrangement of an amplifier stage built in with the condenser microphone to boost its output before being fed to the line between it and the regular amplifier.

Assuming that a double-button carbon microphone is to be used, it is coupled to the input of the amplifier by the impedance-adjusting transformer T_1: If the microphone has the usual resistance of 100 ohms per button, (200 ohms total), the transformer may have a primary to secondary impedance ratio of 200 to 500,000 ohms,

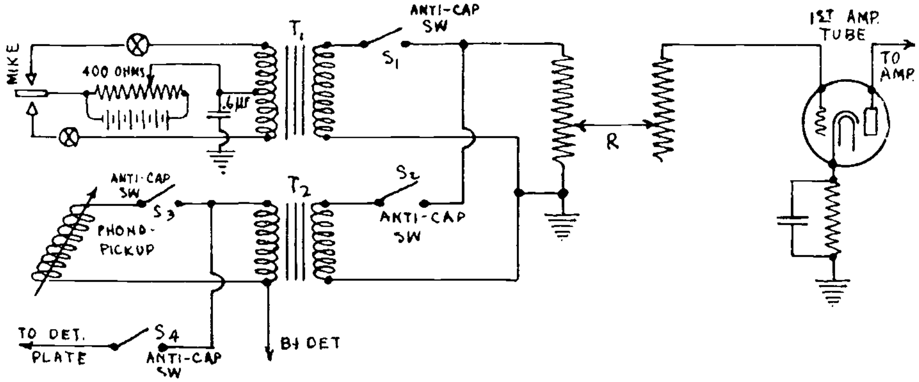


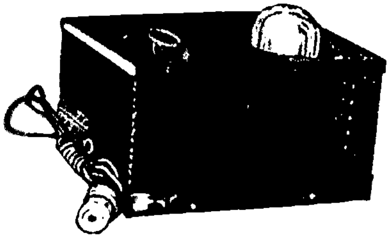
Fig. 419—Simple mixer circuit for selecting the type of program to be fed to the volume control and amplifier, in a sound amplifier system.

the latter being about the proper value for feeding into the grid circuit of the first amplifier tube. Four dry cells in series provide the current for the microphone circuit the current being regulated by the 400 ohm potentiometer. Jacks are provided at points X—X for plugging in a milliameter to check the microphone current. The secondary of T, may be connected at will to the grid circuit of the first amplifier tube through an anti-capacity type switch S_1. If a high-impedance type phonograph pickup unit is employed, it may feed into the primary of the first a-f transformer T_2) and the input from the radio tuner may also feed to this, either one being connected by means of the switches S_3 and S_4. The secondary of the transformer also feeds to the tube input through a switch S_2. The volume control resistor R is common to both circuits. This is of the constant-impedance type (500,000 ohms in this case), which consists of two tapped variable resistors mounted on a common shaft and connected as shown, so that the resistance looking from either direction at R is always the same, while the signal voltage allowed to act on the grid of the amplifier tube can be varied from zero to maximum by moving the arm upwards. In this way either radio, microphone or phonograph pickup signal voltages may be fed to the amplifier at will and the volume controlled in each case. The various switches can be combined in the form of a multi-section switch for easy manipulation, and other refinements and additions may be made for more elaborate systems.

Where the amplifier is located some distance away from the pickups, additional impedance-adjusting transformers are required.

551. The loud speakers: For large outdoor or indoor installations, loud speakers of the general types shown in Figs. 353, 355, 356, and 495 are used. In many cases where the speakers are to be distributed over a large area, the permanent magnet type driving unit is employed because no field current and field supply wiring are then required—making the installation simpler and cheaper.

Electro-dynamic units for horn speakers may be of the type shown at the left of Fig. 420. The direct field current for a unit of this type may be supplied by a



Courtesy Amplion Products Corp.

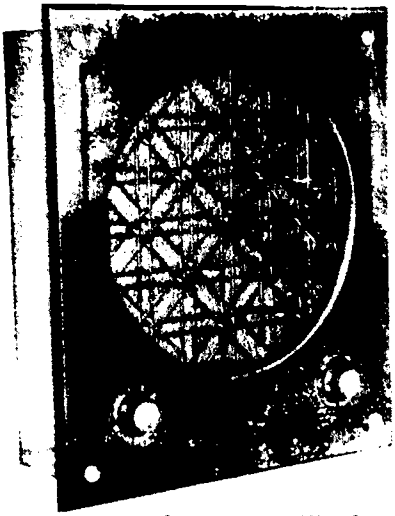
Fig. 420—Left: Typical electro-dynamic driving unit for an air-column type loud speaker. Right: An exciter unit for supplying low-voltage direct current for the field of the speaker unit at the left. The exciter operates from the 110 volt a-c line and contains a suitable transformer and rectifier bulb.

separate exciter units such as that shown at the right, operating from the nearby a-c electric light circuit. This contains a suitable transformer and rectifier, supplying d-c to the speaker field. For individual room installations in hotels, schools, apartment houses, etc., either a permanent magnet reed-type or a moving-coil type loud speaker having a cone type diaphragm, is usually built into a box in the wall of each room, with a decorative grille at the front. A speaker of this kind inside its enclosing box, is shown at the left of Fig. 421. Program channel selection and volume control is provided at the speaker itself, or at a control plate conveniently mounted on the wall.

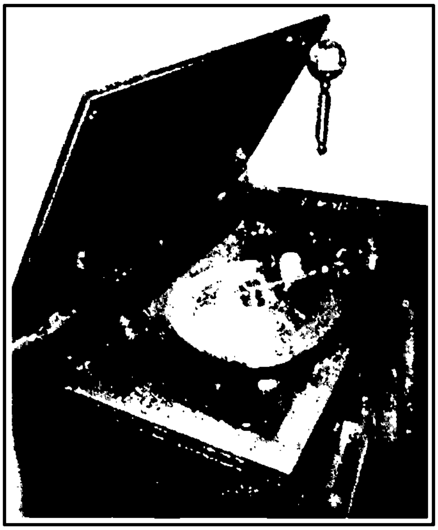
Various circuit combinations of speakers are employed in large systems. In all cases, proper impedance-matching transformers (Art. 445) must be used when necessary. Some manufacturers provide the power stages in their amplifiers with output transformers having several taps to enable matching of the impedance values of different types or combinations of loud speakers. Thus, where dynamic and magnetic speakers operate from the same amplifier, they can be connected to different taps so that each type will be operating under the best conditions. Magnetic speakers require about ¼ watt for operation at maximum volume but only about one-twentieth watt for hotel room volume. Ordinary electro-dynamic speakers require from 1 to 3 watts each for full-room volume, depending on make and type. Headphones, of course, require very low power—around 1/200 watt each. The large auditorium-type dynamic speakers handle much more power.

The wiring of sound amplifier systems assumes great importance particularly where the circuits are extensive, as in hotel, school and similar systems. The practices of installation men and also the recommendations of equipment manufacturers vary considerably as to the wiring specifications and requirements for sound amplifier installations.

No. 18 wire is probably the most commonly used size. In some installations it takes the form of twisted pairs, in others telephone cable is used, and in still others



Courtesy Best Mfg. Co.



Courtesy Presto Corp. of America

Fig. 421—Left: A magnetic type speaker in a wall for apartment house and home installation. Volume control and program selector knobs are provided at the bottom. A decorative grille is shown in front of the speaker.
Right: A home recording installation in a phono-radio combination. The phono-pick-up is at the left; the recorder is at the center; and the microphone is suspended from the cabinet cover. This type cuts its own groove into the surface of a smooth aluminum disc.

the wiring system is made up of shielded pairs, each pair being sheathed in a metallic wrapping to eliminate any possibility of cross-talk where the wiring of two or more channels is carried in the same conduit.

The use of standard rigid conduit to safeguard the wiring is to be strongly recommended, since this type of conduit provides against all possible forms of physical injury to the wiring. Another is the complete electro-magnetic shielding provided, preventing the pick-up of hum or other interference from neighboring electrical circuits. The third and an especially important reason for the use of rigid conduit in sound amplifier installations is that it provides the only type of wireway from which the wiring may be withdrawn for circuit alterations or into which additional wires may be drawn at any time without damage to the plaster. Thus, if additional channels are later added the new wires may easily be drawn into the same conduit with the old ones which are already installed.

552. Home recording: Home recording of speech or music on special aluminum-alloy or celluloid phonograph records makes possible the recording of special radio programs, historic events, etc., in the home, at any time. After the recording is made, the ordinary phonograph pick-up, with a special fibre needle, is used to play back the recording through the audio amplifier and loud speaker of the ordinary home radio receiver.

There are two systems of home recording in use. In one, pre-grooved record blanks are used, the grooves guiding the cutter stylus during the recording. Either the output signal from the radio receiver, or the voice signal picked up by a special microphone and fed through the audio amplifier of the receiver, is used to actuate the cutter, while the disc is revolving on the rotating phonograph turntable.

In the other system, smooth metal discs are used. In this, the recording equipment includes a special feed mechanism operated by the turntable which feeds the cutter of the recording head toward the center of the disc as the recording proceeds. In this way the cutter cuts its own spiral groove and also records the program by means of wiggles or waves formed in the groove. Fig. 421 shows the equipment for this type of home recording installed in the phonograph compartment of a phonograph—radio combination. The recording cutter is actuated by power from the output of the audio amplifier in the radio receiver. At the left is the ordinary phonograph-pickup unit used for playing the home recorded records. At the center of the turntable is the recording head mounted in place on the feed mechanism. The hand type carbon microphone, which feeds into the audio amplifier, for speech recording, is suspended from the cabinet top. While the quality of reproduction from recordings of this kind is not comparable with that from ordinary phonograph records, home recording has entertainment value and practical worth for permanently recording programs of sentimental or historic nature, etc.

REVIEW QUESTIONS

1. Describe the process of reproduction of sound from a phonograph record of the lateral-cut type.
2. A note of 1000 cycles is recorded on a phonograph record with the turntable running at 70 r.p.m. What will be the frequency of the sound produced when the record is played back, if it is run at, (a) 80 r.p.m.; (b) 60 r.p.m.?
3. Explain, (with diagram), the construction and operation of the iron-reed type phonograph pickup. What is the purpose of the permanent magnet? In your estimation, from the point of view of lightness and small magnet dimensions for a given field strength, which would be preferable for the magnet, (a) tungsten steel; (b) cobalt steel?
4. How will wobbling of the turntable affect the reproduction from a phonograph pickup? Explain!
5. How do the low-impedance and high-impedance types of phonograph pickups differ in construction? What are the relative advantages of each type? What is the purpose of the impedance-adjusting transformer used with the former type?
6. What form of power supply is preferable for sound amplifier systems? Why?
7. Mention two important features of push pull amplification that recommend it for use in sound amplification systems?
8. What is the difference between the requirements of the audio amplifier used in an ordinary radio receiver, and those of an

amplifier used for a large sound amplifier system? How are the special requirements of the latter satisfied?

9. What is meant by rack-and-panel amplifier construction? Why is it used?
10. What is the purpose of the "mixer" circuit in a sound amplifier system?
11. A particular sound amplifier system is to be used for radio reproduction, and for phonograph reproduction from a pickup having an output of 1 volt. The power output required from the amplifier is about 5 watts. Draw a complete circuit diagram for the a-c electrically operated amplifier, with proper input circuit for either radio or phonograph reproduction, and to operate two electro-dynamic speakers with their 10-ohm voice-coils in parallel across the secondary of the output transformer. What must be the impedance-ratio of the windings on this transformer? Now add to your diagram an input circuit for a two-button carbon microphone.
12. Explain the construction and operation of the condenser-type microphone and its associated amplifier stage. Why is this amplifier stage necessary?
13. The total a-c plate resistance of the output tubes of a power amplifier is 4000 ohms. This is to be coupled to a 200 ohm distribution line, at the far end of which are to be connected six loud speakers, three of which are magnetic speakers having an impedance of 3000 ohms each and three of which are of the electro-dynamic type having an impedance of 30 ohms each. They are to be connected in two separate groups, with three of each kind in parallel in each group. Each group is fed from a separate secondary winding on the impedance-adjusting transformer. Draw the circuit diagram for this condition, and determine the impedance-ratios and turn-ratios of the windings on the two impedance-adjusting transformers required.
14. What is the essential function of the equipment used in a sound amplifier system?
15. Explain briefly the circuit arrangements and the principles involved, in home recording of sound or radio programs on both the pre-grooved type, and blank type discs. What equipment is necessary for each method?

CHAPTER 31

SHORT WAVE RECEPTION

SHORT WAVE COMMUNICATION — AMATEUR TRANSMISSION — TYPES OF SHORT WAVE RECEIVERS — SHORT WAVE TUNER SYSTEM — PLUG-IN COILS AND SWITCHING SYSTEMS — SHORT WAVE TUNER DESIGN — BAND SPREADING COILS — SIMPLE REGENERATIVE RECEIVER — FRINGE HOWL — DEAD SPOTS IN TUNING — WAVEBAND-SWITCHING SYSTEMS — SHORT WAVE SUPERHETERODYNE — SHORT WAVE CONVERTERS — SHORT WAVE ADAPTERS — OPERATING THE SHORT WAVE RECEIVER — TIME DIFFERENCES — FADING AND SKIPPING — MICRO, OR QUASI-OPTICAL RAYS — REVIEW QUESTIONS.

553. Short wave communication: While reception of programs from those radio stations which operate with carrier frequencies within the ordinary broadcast band of approximately 545 kc (550 meters) to 1,500 kc (200 meters), is perhaps most common to the average layman, a great deal of amateur, commercial, and general broadcasting transmission is also carried on by transmitting stations employing very high carrier frequencies, producing what are popularly known as *short wave* radiations. Remembering from our previous work, that the relation between wavelength and frequency for radio radiations is

$$\text{Wavelength (meters)} = \frac{300{,}000{,}000}{\text{frequency in cycles per second}}$$

it can be seen that the higher is the frequency, the lower or shorter is the wavelength. *Short* waves mean *high* frequencies. Short wave communication is therefore carried on with carrier currents, voltages, and radiations of very high frequency. Thus, a wavelength of 500 meters corresponds to a frequency of about 600 kc; a wavelength of 10 meters corresponds to a frequency of about 30,000 kc. A chart which gives the wavelengths corresponding to the various frequencies, and vice-versa, will be found in Appendix K at the rear of this book. This is very handy, as it saves the time usually required for calculations by the above formula. In general, all communication with carrier frequencies above 1,500 kc (wavelengths below 200 meters) is classed as *short wave communication.* This band is shown at the right, in the chart of Fig. 163, which should be studied carefully at this point. The general short wave band is divided up for convenience into smaller bands in which communication of particular classifications is carried on.

While ordinary short wave communication is carried on with wavelengths down to perhaps 10 meters or so, experimental transmitting and receiving apparatus is being developed to produce radiations of higher and higher frequencies. At the present time considerable experimental work is being carried on with frequencies which are so high that the radiations produced have wavelengths as short as 18 cm. (7 inches), and possess many of the properties of light, since they are somewhat of the same character. These are called "micro-waves" or "quasi-optical" radiations, and may be reflected by ordinary reflectors just as in the case of light rays. They promise to open up a new field in radio communication. We will consider these in greater detail in Art. 570. We will confine our studies for the present, to apparatus and circuits used for ordinary short wave communication with radiations having wavelengths between about 5 and 200 meters.

Contrary to popular opinion, short wave transmission and reception, which is becoming so widespread, is not a new discovery. Owners of amateur radio transmitting stations have been communicating regularly with radiations of short wavelengths for some years Many of the leading broadcasting stations operating regularly on the broadcast band, also transmit their programs simultaneously by short wave transmission. These short wave transmissions have been heard almost all over the world, far beyond the range obtainable with the regular broadcast band transmission. As a matter of fact, high-frequency radiations are characterized by an uncanny carrying power. Low-power stations transmitting at high carrier frequencies transmit over distances that could be spanned by the lower frequencies (higher wavelengths) only by an expenditure of hundreds of times as much power. Reports of reception, on one or three tube receivers, of short wave stations thousands of miles away, has so fired the imagination and interest of many people that short wave reception of both code and phone signals has become very popular.

554. Amateur transmission: The thousands of privately-owned amateur stations throughout the world have done much to increase our store of knowledge concerning short wave transmission and reception. Owners of moderately equipped stations in widely scattered parts of the world have become neighbors and exchange almost daily conversations with their friends. The extremely low power used in most cases, makes these achievements seem almost incredible to those familiar only with the large broadcasting stations operating on the regular broadcast wavelengths, with as much as 50,000 watts of power.

Several important advantages of short wave communication are, the fact that even long-range short wave communication can be accomplished with comparatively small amounts of power; that short-wave communication is fairly free from "static"; and that the short wave band covers such a large range of frequency making it possible to assign wavebands to thousands of stations, without danger of interference. Signals from short wave stations employing but a few watts of power have been heard thousands of miles away, whereas our large broadcast band stations may use 50,000 or more watts of power and be received within a radius of only a few hundred miles. The large frequency band in the short wave range is very important. In the ordinary broadcast band between 200 and say, 550 meters, (a range of 350 meters), there is only a frequency range of approximately 1,000 kc. In the short wave band between 5 and 200 meters (a range of only 195 meters) there is a frequency range of 59,000 kc. Obviously, many more transmitting stations can be accommodated when such a large frequency range is available, assuming that each station takes up a frequency band or channel 10 kc wide. This is one of the reasons why television broadcasting is carried on in the short wave range, as we shall see later.

555. Types of short wave receivers: Short wave receivers must perform exactly the same tuning, amplifying and de-modulating functions as do the ordinary broadcast band receivers which we have already studied, so it is natural to find that the general circuit arrangements employed in short wave receivers are the same as those used in the broadcast band types. Very simple short wave receivers usually consist of a regenerative detector with or without one or two stages of transformer-coupled a-f amplification. Next we have the receivers employing a stage or two of tuned screen grid r-f amplification. The more elaborate receivers are of the superheterodyne type. These have come into popular favor on account of their greater sensitivity, due to the fact that considerable amplification may be more readily obtained at the low intermediate-frequency existing in the i-f amplifier than can be conveniently obtained when amplifying the incoming high-frequency signal directly.

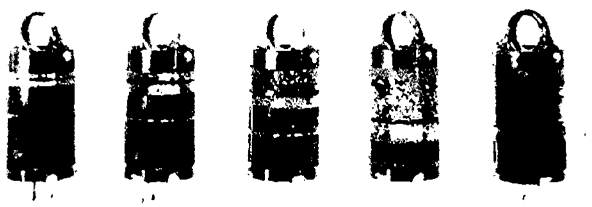
In general, the tuner circuit and construction in a short wave receiver, is possibly the only part of the receiver system which differs radically from that of the ordinary broadcast band receiver. We might possibly say that the detector also differs somewhat, since detectors of the sensitive grid leak-condenser type are commonly employed, in the simpler receivers, usually with regeneration. The audio amplifier systems are practically identical with those of broadcast-band receivers.

In designing and constructing short wave equipment, many problems are encountered, which are not met with in dealing with equipment designed for reception of signals at the lower carrier frequencies (higher wavelengths). Due to the high frequency of the signal voltages and currents existing in the circuits, the layout of all parts and wiring must be given much thought, as inductance and capacity effects between wires and between coils, etc., are very important. All wires from grids and plates of tubes should be kept short and well separated. Unless care is exercised in wiring the variable condensers, troublesome hand capacity effects are liable to result. This makes tuning very difficult, and is manifested by a change in the tuning of the set whenever the hand is brought near the tuning dial. The wire from the grid of the tube to the tuning coil and condenser should always be connected to the *stator* plates of the tuning condenser, and the frame and *rotor* plates should go to the grid-return circuit and ground. Complex circuits using multi-stage amplifiers are usually either unstable, or have too many operating controls, to be of value. As the tuner design in short wave receivers is a special problem we will consider it first.

556. Short wave tuner system: The purpose of the tuner in any radio receiving system, is to allow the varying signal voltages of the one station it is desired to receive, to get through and act on the grid circuits of the amplifier tubes, and to offer a high opposition to the signal voltages and currents which have been induced in the antenna circuit by the radiations of all other stations—thus suppressing them so they are not heard. Furthermore, the tuner must be adjustable, so that it may permit the reception of the modulated carrier-signals of any of many stations, within the frequency range for which the receiver is designed to operate.

In most broadcast receivers, the matter of tuner design is comparatively simple. Experience has shown that a single inductance coil of proper value, associated with its single variable tuning condenser of about .00035 mf. maximum capacitance will form a resonant or tuned circuit, which, by varying the capacitance of the tuning condenser, may be adjusted to resonance to incoming signals of any frequency within the broadcast band range of say 200 to 600 meters (1,500 to 500 kc). Thus, a single tuning condenser and coil in each tuned stage will easily cover the tuning range of 1,500 minus 500, or 1,000 kc required. The broadcast receiver usually has a dial with 100 divisions to cover the 180 degree movement of the rotary plates of the tuning condenser. If the tuning dial is moved through 100 dial divisions and if the condenser and coil arrangement is such as to give say, absolute straight-frequency tuning over the entire dial, then it would be possible to tune in 100 different broadcasting stations, one at each division of the dial, each with a separation of 10 kc, providing the receiver were sensitive enough to receive this many stations and it were selective to 10 kc. We find therefore that our broadcast band receivers use a single tuning coil and a single condenser in each tuning circuit, to cover the entire broadcast band of frequencies.

The tuning problem in short wave receivers is not nearly so simple. If we consider the required tuning range of the receiver to be from 10 to 200 meters, we find that this corresponds to a frequency range from about 30,000 to 1,500 kc, or 28,500 kc—just 28.5 times as large as the tuning circuits in our broadcast receiver must cover. This is because each change of one meter in wavelength at the low wavelength ranges, is caused by a much greater frequency change than a change of one meter



Courtesy Pilot Radio & Tube Corp.

17 to 30 Meters	30 to 52 Meters	45 to 105 Meters	93 to 203 Meters	200 to 500 Meters

Fig. 422—A set of 4 plug-in type tuning coils for use in a short wave receiver. The waveband which each coil covers with a .00016 mf. tuning condenser is marked under the coil. Notice that the coils have been purposely designed so that the wavebands overlap somewhat

wavelength in the upper ranges. This may be seen graphically in the Wavelength—Frequency Channel Chart in Appendix J at the rear of this book.

This means, that if a short wave receiver were designed to cover this entire short wave band with a single tuning coil and condenser in each tuned circuit, they would have to cover a tuning range of 28,500 kc. If the dial had 100 divisions, each division would represent 285 kc. If transmitting stations are assigned frequencies 10 kc apart, 28 different stations might be tuned in and out by a movement of one division of the dial. Obviously, such crowded tuning is absolutely impractical. Even if this crowded tuning were practical, the system itself would be impossible to design with any degree of efficiency, since no simple tuning circuit with a fixed coil and a variable tuning condenser can be made to cover a frequency range of anywhere near 28,500 kc. The tuning condenser adds some capacity to the circuit even when it is set with its rotor plates all unmeshed from the stator plates. In addition to this, the distributed capacity of the tuning coil winding, and stray capacities existing in the circuit tend to tune the coil even when the tuning condenser is set at its zero dial setting. Therefore while a particular coil and condenser might be designed to tune to the lower frequency of the band satisfactorily, they would never tune to the higher frequency, or vice versa.

557. Plug-in coils and waveband-switching systems: This problem has been solved in two ways in practice. One method is to construct the receiver either with several easily-removable tuning coils or condensers, or both. In the latter case the coils or condensers can be changed for each of the many narrow wavebands into which short wave transmission is now divided. In this way, each coil-condenser combination is required to tune over only a reasonable frequency-band. These are, the 160 meter, 80 meter, 40 meter and 20 meter amateur bands and the broadcast short-wave bands at 50, 25 and 20 meters. While the short wave band is considered to extend to 200 meters, there is very little communication of interest on wavelengths between 150 and 200 meters.

Many short-wave sets have been built with a non-removable variable tuning condenser, and a number of removable plug-in coils, which are wound for tuning to the various wavebands. Fig. 422 shows a typical set of these plug-in coils used in a popular short-wave receiver. The coils with the larger secondary windings are for tuning to the higher wavelengths, (lower frequencies). In this way, each coil is used for tuning only to a narrow range of frequencies and the tuning is not so crowded on the dial. The tuning coils for short wave receivers are mostly of the simple solenoid type. For the high frequencies, only a small inductance is required, and comparatively few turns of wire are necessary. The turns are usually spaced from each other to reduce the distributed capacitance of the winding. These coils must be wound accurately, as the change in inductance caused by one turn more or less of wire will cause quite some difference in the tuning range of the coil-tuning condenser combination. Some special receivers are built with removable plug-in variable condensers of various sizes.

The more common method now is to use a switching arrangement for switching in additional inductance sections for tuning to each successive band of higher wavelength (see Art. 563). While such switching arrangements are often rather complicated, they simplify the operation of the receiver, since it is merely necessary to turn the "waveband selector" knob in order to select the proper tuning inductance for tuning in the particular waveband desired, instead of opening up the receiver cabinet and inserting different plug-in coils. A typical receiver employing such a switching system will be described in Art. 563.

558. Short wave tuner design: When the tuning condenser plug-in coil arrangement is used, it is necessary to employ tuning condensers of lower maximum capacitance than is common for broadcast band reception, in order to be able to tune down to the low wavelengths around 15 meters.

Ordinary 0.00035 mfd. condensers have a *minimum* capacity which is too high to enable the set to get down to 15 meters if a practical coil with any turns at all is to be used with it. Tuning condensers having a smaller maximum capacity employ less plates and therefore their minimum capacity (plates all un-meshed) is very much lower. Consequently they are always used in short-wave receivers. A common short-wave set tuning condenser size is about 0.00016 mfd. maximum capacity. This usually has a total of about 8 or 10 plates. While the arrangement of plug-in tuning coils or a switching arrangement, solves the problem of covering all of the wave bands, each coil having a slight overlap over the next smaller size so that there will be no "holes" in the wave-band covered, there is set up one disadvantage which, is quite serious. This disadvantage has to do with the crowding of the dial for a particular wave-band. Let us suppose that for the 40- and 80-meter bands ample spread of the tuning response is obtained over the tuning dial. Yet when the 20-meter coils are plugged into the coil sockets the whole band might be bunched together within a few divisions of the dial. To overcome this evident crowding on the 20-meter band, we may resort to the expedient of removing plates from the tuning condenser, but this procedure has a detrimental effect on the tuning for other wave-bands.

This problem may be solved by the use of *special band-spread coils.* Coils of this type are plugged in in the same manner as the standard coils and without making any changes in the receiver itself. The result, in the case of the 20- and 40-meter amateur bands, is a 50-division spread, located right in the center of the dial.

Unfortunately it is impossible to spread the tuning out on the dial and still have the same frequency-range completely covered by a given number of coils. If it is desired to cover the same range but have the tuning opened up it can only be done by using a larger number of coils and lower tuning capacity or something else which will be the equivalent. However, it may be that the owner of a short-wave receiver is interested only in certain portions of the band between 20 meters and 200 meters. An amateur, for instance, may be interested only in the American amateur bands. All he wants is to cover a narrow band at 20 meters, another at 40 meters and another at 80 meters. The wavelengths in between hold little interest for him.

The use of old vacuum tube bases as forms on which to wind short wave plug-in tuner coils has become very popular since these bases already contain the plug-in prongs and a suitable Bakelite form for winding. The primary and secondary winding on coils of this type may be arranged as shown in Fig. 422A. The ends of the coils are soldered to the tips of the hollow brass prongs. A time-saving design chart for short wave coils wound on vacuum tube base forms is shown in Fig. 422A. This is published here by courtesy of Mr. George Crammer, its originator. The instructions for using this chart are reprinted herewith by courtesy of Q. S. T. Magazine in which they originally appeared.

"Perhaps the most common case is that of determining the proper number of turns of a given size of wire to obtain a desirable tuning range in the receiver, when used with a tuning condenser of given capacity range. The first step is that of determining the capacity range of the circuit. The minimum and maximum capacity of the tuning condenser should be known and to these values should be added the "dead" capacity of the other parts of the circuit which parallel the coil and condenser. These comprise the capacity of the tube and coil base and socket, grid-to-filament capacity of the tube, capacity of the wiring, etc. If the antenna is coupled through a small capacity, this will cause a further increase. It is extremely difficult to assign a value for this capacity but in most cases it will probably fall somewhere between 20 and 40 mmf., although it is perfectly possible to have values differing from these."

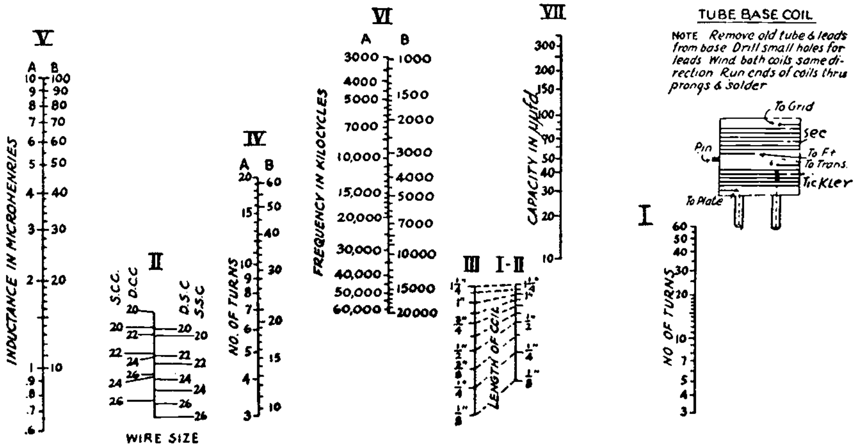
"A straight edge should be run from the point on Scale VII corresponding to the capacity of the circuit with the tuning condenser at maximum, through the point on scale VI corresponding to the lowest frequency desired in the range of that coil. The point at which it crosses scale V will give the required inductance. Holding this inductance value, the straight-edge can be shifted along scale VII to the condenser's "minimum" capacity value to check the highest frequency to which the circuit will tune. If the range is too large, the tuning capacity may be reduced or additional fixed capacity employed; the former is preferable. If the range is sufficient, the value of inductance can be varied to put the desired frequency range in the center of the capacity range which will give more margin as regards the difference between the actual and the guessed-at value of 'dead' capacity."

"In order to determine the number of turns of wire necessary to give the desired inductance, the number of turns of wire per inch should be known. For a tight winding, this may be obtained from the table in Fig. 288. By lining up on the one-inch point on scale, I-II with the size wire and type of insulation as given on scale II, the straight-edge will indicate the number of turns per inch on scale I, (Fig. 422A)."

"The last step is to find the number of turns to give the required inductance and give the proper length of winding. This value has been reached when the straight-edge connects the inductance value on scale V with the number of turns on scale IV which will just take up the length of winding indicated on scale III. A few trials may be necessary to arrive at this value, but there should be no great difficulty in reaching the proper answer. After the figure has been obtained it would be advisable to check through the problem from the other end to see if the coil determined upon will give the frequency range desired with the change in capacity permitted by the circuit."

"The above solution is predicated on the assumption that the wire will be wound with no spacing between the turns. The desired inductance may be obtained without reference to wire size by choosing any convenient length and winding in that space the number of turns indicated on scale IV by the straight-edge when placed so as to connect the proper values on scales III and V. In this case the only limitation to be observed is that a size of wire must be chosen which will allow winding the necessary number of turns in the given space. The use of scales I, II and I-II will readily check this. The wire should be wound so that the spacing between the turns is uniform."

"The formula from which the chart was constructed, assumes that the coil is in free space, a condition which is of course not realized in practice. The presence of another coil near the one under consideration, such as a tickler coil wound close to the tuning coil or an antenna coil closely coupled thereto, may result in an effective



Courtesy Q.S.T. Magazine

Fig. 422A—Rapid design chart for designing tube-base plug-in coils for short wave receivers.

value of inductance quite different from that which might be expected from calculation. However, if coupling between the coils is loose, or capacitive instead of inductive antenna coupling is used, the inductance of the coil will not be affected to any great extent. For many reasons a tickler coil of small diameter compared to that of the tuning coil is desirable, and it has been found that a jumble-wound coil of about ¼-inch diameter placed inside the tube base at the bottom is very satisfactory. This construction has the added advantage that the coil is easily removed for changing the number of turns if necessary, its field can be readily reversed without rewinding or changing connections, and fine adjustment of feedback may be had by bending it in relation to the tuning coil. Such a coil also has less effect on the constants of the tuning coil than one wound directly alongside it. Final adjustment of the inductance to exactly cover the bands desired is usually accomplished by adding or taking off a fraction of a turn of wire. The antenna winding usually consists of one or two turns of wire wound around the coil socket base."

559. Band-spreading coils: In cases such as mentioned above, the band-spread type of tuning coil is very useful. Instead of the entire winding of a coil being shunted by the tuning condenser, only a part of it is so shunted. The range of the coil is therefore accordingly reduced, and the tuning is opened up proportionately. In order to shift this particular desired band to the most suitable place on the dial, a trimmer condenser included in the coil is adjusted once and therefore requires no attention unless some further movement of the band is desired at a later date. In other words, the trimmer condenser permits the operator to select the particular portion of the band to be included within the tuning range.

One consideration involved in shunting a tuning condenser across only a part of a coil is that when the condenser is adjusted for minimum capacity, the coil is tuned close to its natural period. Unfortunately, the circuit resistance increases rapidly as

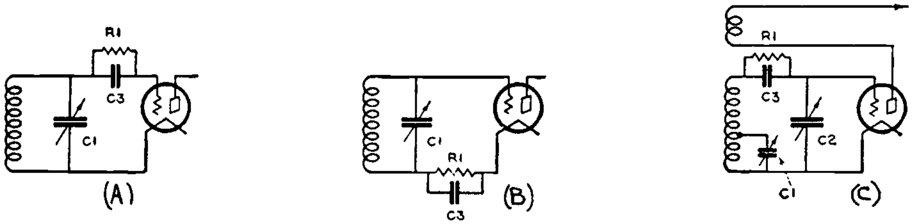
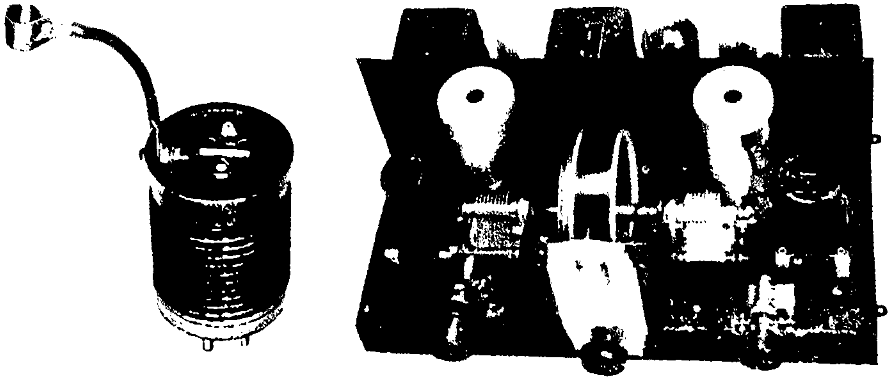


Fig. 423—Band-spread coil arrangement. (Left) The conventional detector circuit with grid-leak and condenser at the top of the coil between it and the grid of the tube. (Center) Here the grid-leak is located in the grid-return to filament line, providing the same results as at the left. (Right) The band-spread circuit showing the grid-leak and condenser in a new position.

the frequency approaches the natural period of the coil. But in the case of the band-spread coils the shunt capacity furnished by the trimmer condenser plus the capacity of the tube itself keeps the circuit well below the natural frequency of the coil.

Inside the band-spread type coil is a small grid leak and grid condenser as well as an adjustable low-capacity trimmer condenser. To understand the band-spread arrangement, let us refer to Fig. 423. At (A) is shown the conventional tuned circuit for a detector stage. Here, a coil is shunted by a variable tuning condenser, the top end of the coil connecting to the grid of the tube through a grid leak which is shunted



Oourtesy The National Co.

Fgi. 424—A band-spread type s.w. coil is shown at the left. Under the trimmer condenser shown at its center, are the grid-condenser and grid leak. At the right is a typical s.w. receiver with the band-spread coils in place.

by a grid condenser, while the lower end of the coil is brought directly to the filament. A variation of this circuit is shown at (B) where the grid leak and condenser are connected in the grid-filament return lead. (C) shows the band-spread arrangement. C_1 the regular variable tuning condenser of about .0001 mf. now shunts only a portion of the total inductance, while the grid leak R_1, and the condenser C_3, connect directly to the top of the coil. Finally, the trimmer condenser C_2 shunts this whole arrangement and is in parallel with the tube capacitance (about 3 mmfd). A typical plug-in coil of this type is shown at the left of Fig. 424. Notice the mica compression-type condenser inside the coil and the connection clip for the cap of the screen-grid tube. A typical short wave receiver in which these coils are used is shown at the right. This uses a stage of t-r-f amplification, regenerative detector and an audio amplifier. Single-dial control of the two tuning condensers is employed. This illustration gives a good idea of modern plug-in coil type short wave receivers arrangement and construction.

560. Simple regenerative receiver: The circuit diagram of a simple short wave receiver designed to use plug-in tuning and regeneration coils L_2 and L_1 is shown in Fig. 425. This employs 2-volt type tubes and

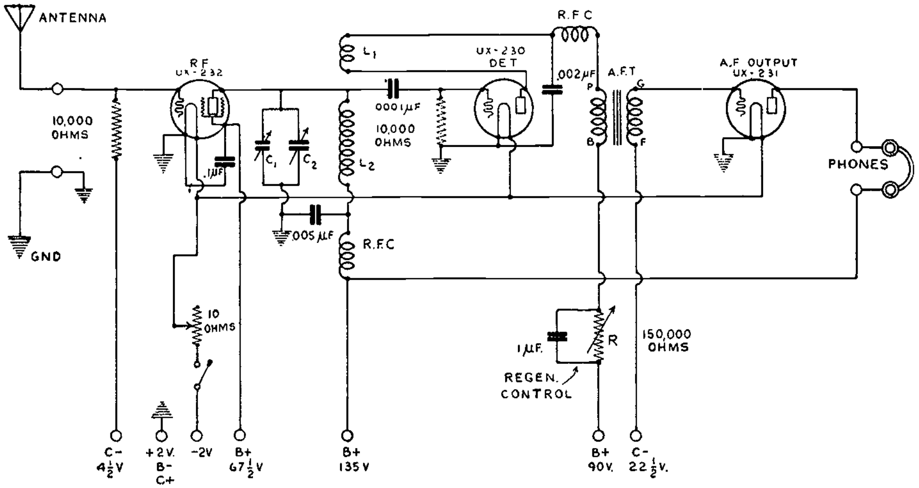


Fig. 425—A simple 3-tube regenerative s-w. receiver employing 2-volt type tubes and designed for home or portable use. Regeneration is controlled by resistor R in the detector plate circuit. For greater volume, an additional audio stage may be added. This receiver is designed for dry battery operation.

is designed for battery operation for either home or portable use. For home use, an additional stage of transformer-coupled a-f amplification may be employed.

The antenna-ground circuit is completed across the 10,000 ohm resistor. The r-f variations in the signal voltage appearing across this are applied to the grid circuit of the screen grid r-f amplifier tube and are amplified by it. The coupling between the r-f and detector tubes is of the tuned-plate type. Band-shifting condenser C_1 (and a midget condenser C_2 across it for vernier tuning) tune the plug-in coil L_2. The r-f choke and .005 mf. by-pass condenser are for filtering the r-f impulses from the plate supply unit. The .0001 mf. coupling condenser and grid leak resistor complete this part of the circuit. The tickler or regeneration coil L_1 is connected in the plate circuit of the detector. Since the .002 mfd. plate circuit condenser is connected outside of this, the rectified r-f varying plate current flows through L_1, and since it is inductively coupled to L_2 with the proper phase relation, some energy is continuously being fed back from the plate circuit to the grid circuit and is therefore re-amplified by the tube. This *regeneration* results in additional amplification and so increases the loudness of the signal. The detector is followed by a single stage of transformer-coupled a-f amplification, although an additional stage may be added to produce louder signals. The amount of regeneration obtained by coil L_1 may be varied very smoothly by means of resistor R which really controls the plate voltage and plate current, and therefore controls the amount of r-f current flowing through L_1, and therefore the feedback. Resistor R should be well constructed, since a poorly designed resistor here will cause rapid variations in the plate voltage and current which will be heard as "scratchy" noises in the earphones or loud speaker.

Simple short wave receivers of this general type are very effective, and capable of excellent reception under favorable receiving conditions. The use of regeneration in broadcast band receivers was common at one time, but fell into disrepute because in practice, it was usually pushed to the point where side-band frequency suppression or cutting resulted, and the tone quality was impaired. Regeneration has been used extensively in short wave receivers simply on account of the extra sensitivity gained by it, but as more sensitive circuits are perfected, the need for the regeneration will no longer exist, and it will probably not be used to such a great extent. There is no doubt but that regeneration is really helpful in short wave receiver operation however. It really serves two purposes; it makes the receiver more sensitive and makes it easier to find the stations, since by setting the receiver into oscillation, the various short wave transmitters can be located by the whistle produced when they are passed over. This is a great advantage where several stations may come in and out for a movement of one division of the tuning dial. Then the regeneration is backed down to stop the whistle, and the program is there. The objection to this, is that each regenerative receiver acts like a miniature transmitter when it is set into oscillation. In congested districts, this causes interference in the receivers of neighbors.

The grid leak size is important in short-wave sets. It is sometimes found that higher values of grid leak greatly control the ease with which the detector goes into oscillation, (see Arts. 331 and 333).

561. "Fringe howl:" A great many short wave receivers are troubled with a condition known as *fringe howl* or threshold oscillation, that is, when the regeneration is increased just under the point where the tube acts as an oscillator, the receiver breaks out into an audio howl. This condition is caused by radio-frequency disturbances which have found their way into the audio amplifier. It is not usually troublesome with one stage of amplification, but when two stages are used, the receiver becomes unmanageable.

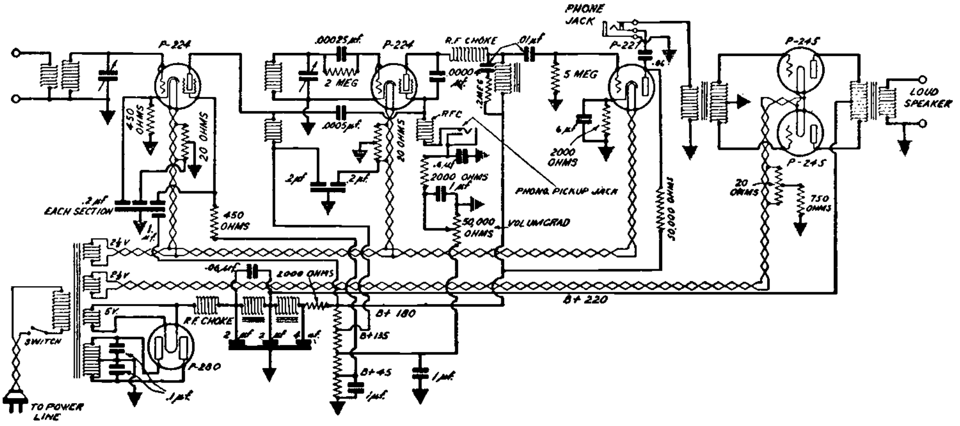
Increasing the amount of regeneration will stop it, and taking the tube completely out of oscillation will stop it, but since the most sensitive point by far is just under oscillation and since the noise is usually of an extremely annoying character, it is very desirable to remedy it if possible. One common, simple method of eliminating it is to shunt about a 100,000 ohm resistance, (commonly of the grid-leak type)—as high a resistance as possible—across the secondary of the first audio-frequency transformer If a 100,000-ohm grid leak is sufficient to stop the howls, it will be found that it does not cause any appreciable loss in amplification and the circuit seems to remain exactly as it was before the addition of the resistance, except that the "fringe howl" has stopped.

562. "Dead spots" in tuning: Many owners of short wave receivers are troubled by the fact that at certain dial settings so-called *dead spots* or narrow frequency bands exist, over which either the receiver cannot be made to regenerate at all by means of the regeneration control, or an unusually large increase in its setting is necessary. These dead spots are caused in a variety of ways, and they may also be eliminated if their cause and nature is thoroughly understood.

A "dead spot" on the tuning scale of a receiver means simply, that at the frequency corresponding to that dial setting, there exists a condition which causes the feedback to be reduced and the receiver does not oscillate properly. For the purpose of studying "dead spots", a regenerative receiver may be considered simply as an oscillator. Any oscillator can produce only limited power up to a certain point, beyond this the output drops rapidly, and finally the oscillator ceases to operate.

Any circuit tuned to resonance with an oscillator absorbs energy from it. If this absorption is too great for the power of the oscillator considered, the latter cannot operate properly. This is the reason for the "dead spots" on the dial of a short-wave receiver; there are tuned circuits which absorb power at those frequencies. One of the offending circuits, is usually the antenna circuit of the receiver. The antenna, with its coupling coil, is tuned by its total antenna-ground capacity, (see Fig. 179) to a definite frequency, determined by the values of inductance and capacity in the antenna circuit. If these values are such that the "natural frequency" is the same as that to which the regenerative receiver is tuned, the antenna circuit absorbs energy from the oscillating detector circuit, and the oscillator will "plop" out of oscillation, simply because it can no longer supply the total power required to keep it oscillating, plus that being absorbed from it by the tuned antenna circuit. Under this condition, no oscillations can be produced, ordinarily; or else a large increase in the setting of the regeneration control is necessary.

The regeneration-control, however, has a limited range, and cannot be increased



Courtesy Pilot Radio & Tube Corp.

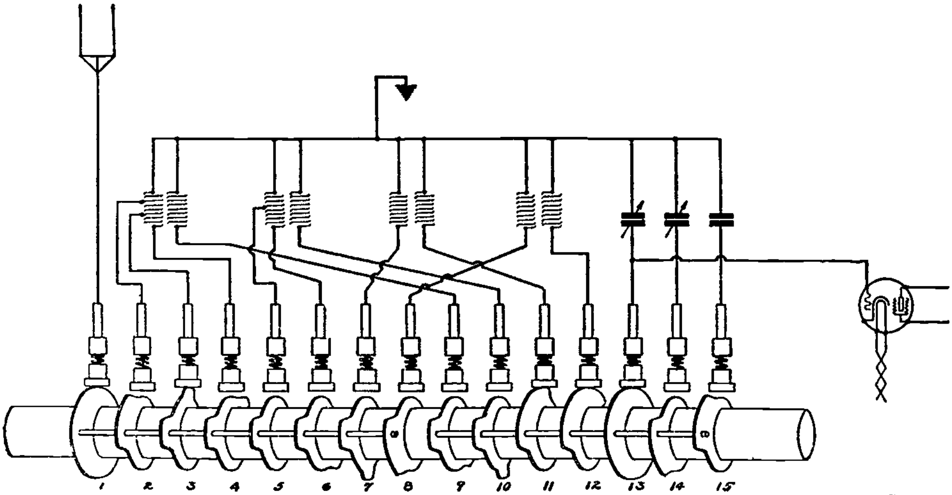
Fig. 426—This schematic circuit diagram of the Universal receiver described in Art. 563 is a functional diagram and does not show the actual connections to the cam switches. (See Figs. 427, 428 and 429.)

very far before its entire range has been covered; so that the receiver will no longer oscillate.

The antenna system causes dead-spots also at the *harmonics* of its natural frequency; but these are less pronounced and not so disagreeable, because the regeneration control setting need be increased only slightly for these. Dead spots may also be caused by resonance in the r-f choke used in the plate circuit of the detector itself, or by apparatus near the receiver. It is possible to obtain dead spots from choke coils or tuned circuits near the receiver; and it is not necessary for a circuit to be closed upon itself in order to produce a "tuned" circuit.

Assuming that all apparatus has been removed from the immediate vicinity of the receiver, let us consider various means for removing all dead spots from the dial. Since a dead spot is caused by resonance, it will, in general, be possible to eliminate such resonance by detuning the circuit causing the trouble. It is possible not to remove a dead spot entirely, but to shift it to some frequency which is not covered by the receiver dial. In the case of dead spots caused by the antenna circuit, a variable condenser of the 23 plate midget type (.00001 mf.) connected in series with the antenna circuit will usually permit of shifting the dead spot to another frequency each time. In sets employing plug-in coils, the dead spot may reappear when a different coil is plugged into the receiver; but, if the series condenser in the antenna circuit is variable, the dead spot can again be shifted outside the new tuning range. In the case of an r-f choke causing a dead spot, turns of wire may be added to or removed from the choke to shift its natural resonance frequency and the dead spot.

563. Waveband-switching systems: While the use of the plug-in type tuning coils in short wave receivers satisfactorily solves the waveband tuning problem from the electrical point of view, it is rather inconvenient to be constantly unplugging and plugging in different coils when operating such a receiver and "fishing" for stations on the various wavebands. It is convenient to employ a coil-switching arrangement by which the proper tuning coil and condenser combination for tuning over a certain band may be selected at will by the mere twist of a selector switch or knob. While lack of space does not permit of a complete detailed de-



Courtesy Pilot Radio & Tube Corp.

Fig. 427—Schematic diagram showing the switching arrangement for the four antenna coupling coils and tuning condensers. The metal cams make contact with the respective contact plungers when rotated to the proper positions.

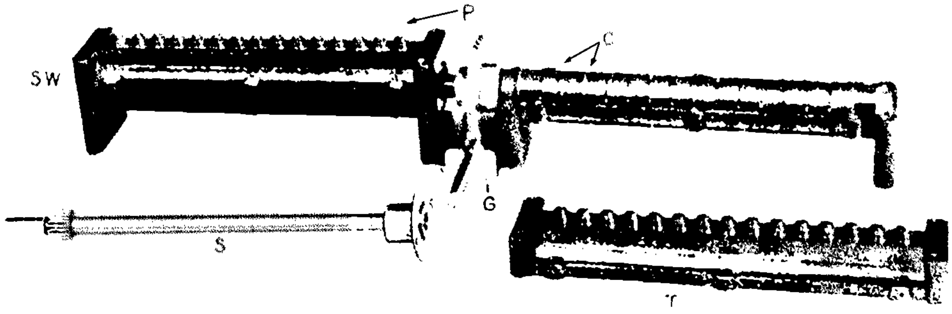
scription of such switching devices and systems, some idea of a commercial arrangement which has been developed for this purpose may be obtained from the accompanying illustrations of the Pilot "Universal" Super Wasp receiver. The circuit diagram of the entire receiver is shown in Fig. 426.

This receiver uses one stage of screen-grid t-r-f amplification, a regenerative screen-grid detector, one impedance-coupled audio stage using a '27 type tube, and a push-pull output stage using two '45s. Notice the r-f choke in the "B" power supply unit circuit, to prevent r-f disturbances originating in the '80 rectifier tube, from being transferred to the plate circuits of the receiver and causing noises in the output.

The tuning coils are fixed inside the set, and are thrown in and out of the circuit by means of a very ingenious pair of rotary cam switches encased in molded Bakelite housings, (shown in Figs. 427 and 428). This switch, which is controlled by a simple little knob on the front panel, has seven positions, and covers seven wavelength ranges as follows: (1) 15 to 23 meters; (2) 22 to 41; (3) 40 to 75; (4) 70 to 147; (5) 146 to 270; (6) 240 to 500; and (7) 470 to 650. This unusually wide wavelength range takes in not only all the short-wave channels, but also the entire broadcast band, and even the calling waves used by commercial ship and shore telegraph stations.

For the sake of simplicity, the four antenna couplers used, are represented as a single antenna coupler in the diagram. and the four detector coils are also represented as a single coil. Each of these coils has two windings. One end of each coil is brought to a contact on the cam switches, and they are automatically connected in the proper sequence as the switches are turned.

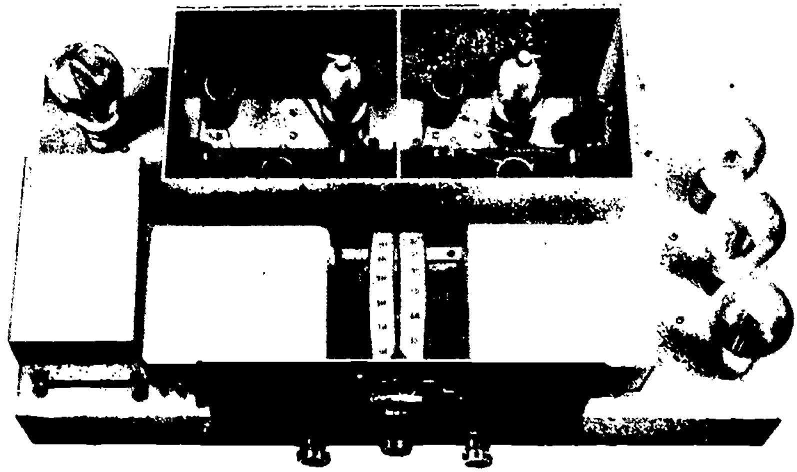
The antenna and detector tuning condensers, shown in the diagram, are actually double units; one section has a maximum capacity of 130 mmf. and the other 415 mmf. They have a common rotor connection but separate stators; the latter are also



Courtesy Pilot Radio & Tube Corp.

Fig. 428—Central switching arrangement. The switch for the antenna coupling circuit is at the left. The one at the right is for the detector circuit. (See Fig. 427.)

brought out to contacts on the cam switches, there being 15 contacts altogether on each stator, as shown in Figs. 427 and 428. At different positions of the wave-band switch, different combinations of tuning inductance and capacitance are obtained automatically by means of the cam switch, and tuning in that particular band is accomplished in the usual way by varying the setting of the variable tuning condensers.



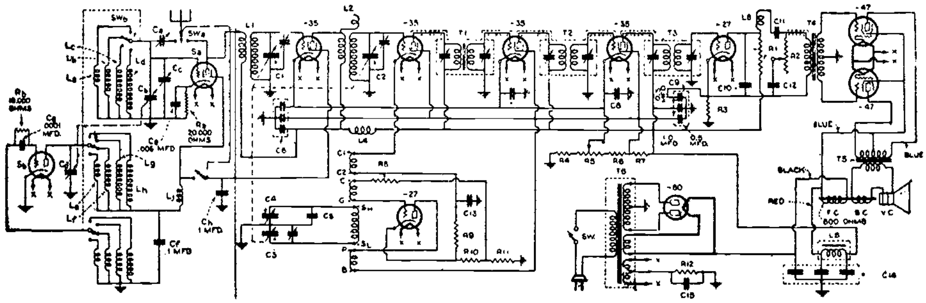
Courtesy Pilot Radio & Tube Corp.

Fig. 429—The complete short wave receiver whose circuit diagram is shown in Fig. 426. The various coils are shown in the two center shield boxes.

The shift from one waveband to another is made in an instant and it is not necessary to open the receiver cabinet or disturb anything.

Fig. 427 shows a schematic view of the connections of the tuning coils and condensers, and the cam and contact plungers of the half of the rotary waveband selector cam-switch used for the antenna-coupling circuit. As the shaft is turned, the metal cams 1-2-3-4 etc., which are insulated from each other, come around in proper order and make contact with the metal plungers above. The fixed condenser at the right is a .0004 mf. loading condenser used only to tune to the highest waveband, above 470 meters. The actual switching device is shown in Fig. 428. P is the contact plungers on the assembled switch for the antenna coupling coils. C shows the cams molded in Bakelite, for the detector coil switch. G is the worm gear drive. S is the drive shaft and T is the top piece for the detector switch. A top view of the complete receiver is shown in Fig. 429. The r-f and detector shielded compartments with the coils and tubes are at the rear center. The tuning dial and shielded tuning condensers are at the front center. The power supply unit is at the left. The wave-band selector knob is at the lower center.

The receiver circuit of Fig. 426 shows a novel regeneration system. The r-f current for the plates of both the r-f and detector tubes, and the screen grid current of the detector tube, is led back to the tickler winding through the .00004-mf. condenser between the screen grid and the plate, and C4 the .0005-mf. condenser at the lower junction of this circuit. The r-f choke coils in the plate and screen-grid leads prevent the r-f current from taking any other path. The control of regeneration is pro-



Courtesy Radio News Magazine

Fig. 430—Circuit of a typical short wave and broadcast band superheterodyne with a wavelength range of 10 to 550 meters (550 to 30,000 k.c.). The various wavelength ranges are selected by the selector "tap-switch" SW-6. No plug-in coils are employed.

vided by a 50,000-ohm potentiometer, regulating the screen-grid voltage. This arrangement provides very smooth regeneration, the control of which does not affect the tuning circuits. Thus it is possible to log station settings very definitely.

Other waveband switching systems in which specially designed multiple "tap switches" are used to perform the coil-switching operation, are in common use and are very satisfactory, (see Fig. 430).

564. Short wave superheterodyne: The use of the superheterodyne principle (see Chap. 22), in short wave receivers, presents the practical advantage of doing the amplifying of the weak signal voltages more efficiently at the comparatively low frequency existing in the i-f amplifier, than it can be done with an equal number of amplifier stages directly at the incoming carrier frequency. The general circuit arrangement of a short wave superheterodyne receiver is practically similar to that of an ordinary broadcast band receiver, as will be seen from the circuit diagram of the Silver Marshall 726 S.W. combination short wave and broadcast band superheterodyne receiver shown in Fig. 430. Compare this for general arrangement with the circuit of the somewhat similar type of receiver for broadcast-band reception only, which is shown in Fig. 283.

Since the conditions regarding image frequency, etc., are different in the case of short wave receivers than they are in broadcast band receivers it is common to use an intermediate frequency of around 650 kc in the receivers for short wave reception instead of the 175 kc commonly used in broadcast band receivers. For broadcast band reception, the requirements make it common to use 175 kc as the intermediate frequency. Therefore, if the receiver is to be used for both short wave and broadcast reception, both i-f's should be employed, (see Art. 386).

It is obviously not practical to build a superheterodyne receiver for both short and broadcast wavelengths with two different intermediate-frequency amplifiers, for the equipment cost would be very considerable. This problem has been nicely solved in this receiver by designing the main i-f frequency amplifier for 175 kc, this being preceded by the oscillator, first detector, and r-f tube for broadcast band reception. As soon, however, as the receiver is shifted over to operation in the range of 10 to 200 meters, a scheme popularly known as *double suping* is resorted to—the use of two intermediate frequencies with two oscillators, one fixed and one variable.

Specifically, the broadcast tuning dial is set to some clear channel in the neighborhood of 650 kc—it may actually be anywhere between 600 and 700 kc and this done, the broadcast band r-f amplifier tube and first detector together with their tuned circuits comprise the first level of intermediate-frequency amplification, which takes place obviously at the setting of the broadcast dial or at 650 kc, approximately. A short-wave first detector is then placed ahead of the r-f amplifier tube which has now become an i-f amplifier tube, and to this tube is coupled a short-wave oscillator which is arranged to track away from the short-wave first detector by approximately 650 kc in order to produce the first intermediate-frequency. At first glance, it may be a little difficult to grasp the exact operation of this arrangement, but a little consideration will undoubtedly make it clear.

The coils for the various wavebands are easily selected by means of the four-position switch SWB, controlled by a knob. This same switch selects one of four oscillator coils, in proper order to work with the four first-detector tuning coils.

565. Short wave converters: Without doubt, the superheterodyne system is the best known system for short wave reception, inasmuch as it is the only one which permits a high order of amplification to be obtained, due to the insurmountable difficulties encountered in building high-gain short wave r-f amplifiers. While it is of course desirable to employ a superheterodyne receiver designed especially for short wave reception, it is a fact that a large proportion of radio enthusiasts already own a broadcast band receiver which may represent a considerable investment. They do not care to purchase a separate receiver for short wave reception. Where a suitable broadcast band receiver is available, it may be converted into a short wave superheterodyne receiver by means of a "short wave converter".

One often hears the terms s.w. converter and s.w. adapter used interchangeably, while actually there is quite a difference between the two. The term "converter" should be applied only to devices which convert one frequency into another frequency. A converter may be used as the first detector of a superheterodyne arrangement. A *short-wave converter* is an electrical arrangement which converts the short wave signals into corresponding long wave signals so that the short wave programs can be received on an ordinary broadcast receiver. The r-f amplifier in the broadcast receiver itself functions as the intermediate-frequency amplifier of the superheterodyne. It is usually necessary that this intermediate-frequency amplifier should give considerable amplification for good loudspeaker reception. Usually, this requires that it shall consist of radio-frequency stages employing screen-grid tubes. Short wave "adapters" will be considered later.

The *short wave converter* is really a frequency changer. It consists usually of a first detector, tunable local oscillator, and self-contained power supply unit, although in some cases it may also have a stage of t-r-f amplification ahead. The converter is connected to the antenna and ground terminals of the broadcast-band receiver. The oscillator output heterodynes with different incoming short-wave signals, resulting in a beat-note or "difference frequency" in the intermediate amplifier, which in this case consists of the tuned r-f stages of the broadcast receiver set at some fixed tuning frequency. Some converters used the filament and "B" voltages from the broadcast receiver, others use separate batteries, and still others have their own socket power supply unit. A circuit of an a-c tube electrically operated short wave converter with its own power supply unit is shown at (A) of Fig. 431.

The '27 type tube acts as the oscillator, due to the magnetic coupling between plate and grid coils L_2. The grid circuit of the oscillator is tuned by condenser C_2.

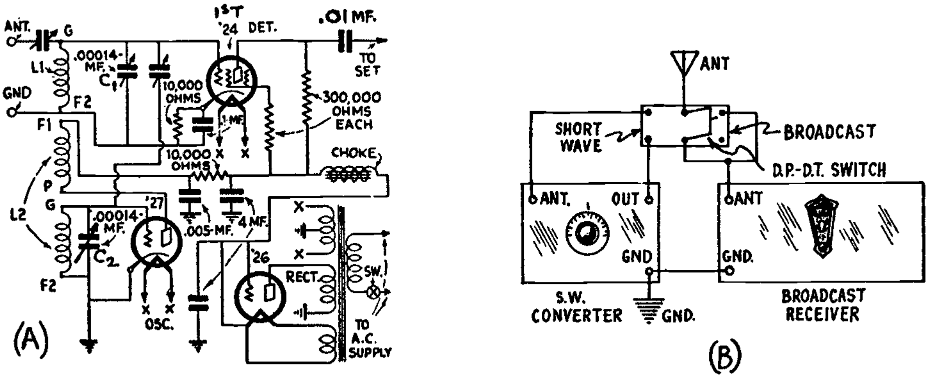


Fig. 431—Left: Circuit of an a-c tube electrically-operated short-wave converter with its own power supply unit.
Right: Connection of a s.w. converter to an ordinary broadcast band receiver.

Two trimmer-type condensers are used, one an antenna coupling condenser for the first detector and the other an oscillator coupling condenser—both of these require a screw driver for adjustment. C_1 tunes the first detector input circuit in combination with the tuning coil L_1, which may be of the tube-base type (see Fig. 422A). The plate circuit of the detector feeds into the "ANT." terminal of the broadcast-band receiver as shown at the right of Fig. 431. The power supply unit consists of a small power transformer furnishing filament current for all the tubes, and high voltage a-c for "B" supply which is rectified by a single '26 type tube, and filtered by a single choke and two 4 mf. dry electrolytic condensers. The '26 type three electrode tube is connected as shown, since the power supply unit is called upon to deliver only a small current, and the use of a tube of this kind which is amply large and rugged, makes the use of a smaller power transformer possible.

When the converter is placed beside any standard broadcast receiver, by simply connecting the antenna to the converter, one lead from the converter to the antenna post of the receiver and one lead from the ground terminal of the receiver to the ground terminal of the converter (already grounded), as shown at (B) of Fig. 431, and the power plug is inserted in the socket, the full conversion of the broadcast receiver to a short wave superheterodyne has been accomplished. To eliminate the converter, it is only necessary to shift the antenna lead back to the broadcast receiver again, leaving the ground connection between the broadcast receiver and converter permanently made, if desired. This may be accomplished by the simple switching arrangement shown. These connecting wires should be kept very short to prevent them from acting as antennas and picking up signals direct from broadcast-band stations. In many cases, the antenna lead from converter to set need not be disconnected, although it is desirable to do so. When this connection is made, the r-f amplifier of the broadcast receiver tuned to some clear channel in the neighborhood of 1,000 kc, serves as the i-f amplifier for the superheterodyne, the broadcast receiver detector functioning as the second detector, and the audio channel operating in the conventional manner. In this manner, the full amplification of the broadcast receiver is utilized at short waves. The tuning of the broadcast receiver is left fixed and is not varied at all when receiving short wave programs. It is only varied when broadcast-band stations are to be received.

Unless a coil-switching arrangement is used (see Art. 563), two short-wave plug-in coils are required for each frequency band to be covered, one for the oscillator and one for the first detector. For the whole short wave band of 17 to 200 meters, a total of eight coils, or four sets, are usually required. A converter may also be used successfully in connection with a number of present-day superheterodynes, resulting in a "double super" because the frequency is shifted twice, and three detectors are employed. This combination, is capable of very satisfactory results.

566. Short wave adapters: Short wave signals may also be received with an ordinary broadcast-band receiver by using a short wave adap-

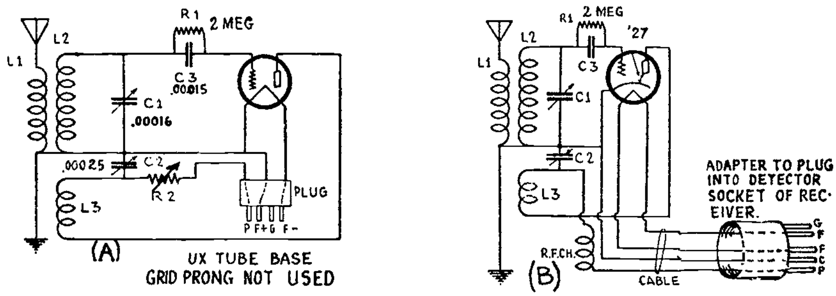


Fig. 432—(A) A short wave adapter circuit designed for use with a battery-operated broadcast band receiver.
(B) A short-wave adapter for use with an a-c electric broadcast band receiver.

ter ahead. A *short wave adapter* usually is simply a short wave detector, and its tuning circuit is designed to tune to the short wave signals. No change in frequency takes place in an adapter. By means of a socket plug which is connected to the adapter, connection is made from it to the audio channel of the broadcast receiver by first removing the detector tube from the socket in the broadcast receiver, and then plugging in its place this special socket plug. In this way, the r-f amplifier and detector circuit of the broadcast receiver are cut out, and in its place is used merely the short wave detector unit which comprises the adapter. What we have then, is a simple short-wave detector circuit followed by the one or two stages of audio-frequency amplification in the broadcast receiver. In some of the older types of broadcast receivers, the radio-frequency amplification is so low that one may just as well use a s.w. adapter instead of a s.w. converter, obtaining almost equal results. If properly adjusted, an adapter gives fairly satisfactory short wave reception, and it has the advantage of having a considerably lower first cost.

Since the s.w adapter is simply a short wave detector, it is very simple to construct . A simple s.w. adapter for use with a battery-operated receiver is shown at (A) of Fig. 432. This is simply a regenerative detector employing proper short-wave plug-in tuning coils L_1, L_2, and tuning condenser C_1. The coils may be of the tube-base plug-in type designed from Fig. 422A if desired. Regeneration is obtained by tickler coil L_3 and controlled by C_2. The terminals go to a four-prong plug, which may be the base of an old vacuum tube. To use the adapter, the antenna and ground are connected to it, the detector tube in the broadcast band receiver is removed from its socket, and the 4-prong plug from the adapter is inserted in this socket instead. In this way the filament voltage from the receiver is led to the filament of the adapter tube, and the plate circuit of the adapter is completed through the plate circuit of the first audio coupling unit in the receiver. The signal output from the adapter is thereby fed to the audio amplifier and is reproduced by the loud speaker. The r-f tuner unit of the broadcast receiver is not used at all when receiving short wave signals. It is usually helpful to include variable resistor R_2 in the adaptor plate circuit to enable adjustment of the plate voltage for best regeneration control. The tube used in the adapter is usually of the same type as that used in the detector socket of the broadcast receiver. To prevent fringe howl, it may be necessary to connect a 0.1 megohm resistor across the secondary of the first a-f transformer in the receiver.

Short wave adapters used with a-c electric broadcast receivers do not always give satisfactory results, because most of these receivers use plate rectification in which plate voltages as high as 180 volts may be applied to the detector. When the adapter plug is inserted, the same plate voltage is being applied to the tube in the adapter. Also, in many a-c electric receivers, which use resistance-coupling between the detector and first a-f tube, the actual effective voltage on the plate of the detector is very low. This causes inefficient operation of the adapter detector. Since the tendency in modern receiver designs is to do most of the amplifying in the r-f amplifier and use only one audio stage, short wave adapters used with these receivers do not usually operate satisfactorily, merely because there is not enough audio amplification provided. These points are important, for in many cases, poor reception is blamed on an adapter when in reality it is due to improper operation of the receiver.

A circuit diagram for a s.w. adapter for use with an a-c electric receiver is shown at (B) of Fig. 432, but the above statements should be kept in mind regarding the undesirable operating conditions which may be forced upon such devices. It is generally more satisfactory to use a short wave *converter* with a-c electric operated receivers, unless the receiver is of such design that proper voltages are provided for an adapter. If it is desired to increase the sensitivity of a s.w. adapter, a stage of screen-grid r-f amplification can be added to it. This will give a general r-f and detector arrangement somewhat similar to those in Figs. 425 and 426.

567. Operating the short wave receiver: The knack of correctly operating short wave receivers is usually learned only after considerable experience in tuning a particular set.

Possibly the greatest trouble is caused by the fact that the novice manipulates the tuning controls much too rapidly. Due to the fact that several stations may often be tuned in and out with a movement of a division or two of the tuner dial, it should be turned *very slowly* when tuning for stations, or they will be passed right by without being heard. Short wave receivers of the regenerative type should oscillate smoothly over the entire range of the tuning condenser, with each coil. If the set is correctly designed and the batteries (or socket power device) and tubes are in good condition, the fact that usually determines whether or not the set will oscillate, is the antenna series condenser. If the antenna is too long the set will not oscillate. Instead of cutting the aerial length, a midget condenser with a capacity range of from about 0.00001 to 0.00005 mfd. may be connected in series with the aerial. Different settings of this condenser should be tried at the various wavelengths, until the set oscillates smoothly. Antennas from 30 to 60 feet in total length, (including lead-in and ground wires), are usually suitable for short wave reception. It is important that all connections be well made and soldered. The ground connection should be made to a cold water pipe or to a separate pipe or plate buried in moist earth. The importance of good ground connections cannot be overstressed, as they are often responsible in a large measure for the good or poor results obtained with an otherwise good receiver system.

Short wave receivers of the *non-regenerative* type are tuned in exactly the same way as ordinary broadcast receivers are, only the tuning dials should be rotated more slowly. There are two methods of tuning either short wave or broadcast receivers of the regenerative type.

In tuning for short wave signals, set all controls such as the antenna series condenser, volume control, etc., at the point where loudest signals are heard on local stations. Then, throw the detector into oscillation by advancing the regeneration or volume knob *very slowly* until you hear a soft rushing sound. As you continue to turn, the noise will build up quickly in intensity and then drop off in an abrupt click. The condition of the set during the first rushing period is known as "regeneration," and in it the set is extremely sensitive. The condition just beyond regeneration is "oscillation". If you keep the set in oscillation, and turn the tuning dials slowly, you will hear a whistle when you run into a broadcasting station. With this whistle may be mixed the voice or music. The whistle or "beat note" is produced by the heterodyning of the incoming signals with the oscillations of slightly different frequency generated by the oscillating detector. To clear up the signal, simply turn back the volume knob until the set crosses the border line and slides back into regeneration.

If the incoming signal is fairly strong, the program will come through free of the whistle. However, if it is weak, the whistle will dominate the voice, as this whistle is caused by the beating or "heterodyning" of the carrier wave of the station and the oscillations generated in the detector circuit. In this case, the "zero beating" tuning method should be tried. This is always the best for weak signals, although it requires some experience in tuning.

To *"zero-beat"* an incoming signal, throw the receiver into oscillation by advancing the regeneration control, and then tune it very carefully so that the frequency of the oscillations set up by the detector are *exactly* of the same frequency as that of the incoming signals to be received. When this exact point is reached, no whistling is heard, since there is no difference in frequency, and the beat whistle disappears. The signals are likely to be somewhat distorted, but this is not usually very objectionable.

You can tell when you have zero-beated a station, by turning the tuning condenser a hair's breadth above and below the point at which the signals are understandable and clear of whistling. You will hear a whistle each time, as each time you move the condenser you change the frequency of the local receiver circuit and therefore cause a beat note to be set up which is heard as a whistle. Zero beating is an excellent means of fishing out very weak signals, because the receiver is in a very highly sensitive condition when it is oscillating. Many weak and distant stations that you cannot hear at all with the set thrown just out of oscillation you at least will be able to identify if you zero-beat them.

When attempting distant or foreign reception, the time differences between the locality of the receiver and that from which the signals originate must be taken into consideration. This will now be considered.

568. Time differences: In attempting long-distance short wave reception it is important to consider the differences in time which exist at various places on the earth's surface. For instance, it would be rather foolish for a man in New York City to listen at 8 P. M. New York time for a station in London, England which is scheduled to sign off at 12 P. M. London time. The reason for this is, that when it is 8 P. M. in New York, it is 1 A. M. the following morning in London. Therefore that particular London Station had signed off one hour before.

Greenwich Mean Time is the system of time in which noon occurs at the moment of passage of the mean sun over the meridian of Greenwich, England. Standard time is the time of a certain meridian adopted for local use over a large region in lieu of true local time. The meridian of Greenwich, England, was taken as a prime meridian, and there are twenty-four standard meridians differing from it by 15 degrees of longitude east and west. These meridians were established in order that the standard times of all countries would agree with Greenwich in minutes and seconds but differ in hours by whole numbers. Clocks at any place within 7 degrees and 30 seconds east or west of a standard meridian are set to agree with the time of that meridian. They may therefore differ by as much as a half hour from local mean time. In the United States, the standard times are: *eastern*, 75 degrees west or five hours slower than Greenwich mean time; *central*, 90 degrees west or six hours slower than Greenwich; *mountain*, 105 degrees west or seven hours slower than Greenwich; and *Pacific*, 120 degrees or eight hours slower than Greenwich.

A chart of time differences showing the time existing at various important cities when it is 6 P. M. Eastern Standard Time in New York City is given herewith. At the right is a column giving the number of hours which the time in any city is ahead or behind that in New York City.

TIME CHART

City	Eastern Standard Time	Numbers of hours ahead of New York City
New York City	6:00 P. M.	
Chicago	5:00 P. M.	— 1 hour (behind)
Denver	4:00 P. M.	— 2 hours (behind)
San Francisco	3:00 P. M.	— 3 hours (behind)
London	11:00 P. M.	+ 5 hours
Paris	11:00 P. M.	+ 5 hours
Madrid	11:00 P. M.	+ 5 hours
Rome	Midnight following day	+ 6 hours
Petrograd	1:00 A. M.	+ 7 hours
Buenos Aires	7:00 P. M.	+ 1 hour
Bombay, India	4:00 A. M.	+10 hours
Calcutta, India	5:00 A. M.	+11 hours
Melbourne, Australia	8:30 A. M.	+14.5 hours
Sydney, Australia	9:00 A. M.	+15 hours

Thus when it is 7:00 P. M. Eastern Standard Time in New York City, it is midnight in London. (This would be 8:00 P. M. Eastern Daylight Saving Time.) A very useful time conversion chart may be obtained by sending 10 cents in American coin, to the Superintendent of Documents, Government Printing Office, Washington, D. C., for a copy of Miscellaneous Publication No. 84, entitled "Standard Time Conversion Chart."

569. Skipping and fading of short wave radiations: One of the peculiar properties of short wave, (high frequency) transmission is that the radiations may skip over certain localities and be received perfectly at points further away from the transmitter. This is known as *skipping*. Also the signals may fade in and out while being received. This is known as *fading*. The explanations of the actions which have thus far been advanced are in the form of theories. The Kenelly-Heaviside layer theory, named after its originators, is the one most commonly accepted and which seems to agree best with observed, measurable phenomena. An explanation of these actions and the basis of this theory follows:

A transmitting antenna sends out electromagnetic radiations, which, if they are not reflected or refracted, radiate out in straight lines as shown at (A) of Fig. 433. Though they are all part of the same radiations, we speak of those rays which are directed and travel near and along the earth's surface, as the *ground rays*. Those which are directed and travel upward, are the *sky rays.* The ground rays, following the earth's surface go through hills, forests, towns steel frameworks of buildings, etc., and are slowed down by the resistance of the path and greatly weakened, (especially at the higher frequencies) so that ordinarily the ground rays are practically non-existant at distances further than 500 miles or so, depending on the frequency. It is evident that if the ground rays alone were received by the antennas of receiving stations, long distance reception would not be possible, because of the curvature of the earth, and the rapid decrease in strength of the rays.

The sky rays do not travel in straight lines indefinitely, for if they did, they would never return to the earth, and would not affect our receiving antennas. According to the *Heaviside layer theory,* there exists all around the earth's surface, at

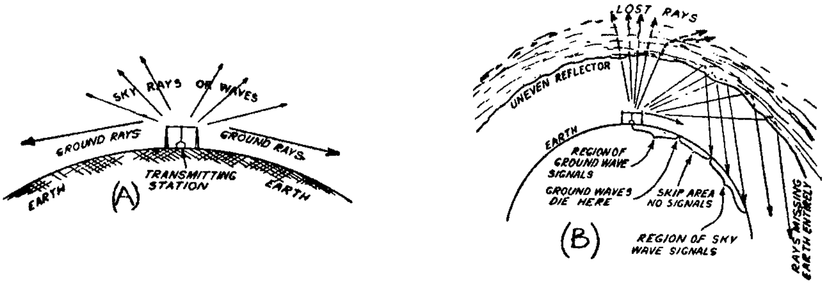


Fig. 433—(A) How the radio rays from a transmitting antenna consist of those which radiate out along the earth's surface (ground rays), and those radiated up toward the sky (sky rays).

(B) The sky rays are reflected by the heaviside layer and return to the earth. They pass over, or "skip," certain places on the earth's surface entirely. Of course, the signals cannot be received or heard at these "skip-areas."

varying height of a hundred or so miles from it, an enveloping layer of ionized gas containing "free electrons." These are produced by ionization of the atoms of the gases of which the atmosphere is composed. The ionization may be caused by the action of the ultra-violet light from the sun, or from electrons shot off by the sun directly. At any rate, this layer is thought to be present around the earth. When the sky rays reach it, they are reflected from it as shown at (B), somewhat as light rays are reflected by a mirror—only the surface of the Heaviside layer is not smooth like a mirror but curved and possibly bumpy.

The action of *skipping* may now be understood. As seen from (B), the receiver may be located so far from the transmitter that it does not receive the ground rays with sufficient strength to be noticed. If the reflected sky rays return to the earth *beyond* the receiving antenna, no signal will be received, since these rays have skipped right over the locality in which the antenna is erected. So great is this Heaviside effect on rays such as are radiated in the 20 to 40 meter band, that the radiations skip nearby sections altogether and are received strongly at distances of 500 to 1,000 miles or more away. Hence the reflecting action which causes skipping, is also responsible for the long distance transmission possible with short wave signals, since it may return the sky rays back to the earth's surface at long distances from the transmitter. In the daytime, the strong ultra-violet rays from the sun penetrate deeper down into the atmosphere, and therefore the Heaviside layer is closer to the earth. On this account the waves are reflected almost straight down again. Hence, we are not able to accomplish much long-distance radio reception in the daytime.

At night however, the ultra-violet rays are very weak and the positive and negative ions of the air come together again. The Heaviside layer is therefore much higher above the earth. This means that the waves are reflected at a less acute angle so that they are able to spread farther out and cover a larger section of the earth. Accordingly, we are able to receive much farther at night than in the daytime.

In locations where the ground rays of a station are received together with the reflected sky rays, *fading* may be caused. In this case the signal voltage induced in the antenna at any instant is the combination of that induced by the ground rays and that induced by the sky rays, at that instant. Remembering that these rays have come by different routes and distances, it is easy to see that they may not be in phase when they arrive at the receiving antenna. If they are in phase, they add, and the signal is strong; if they are out of phase they oppose each other, and the signal may be greatly weakened, depending on how much out of phase they are. Since the under surface of the Heaviside layer is bumpy, and is continually changing its contour, the angle of reflection of the rays changes, and they may travel longer or shorter distances before reaching the receiving antenna. Hence their phase relation with the ground rays is not constant, and consequently the amount of opposing or reinforcing taking place between the two, changes, and causes periodic strengthening and weakening of the signals, (*fading*). A station may be received strongly for a few minutes, then some change will take place in either the height or the contour of the under surface of the Heaviside layer, this changing the angle of reflection of the sky rays and therefore the distance they travel before reaching the receiving antenna. This changes the phase relation of the ground and sky rays effective at the receiving antenna. The loudness of the received signal also changes correspondingly.

Now the amount of absorption of the ground and sky rays, and the angle of reflection of the sky rays depends on their frequency. Also the angle of reflection of the sky rays, depends on their frequency. Also the earth's surface (seasonal conditions, time of day, etc.), and the condition of unevenness of its surface. Hence the fading and skipping actions are very variable, and cannot be predicted with certainty.

However, enough is known about the behavior of short wave radiations so that in practice, short wave transmitting is carried out on the particular frequencies which are most suitable for the requirements of skip and range, depending on the time of day and the distance to be transmitted. In general, for distant station reception on frequencies from 14 to 20 meters, all tuning should be done from daybreak till 3 P. M. local time. From 20 to 33 meters, stations to the east of the listener will be heard best from about 11 A. M. till 10 P. M. Stations to the west of the listener in this band should be heard best from midnight till about two hours after daybreak, when they will fade out. From 33 to 70 meters, distant stations can be heard only after darkness falls. Very little in the way of distance can be heard above 70 meters, although the ships, police, fire, coast guard and aircraft stations are all heard above that wavelength. Although these general instructions are helpful, it should be remembered that since so many varable conditions may affect the sky rays, short waves are notorious for their disobedience of the few laws that have been laid down for them. You are likely to hear stations on certain wavelengths at certain times when you should not hear them at all; also, you may "fish" for a week for stations that you heard strongly during all of the previous week, and not find a sign of them.

570. Micro, or quasi-optical rays: Ultra-short wave radio transmission by means of radiations of such high frequency that the wavelength (distance the disturbance travels during the time it takes to complete 1 cycle) is only in the neighborhood of 18 centimeters (about 7 inches) has been accomplished. These rays or radiations are called *micro*, or *quasi-optical rays,* because their wavelength is so short and they possess many of the characteristics of light rays, in that they may be reflected by ordinary reflectors such as are used for reflecting light rays, etc., (see Fig. 434).

The oscillator tube used to generate the exceedingly high frequency oscillations necessary for this type of communication system is of special interest. The tube, known as the Barkhausen-Kurz (B-K) type or *micro-radion* tube, is one in which the physical dimensions, rather than the electrical constants of the circuit attached, controls the frequency. In this tube, the filament is a straight wire, surrounded by a circular spiral coiled-grid, and outside of this, a curved cylindrical plate. The grid is maintained positive and the plate is negative. Electrons emitted by the cathode are attracted to the grid, many of them pass through it and come within the field of the plate. Since this is negative the electrons are repelled and again come to the grid field. Thus, one oscillation takes place in the time required for an electron to make this trip, which is a very short time. Therefore, the wavelength is a function only of the size and mutual position of the electrodes within the tube, and the voltages thereon, the tube is designed in such a way that all parts which act as coupling devices are exact ratios (in size and spacing) of the desired wavelength. A shield about one inch square protects the radiating parts of the tube from the field of the antenna.

The antenna system for this ultra-short wave transmission system is very simple. In the transmission of 18 cm. rays across the English Channel from Saint Margaret's (Dover) and Calais, two double reflectors were used at each end of the system, one for transmission and one for receiving from the other side.

Fig. 434 shows the essential features of the system: The outgoing signals are applied to one of these special oscillator tubes, in which the high-frequency oscilla-

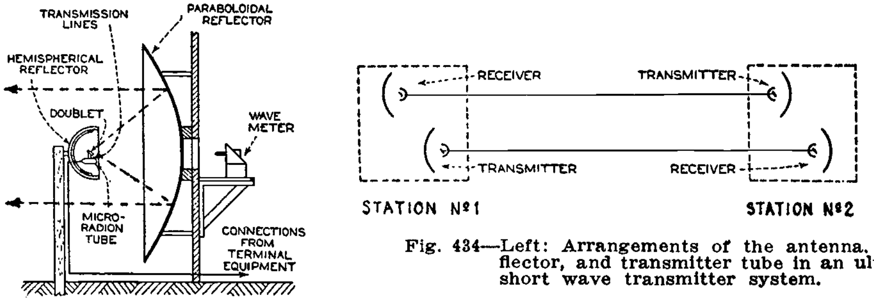


Fig. 434—Left: Arrangements of the antenna, reflector, and transmitter tube in an ultra-short wave transmitter system.

Right: How two radio beams can be transmitted side by side for 2-way simultaneous communication. Interference between them is prevented by the narrowness of the beam, and the placement of the receiving reflector behind the transmitting reflector.

tions are generated. The tube is connected to the radiating system or doublet (see Art. 231), which is about 2 cm. long, in contrast to the larger antenna systems usually employed. The amplitude of this high-frequency current along the doublet at any instant is substantially the same. The doublet is situated at the focus of a paraboloidal reflector some three meters in diameter. After concentration of the rays by the paraboloidal reflector into a fine pencil of rays, somewhat similar to light rays sent out by a searchlight, they are projected into space. In the reflector, the relation between the focal length and the diameter is so proportioned, as to insure maximum efficiency for the diameter used.

In order further to increase the efficiency of the system by the prevention of radiation other than in the required direction, a hemispherical reflector is located at the opposite side of the doublet to the paraboloidal reflector and having the doublet at its center. This serves to collect all the radiations propagated in a forward direction, and to reflect them back again towards the source. The radius of the hemispherical reflector is so chosen that when the reflected radiations reach the focus again they are in phase with those being radiated at that instant. It is estimated that the gain due to the paraboloidal reflectors on one channel is of the order of 46 decibels, to which the hemispherical reflectors add another 6 decibels.

The receiver is a counterpart of the transmitter, except that no high-frequency measuring device is provided. That is to say, it comprises a doublet connected by a line to a tube similar in construction to the oscillator tube just described, where detection takes place. Paraboloidal and spherical mirrors exactly similar to those of the transmitter, are also provided for concentrating the received rays upon this doublet. The simplicity of the system is apparent.

Since the radiations proceed in direct straight lines, they may be aimed directly toward the receiving station in a narrow beam, much as a searchlight is aimed. Since the energy is all directed toward the receiving station in a beam and not scattered or "broadcast" as in the usual transmission system, a given distance can be covered with much less power supplied to the transmitter. It is probable that this system will find commercial application for radio beacons and navigation purposes, for secret communication etc. Since the frequency band available in the quasi-optical ray band between only 10 and 100 centimeters is about nine times as great as in the whole ordinary radio broadcast band from 200 to 600 meters, it is evident that this full band will permit the working of a very large number of transmission channels between nearby places without mutual interference or signals. Further developments are rapidly being carried on in this very interesting field of work. Quasi-optical rays are of course interrupted by any natural obstacles in their path, but, in free space they have great possibilities. Since they are directed in straight lines, they can be transmitted and received only between stations located rather closely together, due to the curvature of the earth's surface. It is possible however, to transmit messages over long distances by relaying them through a number of stations located the proper distances apart.

REVIEW QUESTIONS

1. What is generally meant by the term "short waves"?
2. What are the advantages of short wave transmission and reception? Disadvantages?
3. What is meant by "skipping" of short wave signals? Explain the reason for this action.
4. What is meant by "fading" of short wave signals? Explain its cause.
5. Explain the relation between wavelength and frequency. What is the frequency of an 18 centimeter quasi-optical radiation? (100 centimeters = 1 meter).
6. What is a waveband? What is meant by the expression that "a receiver can tune to a waveband from 10 to 200 meters"?
7. Explain why either plug-in coils or a waveband-switching arrangement must be employed in short wave receivers to cover the tuning range from 10 to 200 meters, whereas in broadcast band receivers, a single coil and condenser in each tuned circuit will cover the tuning range from 200 to 600 meters easily.
8. Why is a tuning condenser of small maximum capacity (about .00016 mf.) usually employed in each tuned circuit of a short wave receiver? Why not use a .00035 mf. condenser as we do in broadcast-band receivers, and use coils of smaller inductance?
9. Draw a circuit diagram of a battery-operated s.w. receiver having a regenerative detector and two transformer-coupled stages of a-f amplification. Plug-in coils are to be used. Explain the operation of each part of the receiver in detail.
10. Explain one method of spreading the tuning in a certain small band, over the complete 100 divisions of the tuning dial.

11. What are "dead spots" in tuning? Explain their cause in the tuning of a s.w. receiver. How would you proceed to eliminate a dead spot occurring in the tuning of a certain receiver?
12. What is the advantage of using a waveband-switching system in a s.w. receiver, instead of using plug-in coils? Has it any disadvantages?
13. Draw a circuit diagram for a superheterodyne short wave receiver and explain the action of each main part.
14. A s.w. superheterodyne is to operate with an i-f of 650 kc. What must be the frequency range of its oscillator, if signals from 20 to 200 meters are to be received?
15. What is the difference between a s.w. converter and a s.w. adapter? What are the advantages of each?
16. Draw the circuit diagram for a single tube s.w. adapter and explain its operation in detail.
17. Draw the circuit diagram for a single-dial a-c operated s.w. converter and explain its operation.
18. Describe the "zero-beat" method of tuning a regenerative receiver. Why is it called "zero-beat"? What are its advantages?
19. Explain briefly what precautions must be observed in operating a s.w. receiver as regards, (a) method of tuning in stations; (b) regeneration control, if any is used; (c) time to listen; (d) bands to listen in on at certain times of the day, etc.
20. Why are short wave receivers usually more difficult to tune than broadcast band receivers are?
21. A transmitting station in Madrid is on the air between the hours of 5 to 8 P. M., Madrid time. During what hours, Eastern Standard Time, should the owner of a s.w. receiver in New York City listen in for this transmission?
22. What are quasi-optical radiations? Why are they given this name?
23. Describe a simple beam transmitting system using quasi-optical radiations. What is the purpose of the reflectors?
24. What are the advantages of transmission in the quasi-optical frequency range?
25. What are the advantages of beam radio transmission? State two disadvantages which are important if it is to be used for radio broadcasting. How may one of these disadvantages be effectively eliminated?

CHAPTER 32

VACUUM TUBE APPLICATIONS AND PHOTOELECTRIC CELLS

HIGH VACUUM TUBES — CIRCUITS FOR MEASURING, OR WEIGHING — THE THYRATRON TUBE — THE PHOTOELECTRIC CELL — PHOTOELECTRIC CELL CONSTRUCTION — NEED FOR AN AMPLIFIER — PHOTOELECTRIC CELL AMPLIFIER CIRCUITS FOR RAPID LIGHT VARIATIONS — PHOTOELECTRIC AMPLIFIER CIRCUITS FOR INTERMITTENT RELAY OPERATION — LIGHT SOURCES FOR PHOTOELECTRIC DEVICES — SOME COMMERCIAL PHOTOELECTRIC CELL CONTROL SYSTEMS — PHOTO-VOLTAIC CELLS — RADIOVISOR BRIDGE LIGHT-SENSITIVE CELL REVIEW QUESTIONS.

571. High-vacuum tubes: While the use of 3, 4 and 5-electrode high-vacuum tubes operating on the thermionic principle is common in ordinary radio work, both these and other special forms of vacuum tubes are employed in a variety of non-radio uses. While lack of space does not permit description of all of these, a few of the more common ones will be described. New uses are being found for these tubes in industry almost every day. Vacuum tubes may be classified according to, (a) the number of electrodes; (b) the content of the bulb, which may be high vacuum, gas, or vapor; (c) nature of the fundamental electrode, the cathode, which may be thermionic, photoelectric, mercury-pool, or cold.

The ordinary forms of high-vacuum tubes which we have studied have very desirable characteristics for radio work, but they have certain serious limitations. Probably the most important of these, is the high power loss within the tube. Part of this loss is represented by the power required to heat the cathode to the point where electron emission takes place; this ranges from about 10 to 150 watts per ampere of plate current passed through the tube. Another limitation arises from the fact that since the path from the cathode to the plate has a very high resistance, from several hundred to about one thousand volts-per-ampere is required to force the current across this space within the tube.

From these facts it will be seen that plate currents of more than a few amperes cannot be handled economically by means of this type of tube. Therefore, it is apparent that in the industrial field the most promising applications of the high-vacuum tube are in various control operations where the useful factor is the unique characteristics of the tube, (such as amplifying or rectifying properties, etc.), rather than its output.

572. Circuits for measuring, or weighing: Ordinary forms of vacuum tubes are used extensively in industry for precision measurement of thickness, and for weighing. In most of these systems, the principle of the regenerative receiver using the "zero beat" tuning method is employed, (Art. 567).

An oscillator is used to supply a signal of constant frequency. A regenerative detector circuit is tuned to resonance with this by the "zero beat" method. The tuning condenser in the grid circuit of the detector controls the frequency of the oscillations generated by it. Part of this tuning condenser consists of a special 2 plate condenser, whose mechanical separation and material between the plates determines its capacitance. The condenser is constructed so the distance between these plates is the distance which is to be measured, (or the weight on one of them is the weight to be measured). Any slight change in the distance between the plates changes the capacity. This changes the frequency of oscillation of the detector, and consequently changes the frequency of the beat-note produced between it and the local oscillator. By means of a suitable indicating device in the tuned circuit, this may be indicated. The instrument is first calibrated with samples of known thickness or weight. Let us consider its application to the measurement of the thickness of paper produced in a mill. If a strip of the paper in the mill, is passing continuously between the plates of this condenser, and the circuit is adjusted to bring the tuned circuit to a point just off the resonance peak, then any variation in the capacity of this fixed condenser as a result of variation in thickness, weight, or dielectric constant of the paper, will produce a change in the capacitance which will in turn change the beat-frequency. The pointer of the indicating meter will then swing away from its central position, the direction depending on whether there is an "increase," or a "decrease," in the weight or thickness of the material of which the moving strip is made. This principle is used in paper-thickness testers, precision gauges, etc.

573. The thyratron tube: A tube designed to overcome the characteristic of large "power-loss" inside the tube, is known as the *thyratron tube.*

Its striking characteristics are the greatly decreased amount of power required to heat the cathode, and a marked reduction in the large voltage drop characteristic of the high-vacuum tube. This is brought about by the introduction of a slight amount of mercury gas or vapor into the bulb, the positively-charged vapor or gas molecules mingling with the electrons and neutralizing the space-charge. This neutralization of the space-charge makes possible a very different design of hot cathode. The thyratron tube is really a development of the hot-cathode type mercury vapor rectifier and contains in addition a "control electrode." Instead of utilizing what might be termed an open-type cathode permitting the electrons to leave the hot surface easily, there may be used an enclosed-type cathode with just a few holes through which the stream of neutralized and negative ions may pass. This means that the heat may be kept within and conserved, whereas the electrons and positive ions may be allowed to travel to the anode. This is accomplished by surrounding the hot cathode with heat insulation and heat reflectors with only relatively small holes for the passage of the current. The resultant power-loss is only about one watt per ampere of current through the tube, compare this with the 10 to 150 watts-per-ampere power-loss in the high-vacuum tube.

Also, neutralization of the space-charge eliminates the high voltage necessary to pass the current through the space; and instead of a large voltage increasing with the amount of current to be carried there is a constant-voltage drop of from 10 to 20 volts.

As a result, a thyratron tube built to about the same physical size as the common UX-250 high-vacuum tube, and costing about the same amount to manufacture, will handle about 50 times as much current as the latter. It is apparent therefore, that the gaseous type of electrostatically-controlled tube is much better suited to the handling of relatively high currents common in the broad field of electrical engineering than is the controlled high-vacuum type.

Nevertheless, a thyratron tube has certain limitations; the high-vacuum type can handle currents up to a frequency of one million cycles per second, whereas the thyratron in its present form is limited to a few thousand cycles per second.

The thyratron tube may be used as a rectifier for changing large amounts of a-c current to d-c. A rectifier circuit of this type is shown at (A) of Fig. 435.

With the larger thyratrons, polyphase circuits are usually employed in order to minimize the amount of filter required for smoothing and to attain the usual advantages of such circuits. A single-phase controlled rectifier circuit is shown.

Another fundamental application principle is the *inverter.* This changes direct current to alternating current and may be either separately-excited or self-excited, depending upon the source of power applied to the grids.

There are several types of inverters, but the general principles are similar. In every case, d-c voltage is applied to the plate of the tube and the grid is supplied with the frequency it is desired to obtain, or else from a circuit tuned to this frequency. In this respect, an inverter may also be considered as a thyratron amplifier or oscillator. The function of the tubes is to commutate, or in other words, perform a switching operation. In all inverters, some form of power storage is necessary in order to supply power during the commutation period. This may be in the form of static condensers, or a power system with leading power factor, or in rotating apparatus.

The fundamental action is simple and may be illustrated by the diagram at (B) of Fig. 435. The plates of both tubes are positive. Assume that the grid of the

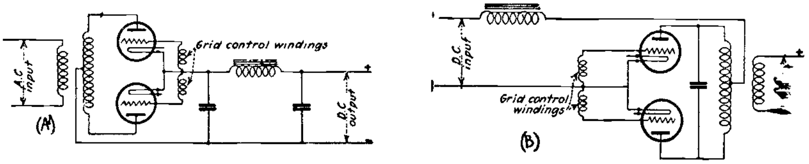


Fig. 435—(A) Controlled single phase rectifier and filter circuit using two thyratrons.
(B) A single phase inverter changing d-c to a-c employing two thyratron tubes.

upper tube is positive. Current will flow from the positive d-c source, through the transformer, to the negative d-c line by way of this tube. The grid of the lower tube is negative and allows no current to pass. The condenser is charged with the potential drop across the output transformer, due to the current flow in the upper half of the winding, the upper terminal becoming negative and the lower positive. Toward the end of the cycle the grids exchange polarity. This has no direct effect on the current flow through the first tube, but allows current flow through the second, which in effect connects the lower side of the condenser to the negative lead. This places a negative voltage of short duration on the upper plate, allowing the upper grid to regain control. As this action continues, voltage is generated in the output winding. As with the controlled rectifier, the usual power applications would be polyphase. One interesting radio application of the thyratron inverter has been its use for converting 110 volts d-c into a-c, in order to make it possible to operate standard types of a-c tube electrically-operated radio receivers from 110-volt d-c lighting circuits.

It seems probable that the rectifier and inverter application of the thyratron will revolutionize the power transmission field. Long distance power transmission has been carried on mostly by means of alternating current. It is now possible to generate the electrical power at high voltage in a-c generators, step it up to very high a-c voltages with transformers, rectify it to very high-voltage d-c by thyratron rectifiers, transmit it over the lines as d-c, convert it to a-c at the end of the line, step it down to normal voltages with transformers, and distribute it in the regular way as low-voltage a-c. The advantages of a system of this type will be apparent from the following consideration.

Every alternating-current line today has to be provided with extra insulation to withstand the momentary voltage peaks during each cycle—that is, has to be insulated for 1.41 times the nominal alternating-current voltage. Substitution of direct current instead of alternating current therefore would at once make it possible to raise the direct-current potential up to the full existing insulation of the line,—reducing the current in the ratio of 1.41 to 1 (for an equivalent amount of power transmitted), and so dividing the energy losses by about 2 ($I^2 = (1.41)^2 = 2$).

But the chief difficulty experienced in loading alternating-current transmission lines to their full current-carrying capacity, lies in their impedance, which, amounting to several times the ohmic resistance, results in excessive voltage drop and wide swings in terminal voltage with load changes. To avoid such voltage regulation troubles a-c lines can usually be operated at only a fraction of their actual total current-carrying capacity.

But with direct current, the full current capacity of the line can be utilized, and this gain, together with that resulting from use of the full insulation voltage, means a total advantage of three to six times in power-transmission capacity for direct current as against existing alternating-current lines.

For example, a certain 200,000-volt line transmits 60-cycle alternating current 200 miles into a leading large city. Were this line converted to direct current, the existing insulation would safely withstand a direct-current potential of 280,000 volts. And since with direct current, reactance vanishes, while the ohmic loss diminishes with the square of the voltage ratio, it becomes evident that from three to six times as much power could be transmitted, with comparable performance, at 280,000 volts direct current as at 200,000 volts alternating current. Thus, the introduction of converter and inverter tubes would create the equivalent of two to five additional transmission lines, like that already built.

574. The photoelectric cell: During the discussion of electron emission from solid bodies, in Article 265, it was mentioned that an electron emission may be produced when light rays of certain frequencies or colors are allowed to fall on certain materials, as shown at (E) of Fig. 189. Article 265 should now be reviewed very carefully. The modern photoelectric cell is used in many commercial alarm, control, sorting, and sampling devices, and has been responsible in a large measure for the advances made in the art of television.

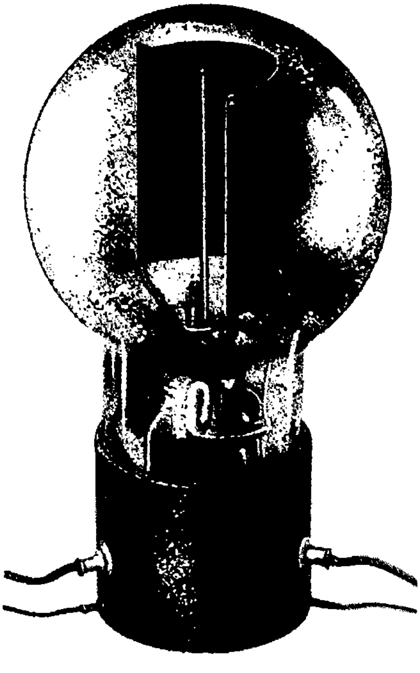
All photoelectric cells depend for their operation on the principle that certain metals, particularly those of the alkali group, have the property of emitting electrons when light rays shine on them. These metals include sodium, potassium, lithium, rubidium and caesium.

Under ordinary conditions, when the surface of the metal is exposed to the air, the emission of the electrons is interfered with by the presence of the larger air atoms. If the metal is put in a vacuum, and a beam of light is then allowed to fall on it, the electrons are free to be thrown off into the space surrounding the metal, and the number of negative electrons emitted per second is proportional to the intensity of the light applied.

If some form of electrode kept at a *positive* potential is put in the vacuum with this illuminated metal, the emitted electrons will be attracted to it and a plate current will flow, as in the case of a vacuum tube. The electrons will continue to be given off and the current due to them will continue to flow just as long as the light is shining on this metal. As soon as the light is cut off, the electron flow stops and the plate current also stops. The current flow will be proportional to the intensity of the light applied to this "active" or "photo-sensitive" metal.

There are really two types of photoelectric cells; one is the *vacuum type,* and the other is the *gaseous type.* In the vacuum type, the space between the photosensitive substance and the anode or plate, becomes conducting due to the pure electron discharge from the substance. In the gaseous type, which is used extensively in television and sound picture work, there is admitted to the cell during its construction and after a high vacuum has been created, a very small amount of one of the rare gases such as argon, neon, or helium. Such gases, when subjected to the bombardment of the electrons that are released from the photo-sensitive material when the cell is subjected to light rays, become ionized due to their atoms being struck by these rapidly moving electrons. The electrons released from the gas atoms by the ionization separate from their atoms and go to the plate, thus increasing the number between the sensitive material and the plate, and so increase the current flowing. This makes these cells more sensitive to the light. We may regard photoelectric cells as perfect insulators in the dark, and partial conductors when exposed to light.

Courtesy Eveready-Raytheon Corp.



Courtesy Electrical Research Products Corp.

Fig. 436—Left: Photoelectric cell employing a wire-hoop plate inside. This connects to a prong on the base. The sensitive coating on the inside of the glass bulb connects to the cap on top. The window in the bulb is plainly visible.

Right: A type of photoelectric cell used in sound picture work. The sensitive coating is on the inside surface of the curved strip of metal. The "anode" or "plate" is the rod at its center. The two connections are brought out at the bottom.

575. Photoelectric cell construction: Two forms of photoelectric cells are shown in Fig. 436. The one at the left has the bulb mounted on a standard 4-prong vacuum tube base, with the wire-hoop plate or anode visible at the center, connected to the usual "P" prong. This anode cannot be in the form of a wide, solid plate since it would interfere with the light shining on to the sensitive material. Therefore, it is made in the form of a hollow hoop. The inside surface of the glass bulb is coated with a deposit of metallic silver, except for the small round *window* or clear space, through which the light is to enter. This window is visible in the illustration. A part of the interior surface of this silver coating is covered with a finely divided form of one of the alkali metals already mentioned, or one of their compounds. This acts as the cathode, and makes contact with the silver coating which is connected to the metal cap on top of the glass bulb for connection purposes. This is a gas-filled cell designed for use in television transmitting equipment.

The cell at the right is an improved form designed for use in sound picture projection work. It is of the gas-filled caesium-oxide type, and has a high sensitivity. The light-sensitive caesium-oxide is coated on the inside surface of the semi-cylindrical metal sheet. Electrical connections to the cell are made by means of the two wires shown extending from the Bakelite base. The "positive" rod-type "anode" or "plate" is visible mounted inside of the curved coated-metal sheet. It is claimed that with this construction, a cell of longer life and greater sensitivity is produced.

The active materials used in photoelectric cells are usually the hydrides or oxides of the materials already mentioned. The hydrides and oxides are more light-sensitive than the pure metals, hence are most commonly employed. The sensitivity of the cell to light rays of different colors, depends on the material used. For example, a gas filled cell with a cathode of potassium hydride is very sensitive to visible light with its peak of sensitivity in the blue light region at about 4,500 angstrom units (see the photoelectric spectrum at the lower left of Fig. 163). The caesium cell is sensitive to both visible light and to infra red radiations, and is therefore particularly adapted to use with a light source consisting of a standard mazda lamp. Other materials are sensitive chiefly to ultra-violet radiation. A cadmium cell with a quartz window, is sensitive to the wavelength band of light between 2,000 Angstrom units and 3,000 Angstrom units.

576. Need for an amplifier: Possibly the most simple type of photoelectric cell circuit is shown in Fig. 437.

Here a source of light at the left shines into the window in the cell, on to the active material P (cathode) coated on the inside of the glass bulb. The anode A at the center is kept at a positive potential with respect to the cathode, by connecting it to

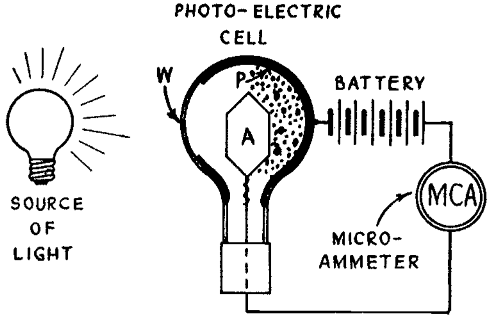


Fig. 437—Simple photoelectric cell circuit arrangement in which the intensity of the light shining through the window W on to the photo-sensitive material P of the cell is indicated by the reading of the microammeter in its circuit. The anode or "plate" is at "A."

the positive terminal of the battery as shown. Light shining on the active material causes electrons to be emitted. These are attracted by the positive anode, and therefore we have a flow of electrons around through the circuit. This constitutes electric current. Its strength depends on the intensity of the light showing on the cell.

Photoelectric cells are usually employed to indicate or measure changes in the intensity of the light coming from the source. Since the operating current of either a vacuum or gas-filled type of photoelectric cell is very low as compared to, say an ordinary amplifier vacuum tube, i.e., on the order of a few *microamperes* (millionths of an ampere), a microammeter is shown as the current measuring instrument in Fig. 437. Although it is possible to construct a relay that will operate on such minute currents, it is not as a rule very practical. The variations in the current of the photoelectric cell may easily be amplified greatly by one or two stages of thermionic vacuum tube amplification. The amplifier circuits used are of

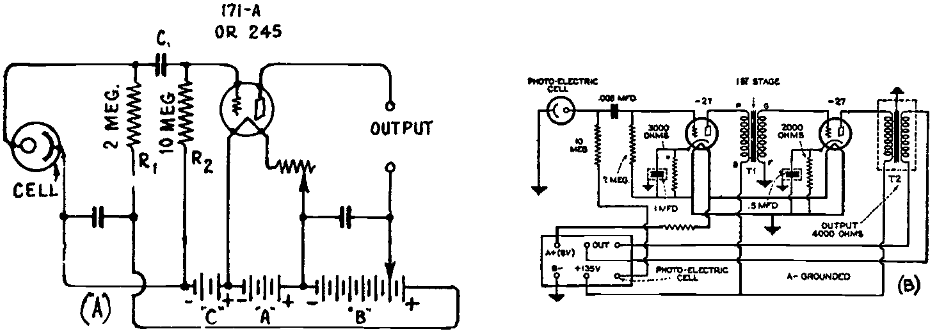


Fig. 438—Left: A simple amplifier circuit for amplifying any rapid current variations in the photoelectric cell caused by changes in the intensity of the light shining on it.

Right: The circuit of an a-c electrically operated combination sound head and sound head amplifier unit employed in sound picture work. The output of this is amplified further by an additional power amplifier.

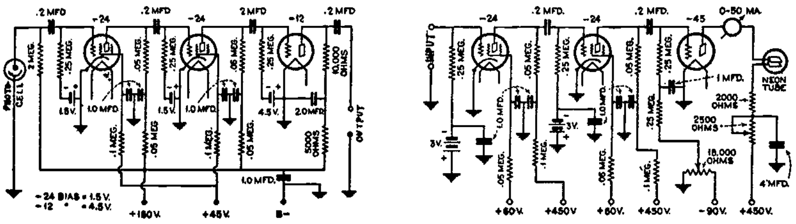
two general types. In one type, employed extensively in sound picture and television work, the rapid variations in the light are translated into amplified voltage variations. In the other type, the changes in the light are made to produce plate current changes sufficiently great to operate a suitable relay.

577. Photoelectric cell amplifier circuits for rapid light-variations: A form of amplifier which is adapted to amplify the rapid changes of photoelectric cell current produced by rapid changes in the intensity of the light shining upon it, is shown at the left of Fig. 438. This type of amplifier circuit is used extensively in television and sound picture work.

The photoelectric cell is really in series with the "B" battery, which acts as a polarizing battery to keep its plate positive. A 1 mfd. condenser shunts the "B" battery. Also in series with this circuit is the high resistance R_1, the voltage drop across which, is to be utilized. This is coupled to the grid of the tube, through a blocking condenser C_1, and a grid leak R_2 in the regular fashion used in resistance-capacity coupled amplifiers. This tube should have as low a mu as possible when high frequencies are to be amplified. If the light shining on the cell varies, the current flowing through it also varies. Since this current flows through resistor R_1 and therefore produces a voltage drop across it, this voltage drop will vary correspondingly. This varying voltage existing across R_1 is communicated to the grid of the tube, which amplifies it. This may be followed by another amplifier tube coupled to the first, as shown in the amplifier circuit at the right.

R_1 should be as large as possible in order to have a large voltage-drop available. It must not be made too large, however, as then an appreciable variation in voltage drop will result and thus affect the positive potential applied to the cell and possibly produce distortion. A low value of R_1 helps the high-frequency response at the tube end. Of course, all wires should be as short as possible and run free from other wires and apparatus. R_1 should be supported by its connecting wires in air to prevent leakage of current.

Upon leaving this first amplifier, the impulses can be amplified in several successive stages to the desired extent. In television this is one of the difficult phases, because generally the initial impulses are so very small that an enormous amount of ampli-



Courtesy Mr. C. W. Nason and Radio Engineering Magazine

Fig. 438A—Left: A typical photoelectric cell amplifier used directly at the cell in television work.

Right: A typical audio amplifier designed to amplify uniformly all frequencies from 15 to 30,000 cycles. This is also useful in television work.

fication is required, and tube noises become important. Also, as we shall see later, the amplifier must have a perfectly flat characteristic over a very large frequency-range.

A complete a-c operated amplifier circuit of this type used in sound picture work is shown at (B) of Fig. 438. Notice that two stages of amplification follow the photoelectric cell. The values of all circuit constants are given. T_1 and T_2 are high-grade audio transformers. The 10 meg. grid leak may be made up by connecting five 2-meg. leaks in series. Care should be taken to suspend it in the air to prevent leakage. The output of this amplifier is fed into a large power amplifier for operating the large loud speakers in the theatre. We will study sound picture systems later. A 3-stage resistance-coupled amplifier designed especially to amplify uniformly a band of audio frequencies from 15 to 30,000 cycles is shown following a photoelectric cell used in television work, at the left of Fig. 438A.

578. Photoelectric amplifier circuit for intermittent relay operation: In many commercial applications of photoelectric cells, it is desired to have changes in light intensity cause the cell to operate a relay, which in turn opens and closes a separate circuit in which a counter, alarm, indicator device, etc., may be connected. Two amplifier arrangements are commonly used in this work. In one, an increase in current through the relay results when the light intensity increases. In the other, a decrease in the relay current results. Photoelectric cells used in relay-operated circuits in industrial work are often referred to by the somewhat abbreviated term *phototube.*

A simple vacuum tube amplifier circuit may be changed to a phototube amplifier by simply connecting the anode (plate) of the phototube to the plate of the amplifier tube, and the cathode (sensitive surface), to the grid, and adding a grid resistor. A simple battery-operated circuit of this kind is shown at the left of Fig. 439. As long as the phototube is dark, the circuit conditions remain unchanged and the plate current will be determined by the grid-bias potential placed on the tube by the grid-bias battery and the setting of the 10,000 ohm potentiometer. As soon as light strikes the phototube, an additional very small current flows through the phototube and the rest of the circuit, as indicated by the heavy lines. Notice that this current flows through the high-resistance grid resistor R. This current flow produces a voltage drop across it (equal to I×R), and since the current flows downward, point A will be at a higher potential than point B. (Current flows in a circuit from a point of higher potential to one of lower potential), i.e., the negative bias effective on the tube has been *reduced.* Therefore this voltage drop results in making the grid less negative, and so its plate current is increased. The increase in the plate current of the amplifier tube is much greater than the increase in current through the phototube, due to its amplifying properties. If the relay connected in its plate circuit is properly adjusted, it may be made to open or close an auxiliary circuit when the plate current increases due to light shining on the cell.

It is important to note that the phototube current is quite small, and in order to produce a voltage drop large enough to secure the desired change in grid voltage, the grid resistor must have a very high value—from 10 to 200 megohms. The higher values of resistance result in a very sensitive amplifier but which is also quite critical and unstable. Leakage across tube sockets and other insulation becomes a considerable factor for very high grid resistors. A comparatively small amount of electrical leakage will conduct as much as a 100-megohm grid leak and thus upset the operation of the entire circuit. A compromise must be made between sensitivity and stability. A value of 50 to 60 megohms (which may be obtained by connecting 5 or 6 ten-megohm grid leaks in series) will be found to be a good value to use.

In order to make intelligent use of a phototube amplifier circuit, a milliammeter may be used in the plate-circuit of the amplifier tube. Although the current range will depend somewhat on the type of amplifier tube used and its plate voltage, a meter with a 0-25 milliampere scale will probably be found to be about the correct size.

It will also be found very convenient to connect a 10,000- or 15,000-ohm potentiometer across the grid-bias battery, and to connect the grid resistor to its movable

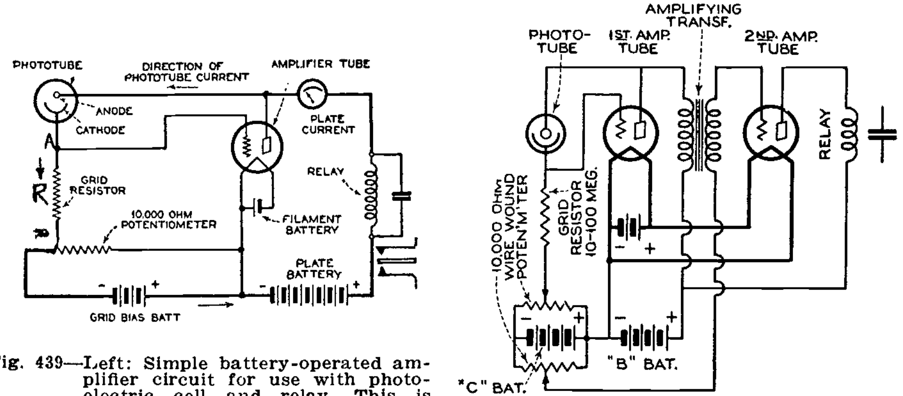
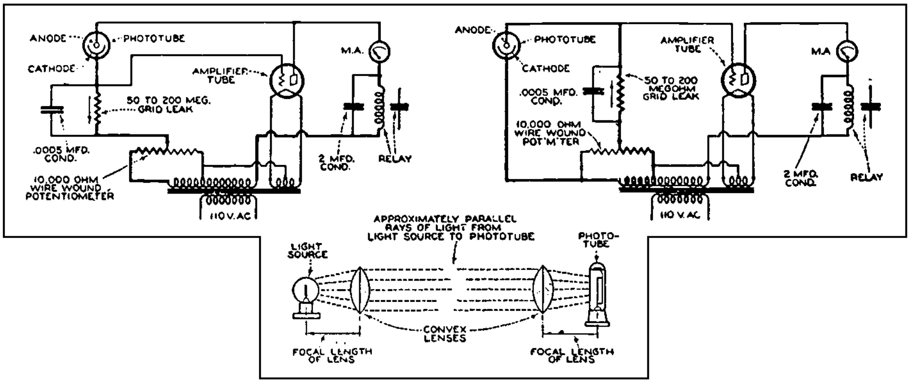


Fig. 439—Left: Simple battery-operated amplifier circuit for use with photo-electric cell and relay. This is arranged so that the plate current of the amplifier tube "increases" when the light shines on the cell.
Right: Another amplifier circuit in which the plate current "decreases" when light shines on the cell.

arm. This will provide a convenient means of adjusting plate current. This potentiometer should be of the wire-wound type. A grid voltage should be used which will result in a plate current *very near zero when the phototube is dark or out of its socket.* The amplification will be materially reduced if a greater bias voltage is used than necessary.

A 2-stage transformer-coupled amplifier of this type, for producing stronger impulses is shown at the right of Fig. 439. When the phototube is exposed to light, a current flows through the grid resistor of the first amplifier tube in exactly the same manner as in the single stage amplifier. This makes the grid more positive and results in a plate current increase. The increase in plate current flowing through the primary of the audio transformer, induces a voltage across the secondary which is applied to the grid circuit of the second tube and is amplified, causing a much larger change in the plate current of the second tube. This current flows through the relay and operates it.

While battery-operated amplifiers are used in many cases, it is frequently more convenient to operate a photoelectric cell and its amplifier from an a-c voltage source than from "A" and B batteries. The characteristics of the circuits given for battery operation are not appreciably changed if the amplifier tube filament is supplied with alternating current and the plate and bias voltages are supplied from any standard "B" eliminator. A circuit that is satisfactory for many applications, although



Courtesy Radio News Magazine

Fig. 440—Left: An a-c operated photoelectric tube amplifier circuit in which an "increase" of illumination causes an "increase" in the plate current of the amplifier tube.

Right: An amplifier circuit in which an "increase" of illumination causes a "decrease" in the plate current.

Bottom: A diagrammatic sketch of a simple optical system for use with a photoelectric cell. The light source may be a simple automobile headlight bulb.

somewhat less sensitive, may be obtained by utilizing "raw" alternating current as a plate and grid-bias supply. When an a-c potential is impressed on a cell and its amplifier, an appreciable current will be conducted only during a portion of alternate half cycles—the result is naturally a lower sensitivity than that obtained in a circuit where the current is flowing continuously.

An a-c operated phototube amplifier circuit arranged to produce an *increase* in the amplifier tube current, when the light on the phototube is *increased*, is shown at the left of Fig. 440. Notice that it is similar in most respects to the battery-operated circuits already considered. The operation of the circuit may be better understood if it is remembered that the devices operate *only* during the periods when the end of the transformer connected to the amplifier tube plate circuit has a *positive* polarity, so as to make the plate positive. When light strikes the phototube, a current flows through the circuit, indicated by the heavy lines. This current, flowing through the grid resistor, makes the grid more positive and causes a rise in the amplifier plate current and operates the relay.

Unless some precaution is taken, the same type of relay that is used in the plate circuit of a d-c operated amplifier, cannot be used with an a-c operated amplifier.

Since a-c voltage is being applied to the plate circuit, the plate current is flowing only during half of each cycle, and even then does not reach a steady value. The relay will attempt to follow the current variations, which will result in a pronounced "chatter". This condition may be prevented by connecting a fixed condenser across the coil of the relay, of about 2 or 4 mfds. This condenser will become charged while current is flowing and then will discharge into the relay coil when current is not flowing, thereby holding the relay closed during the portion of each cycle when current is not flowing.

Another method of accomplishing the same result, is by the use of a "lag-loop" type relay, such as is illustrated at the left of Fig. 443. This type of relay is fitted with a heavy short-circuited turn of copper which has "eddy-currents" induced in it by the magnetism of the relay. The fields created by these eddy currents tends to prevent the collapse of the magnetic flux in the core of the relay during each half cycle, and so prevents "chatter". The fact that this type of relay remains closed for a fraction of a second after the current is shut off, may or may not be a disadvantage, depending upon the characteristics of the device to be operated by the relay.

An a-c operated circuit arranged so that a *decrease* in the phototube illumination will cause an *increase* in the amplifier tube plate current, is shown at the right of Fig. 440. The only difference between this circuit and that at the left is that the phototube is so connected that its current flows through the grid resistor in the opposite direction from that in the arrangement at the left. Therefore an *increase* in the phototube current now makes the grid more *negative*, and so causes a decrease in the amplifier tube plate current, as long as the phototube is illuminated.

The plate and bias voltages in these circuits will depend on the characteristics of the make of the phototube used, as well as the maximum amount of plate current required to operate the particular relay employed. An increase of plate voltage accompanied by a proportionate increase in bias voltage, results in a higher maximum plate current. However, the plate voltage must be limited to the ratings of the tubes used.

579. Light sources for photoelectric devices: In order to employ a photoelectric cell for useful purposes, it is necessary to furnish a suitable source of light, and consider proper methods of directing the light on the cell in order to make it accomplish the particular services required.

In many photoelectric cell applications, the operation is accomplished by the interruption or partial interruption of a light beam from an artificial source. In selecting this, it should be remembered that it is only necessary to direct a small but intense spot of light through the "window" of the light sensitive tube. An incandescent lamp produces light from a heated filament. The filament is heated to practically the same *temperature* for any bulb, from the smallest to the largest. If the image of the filament of a large bulb is concentrated on a phototube, it simply produces a larger spot of light of about the same intensity as a much smaller bulb. This of course means that usually, nothing is gained by using a large bulb as a light source. An ordinary 21-candle power automobile headlight bulb makes an excellent light source for this purpose, since it produces an intense concentrated light.

If the bulb is simply placed in the open, a sufficient light intensity for satisfactory operation will not reach the phototube except for extremely short spacings between the phototube and light source. For greater distances, a parabolic reflector, or simple convex lens placed at a distance from the bulb equal to its focal length, will concentrate the light into approximately parallel rays. If the scheme is to work for distances more than a very few feet, it will also be necessary to use an additional lens in front of the phototube to collect and concentrate the light on the phototube. An optical system of this kind is shown at the bottom of Fig. 440. Plano-convex or double-convex lenses (2 to 6 inches in diameter) of a focal length of from two to six inches will be found satisfactory. A cheap "reading glass" will generally meet these specifications.

The lens in front of the light source should be so placed that a sharp image of its filament will be thrown on a flat surface at about the same distance as it is expected to work the phototube. It will be found that the distance from the bulb to the lens is the focal length of the lens, except for extremely short operating distances. The collecting lens in front of the phototube should be similarly placed at its focal length so that the collected light is focused on a small, intense spot on the cathode of the phototube.

580. Some commercial photoelectric cell control systems: The variety of commercial applications of photoelectric cells in control devices is so varied that no attempt can be made to explain them all here. A few

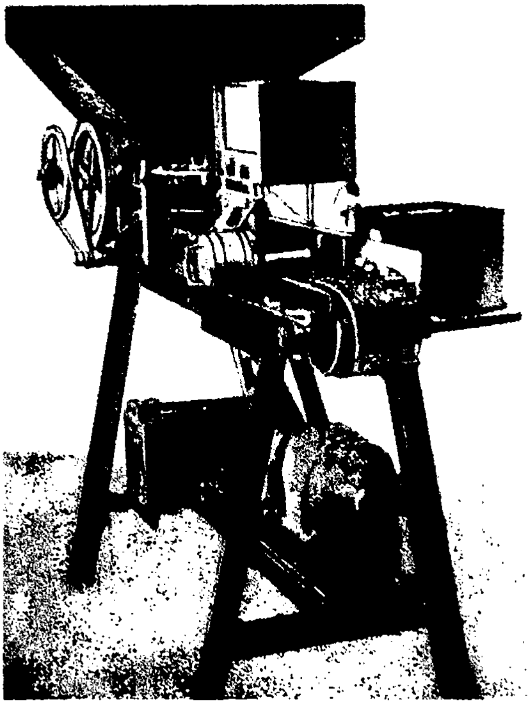
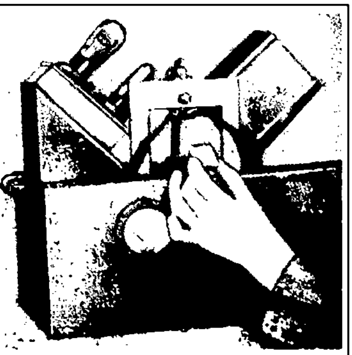


Fig. 441 — Left: A photoelectric counter installed on a machine. It counts the lamp bases which travel along on the conveyer belt.

Right: A sorting device employing a photoelectric cell for sorting light and dark objects. (See Fig. 442.)



Courtesy Radio News Magazine and The Westinghouse Elect. & Mfg. Co.

typical applications will enable the reader to see just how the cell is applied, and will possibly enable him to think up further applications.

Photoelectric cells are used extensively for automatic counting of objects. When applied in this way, the light beam usually is arranged to be interrupted by the passage of the objects to be counted. These may come along on a conveyor belt, etc. The interruptions of the light beam, cause the relay in the plate circuit of the amplifier tube to close an auxiliary circuit each time. This auxiliary circuit may contain an electrically-operated counter device. An arrangement of photoelectric cell, amplifier and counter, to count lamp bases as they interrupt a light beam in passing along a conveyor belt after having been produced in the automatic machine, is shown at the left of Fig. 441. The light source is at the left in the small enclosure having a handle on the cover. The beam of light is projected across the conveyor belt to the photoelectric cell in the rectangular box on the right—which also contains the amplifier and counter.

The passage of each lamp base, a few of which are shown on the conveyor belt, interrupts the beam of light and actuates the counter. A similar scheme may be used to count other objects or vehicles passing on a highway, bridge, or tunnel, only in this case the light is usually projected vertically. Systems of this type may also be used for automatic fire detection, and alarm and sprinkler systems, where the presence of smoke reduces the light falling on the photoelectric cell and causes a relay to operate the fire alarm and sprinkler system. Excessive exhaust gas fumes and smoke caused by automobiles in a vehicle tunnel are detected in the same way, the cell circuit operating proper relays to start up the ventilating fans. Burglar alarm systems can also be operated in this way by arranging the light (preferably an invisible ultra-violet or infra-red light source) so the passage of a burglar interrupts it and operates the relay for the burglar alarm system.

Small objects having a decided difference in light-reflecting qualities

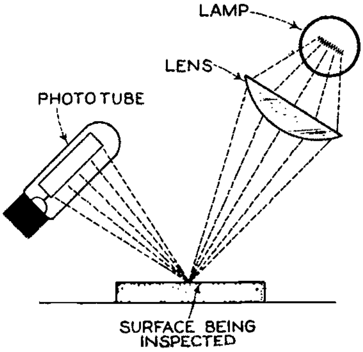


Fig. 442—The simple optical system employed in the sorting device at the right of Fig. 441. The light rays from a lamp are focussed on to the surface being tested, by a lens. The reflected light acts on the photoelectric cell.

may be sorted by photoelectric means by the use of a simple optical system as shown in Fig. 442.

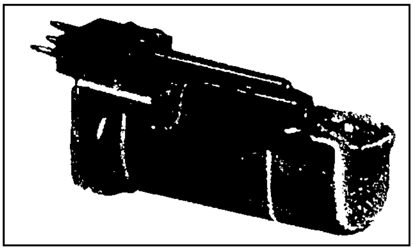
The articles to be sorted may be placed on a conveyor belt and moved into the spot of light. Those articles which reflect a considerable amount of light, will illuminate the phototube sufficiently to cause the operation of a relay, which may be caused to operate an electromagnet so arranged that it will discard such objects; while others having a dull or dark surface, will not reflect light so readily and will pass through. A d-c or properly rectified voltage supply is necessary for schemes of this kind. The setup of a typical commercial sorting device of this kind is shown at the right of Fig. 441. It should be noted that such a device can only be readily constructed to sort objects having a considerable difference in reflecting ability. Special arrangements are required if it is desired to distinguish between articles having a somewhat smaller difference in light-reflection ability.

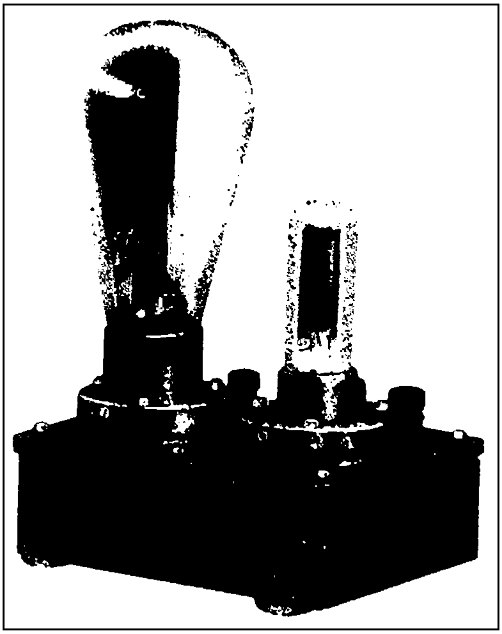
Photoelectric light intensity meters, and color analyzers, in which photoelectric cells sensitive to different colors and a suitable color filter system are used, are employed extensively in many lines of work. At the left of Fig. 443 is shown a lag-loop type of relay used in the plate circuits of a-c operated amplifier systems, and at the right is a typical commercial form of compact photoelectric amplifier unit. The small photoelectric cell is at the right and the amplifier tube is at the left. All necessary coupling and circuit parts for the amplifier are contained in the box below. The particular applications of photoelectric cells in television and sound picture work will be treated in detail in the following chapters devoted to these subjects.

581. Photo-voltaic cells: Another type of light sensitive phenomena is that property which certain materials have of generating a voltage when light shines upon them. This is termed the *photo-voltaic* effect, and this property is exhibited by certain materials, notably copper oxide. This type of cell has generally been considered to be somewhat sluggish in its response to rapid changes of light intensity, but certain improved forms have been developed, that have partly overcome this difficulty. The advantage of this type of cell is that since it actually generates a voltage, in most cases the usual amplifier is unnecessary with it, the cell operating a

Fig. 443—Left: A "lag-loop" type relay suitable for use in the plate circuits of a-c operated photoelectric amplifiers. The flat armature at the right end is attracted by the magnetized core. This pushes up the contact arm of the switch at the upper left, to close the auxiliary circuit.

Right: A commercial photoelectric amplifier unit. The photocell is at the right and the amplifier tube is at the left. All necessary circuit equipment is in the base.





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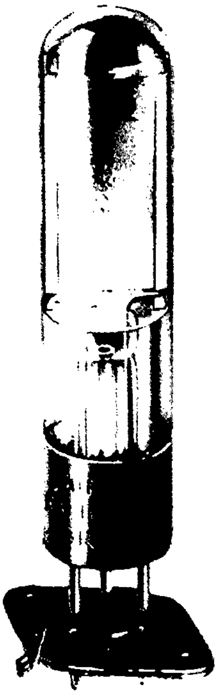
relay direct. Even if an amplifier is necessary, it need not have as many stages as that required for use with the vacuum or gas-filled types of photoelectric cells just described.

582. Radiovisor bridge light-sensitive cell: A new type of light-sensitive cell sold under the trade name of "Radiovisor Bridge", has been introduced in the United States, although originally developed and produced in England. It employs a special form of the element selenium for its operation.

Selenium has long been known to possess the peculiar characteristic of changing (decreasing) its *resistance* when subjected to the action of light rays, but the forms of selenium cells heretofore produced have had the serious disadvantage of being sluggish in their action. The time required for the current flow through an ordinary selenium cell to reach its maximum value when the device is illuminated, is of the order of a number of seconds. The current decrease when the source of illumination is cut off, is similarly sluggish. This feature, more than any other, has been responsible for its very limited application, since it is not capable of satisfactorily responding to rapid light variations.

In the new selenium-type Radiovisor Bridge, this limitation has been overcome by a special construction, and the resistance changing action of the cell is so rapid that it is capable of responding to interruptions or variations of illumination occurring as rapidly as 10,000 per second.



Courtesy The Burgess Battery Co.

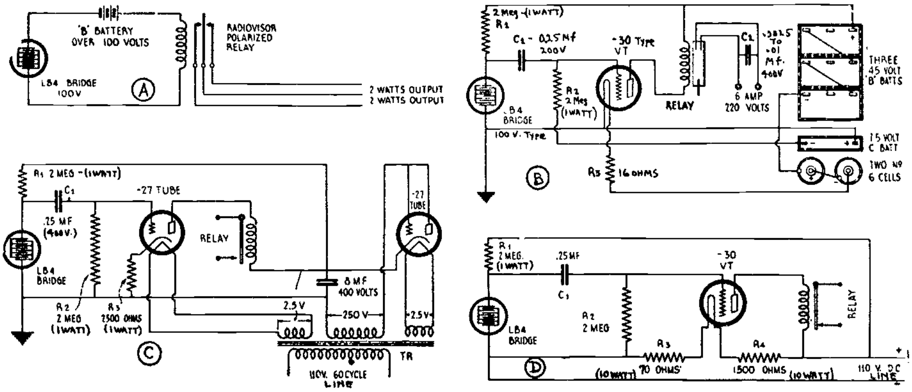
Fig. 444—A Radiovisor Bridge. This is a special form of selenium-type light-sensitive cell in which time-lag has been greatly reduced.

The Burgess Radiovisor Bridge consists of a tall, tubular glass bulb with a three-prong base as shown in Fig. 444. Inside the bulb is a flat plate occupying the center and supported by two heavy lead-in wires. The plate is of glass, upon the front side of which are two interlocking comb-like grids or electrodes of gold, fused in place. These grids or electrodes are covered with a thin enamel of special composition the conductivity of which changes with the amount of light falling on it, thereby providing a light-sensitive cell. The active selenium enamel is spread as a film of the almost infinitesimally small thickness of about .0025 centimeters. This thin layer makes it possible to employ the entire mass, having an active surface about ¾ by 2 inches, for useful purposes, thereby minimizing any useless shunt capacity which might reduce the sensitivity of the bridge. The result is a cell that is claimed to handle many times the current of the usual photoelectric cell, that is highly responsive to light variations, that does not fatigue in continuous use and that does not deteriorate even after long service.

Due to the appreciable amount of current that can be passed through the Bridge, as contrasted with the very limited current passed by the usual photoelectric cell, it becomes possible to utilize simple, practical and quite inexpensive circuits with this Bridge, thereby multiplying many-fold the possibilities of light control. The Bridge can operate a relay direct, for controlling a circuit handling a few watts of electrical energy, while a second relay provided with a novel form of vacuum contact permits of handling several hundred watts for serious work. For more intricate applications, vacuum tubes can be employed, in which event considerably less amplification is required than in the case of the usual photoelectric cell, because of the higher initial current available.

In applying the bridge, use is made of the property of the selenium conductor by which its surface is exposed to light. The bridge, with a dark resistance of the order of 1 to 10 megohms, is connected to a suitable d-c supply in series with a ***sensitive relay*** so adjusted that the normal current passing through it is just insufficient to close its contacts so long as no light falls on the bridge. When the bridge is illuminated, however, the current is increased well over four-fold, and the relay closes instantly. The sensitive or primary relay may be employed to control a circuit requiring only a few watts of energy. If a greater amount of energy is to be controlled, a ***power or secondary relay*** is required. This may be of the telephone relay type, utilizing a special vacuum-type contact.

A simple circuit in which the bridge operates a polarized relay directly, is shown at (A) of Fig. 445. This is the simplest battery-operated circuit arrangement for the application of the bridge. The relay may require adjustment from time to time to allow for variations of the resistance of the bridge. An impulse circuit for dry-battery operation, in which the bridge feeds a '30 type 2-volt vacuum tube, which in turn actuates a power relay, shown at (B). The contact may be of the vacuum type, and is shown beside the relay coil. A basic 110 volt a-c operated impulse circuit with the bridge feeding a '27 type indirect heater amplifier tube, which in turn actuates a power relay is shown at (C). A second '27 type tube rectifies the a-c supply. The detailed operation of these circuits is substantially the same as those



Courtesy The Burgess Battery Co.

Fig. 445—(A) Battery-operated, direct-coupled circuit, of a Radiovisor Bridge light cell and a polarized relay.
(B) Impulse circuit for dry battery operation with a vacuum tube amplifier and relay.
(C) Impulse circuit for 110 v. a-c operation. A vacuum tube amplifier and relay are also employed.
(D) Impulse circuit for 110 v. d-c operation with vacuum tube amplifier and relay.

already explained for the photoelectric cell, in Article 578. An impulse circuit for 110-volt d-c operation employing a '30 type 2-volt tube amplifier, and power type relay is shown at (D). If the circuit is to be operated from a 220 volt d-c line, R_4 should be changed to 3,000 ohms.

REVIEW QUESTIONS

1. What is the main difference in the operating characteristics of an ordinary high-vacuum tube such as is used in the amplifier of a radio receiver and a thyratron tube? What special construction features of the thyratron tube are responsible for this?
2. Explain the operation and principle involved in an oscillator system designed for accurate measurement of weights, thicknesses, etc.
3. What is the difference between the principle of operation of a photoelectric cell, a photo-voltaic cell, and a selenium light cell?
4. Explain why gas-filled types of photoelectric cells are more sensitive than the vacuum type.
5. Explain the construction (with sketches) of a commercial form of photoelectric cell.
6. What is the purpose of the active material; the plate or anode; the window? Name four "photo-sensitive" materials.

7. Draw the circuit diagram of a single-tube battery-operated amplifier for a photoelectric cell, arranged to produce a *decrease* in the amplifier plate current when the light intensity increases.
8. Explain the operation of this circuit in detail.
9. Explain how leakage could take place across the grid resistor terminals, and just what effect this would have on the operation. How may this leakage be minimized?
10. Draw a schematic sketch showing the photoelectric cell and amplifier and all equipment you would employ for automatically counting the number of automobiles going in a single direction over a certain road. The entire apparatus is to be operated from a 110 volt a-c lighting circuit. Explain its operation.
11. Repeat Question 10 for an installation in which black shoes are to be sorted from white shoes.
12. Repeat Question 10 for an installation on a newspaper printing press, printing on a continuous sheet from large rolls of paper. The photoelectric cell device is to actuate the line switch of the printing press motors to immediately stop the press if the paper should suddenly break.
13. Describe the selenium Radiovisor Bridge type of light cell. How does this differ in operation from a photoelectric cell?
14. Draw a circuit diagram for a complete a-c electrically operated Radiovisor Bridge light cell circuit to count the number of bottles of milk coming along on a conveyor belt from a bottling machine.
15. Draw a circuit diagram and complete apparatus arrangement for a photoelectric cell and 3-stage a-c operated audio amplifier circuit feeding to an electrodynamic type loudspeaker. The photoelectric cell is to be arranged to respond to the rapid variations in the light coming to it from a steady source of light interrupted by a series of dark and light bands on a strip of motion picture film moved rapidly between the light source and the photoelectric cell. (Note: This is the arrangement used for the reproduction of the sounds in the sound-on-film system of sound motion pictures.)
16. Explain how the method of emitting electrons in an ordinary vacuum tube differs from that employed in a photoelectric cell.

CHAPTER 33.

TELEVISION

PRESENT STATUS OF TELEVISION DEVELOPMENT — WHAT TO EXPECT IN THE FUTURE — THE RADIO TELEVISION SYSTEM — PERSISTENCE OF VISION IN TELEVISION — HOW THE PICTURE MAY BE SLICED INTO SQUARE ELEMENTS — DIVISION OF THE SCENE INTO STRIPS FOR TELEVISION — THE USE OF THE PHOTOELECTRIC CELL — TRANSMISSION FREQUENCY BAND REQUIRED — THE SCANNING DISC — SCANNING METHODS — SYNCHRONIZED TELEVISION AND SOUND TRANSMISSION — GENERAL TELEVISION TUNER AND AMPLIFIER SYSTEM — THE RADIOVISOR — THE NEON TUBE — THE RECEIVING DISC — SYNCHRONIZING THE DISCS — OPERATING A DISC TYPE TELEVISION RECEIVER TYPES OF SCANNING DISCS — THE MECHANICAL AND THE CATHODE RAY SYSTEMS — THE CATHODE RAY TUBE — THE FARNSWORTH CATHODE RAY SYSTEM — FUTURE OF TELEVISION — REVIEW QUESTIONS.

583. Present status of television development: In its broadest sense, the word *television* has come into general use as a term to indicate the instantaneous transmission of images of objects and scenes, either by radio or by wire. This does not include the art of transmitting photographs by telegraphing (phototelegraphy). While, generally speaking, television includes the transmission of visual scenes by wire, most of the recent development work has been along the lines of transmission without wire lines, although it is not at all improbable that television programs transmitted over existing telephone or electric light circuits may become popular at some future date. Our study will be confined to television by radio.

While the average layman believes that television is an entirely new art brought on by the development of radio, it is interesting to note that the history of television dates back as far as 1873 when the light-sensitive properties of selenium were discovered. Scientists immediately tried to apply this discovery to the solution of the age-old problem of transmission of pictures and scenes. In fact, the principle of the scanning disc, which is still used in one form or another in most television systems, was invented way back in 1884, nearly 50 years ago, by Nipkow, a German. While many more dates and references of early work in this field could be made here, these two will perhaps convince the reader that the idea, and attempts to achieve television transmission and reception are not new by any means. All of our present systems, with the exception of the cathode ray method, are merely improvements on the systems devised many years ago, these improvements being made possible by the development of such devices as photoelectric cells, thermionic tubes, neon lamps, cathode ray tubes, high gain amplifiers, etc., which were really developed in connection with other arts.

Any attempt to write a text on television at the present time, must necessarily be confined to a description and explanation of the operation of the various main systems now in use—imperfect as they are. The author will possibly lay himself open to criticism from some readers, when he states that no system thus far presented has been proved capable of achieving really satisfactory and practical television transmission and reception on a commercial basis.

The requirements for satisfactory performance for home reception, which the author has in mind when making this statement are as follows: (a) The picture projected on the receiving screen should be at least 1 foot square, (b) The detail should be at least as good as that of ordinary newspaper photograph reproductions, (c) The light used for the received picture should be of a nature which will not tire the eyes, and all flicker should be eliminated. (The pink light of the common neon tube usually employed, is about as poor a light source from this point of view as could possibly be used). (d) The receiving equipment should not contain any rotating or moving parts and should have a reasonably long life. (e) The radio transmission channel required should not be over 100 kc, unless transmission on the very short waves is resorted to. (f) The receiving equipment should be fairly inexpensive, certainly the total cost should not be very much over that of an average good radio receiver.

No such system has appeared at the time this is written, although the cathode ray system holds forth considerable promise of being capable of sufficient improvement to meet these requirements.

Anyone who is at all familiar with the technical details and results accomplished by the various systems now in use, must agree that these requirements have not been met by any one system to date. No doubt this will cause a distinct surprise and disappointment to the many whose ideas on the subject have been gained by misleading fantastic dreams and writings of many newspaper feature writers and press agents of manufacturers interested in the sale of television equipment. These writings have placed the large mass of the public in the wrong frame of mind regarding television. They have been led to believe that it is an accomplished fact, and that all of the problems have been solved. Naturally they expect perfect television reception. The true story is that hundreds of men are feverishly engaged in research work almost day and night in the laboratories of the world, in attempts to solve some of the problems which the newspaper writers have apparently solved with a few clicks of their typewriter keys. The public should be made to realize that television today is still in the development stage. This is no disgrace—every art must pass through this stage. The unfortunate difficulty is, that false reports have placed the expectations of the public way ahead of the actual accomplishments of the research engineers and inventors. There is no doubt but that the intense public interest has had a beneficial effect in spurring on research in this field, but public demands for a finished product, at a time when a really satisfactory system has yet to be found, are rather disconcerting.

584. What to expect in the future: What the future will bring in this field, or how long it will take for successful television to arrive, no one knows. The technical problems involved are by no means simple or few. Even the results now obtained are really remarkable, when we consider the obstacles which block the path to successful television. The various workers in this field are to be sincerely congratulated on their persistence and ingenuity. We must be patient, and not expect too much, for television is still but an infant in growth even though old in years.

Since the art of television is still in the formative process of development, the author feels that the interests of the student can best be served by an explanation of the operation and the principles involved in the various systems in use today, with some illustrations of the actual apparatus employed. This will furnish a background for future study and enable the student to keep up to date on the many developments which are bound to come, possibly in the very near future.

585. The radio television system: All radio television systems are electrical in their nature, just as all radio broadcasting systems of sound are electrical. It will be remembered that in our ordinary sound broadcasting systems, as shown at (A) of Fig. 446, the succeeding sound

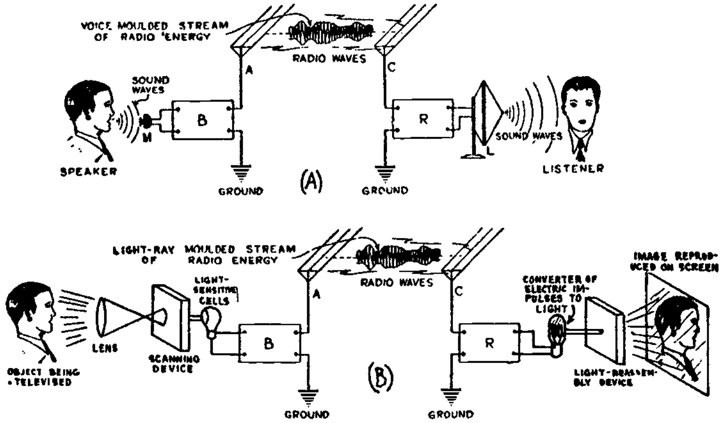


Fig. 446—(A) The typical transmitting and receiving system employed for radio telephone communication. This system starts with sound waves which are to be transmitted. All of the transmitting, amplifying and receiving is done with electrical impulses. Finally these are converted back into sound waves again by the loud speaker.

(B) The typical system employed for television. This system starts with reflected light rays from the object being televised. All of the transmitting, amplifying and receiving is done with electrical impulses. Finally these are converted back into light rays and re-assembled to form the visible picture.

waves produced which follow one another rapidly, are allowed to strike the diaphragm of the microphone M in the transmitting station, and be converted into electric impulses which are amplified and caused to modulate a high-frequency carrier current suitable for radio transmission by the transmitting apparatus B. The signals are radiated in the form of varying electromagnetic radiations which induce corresponding modulated high-frequency electrical impulses in the receiving antenna C These are tuned out from those of all other stations, amplified, demodulated, and possibly amplified further by the receiving equipment R. Finally they are converted back into sound waves by the loud speaker L. This completes the system, (see Chapter 15).

In television, the general system is similar, as shown at (B) of Fig. 446, only instead of dealing with *sound waves* at the beginning and end of the system, we deal with *light rays.* The first step is the so-called *scanning*, or progressive and systematic optical analysis of the scene to be transmitted. The next step is the conversion of the light impulses thus obtained, into corresponding electrical ones, by means of the photoelectric cells. These electrical impulses are amplified and caused to *modulate* a high-frequency carrier current suitable for radio transmission by the transmitting apparatus B. The signals are radiated in the form of electromagnetic radiations which induce corresponding modulated high-frequency electrical impulses in the receiving antenna C. These are tuned out from those of all other stations, amplified, demodulated, and amplified further, in the receiving equipment R. These electrical impulses are finally re-converted into *light* rays by the light source, and are then re-assembled in a progressive and systematic order to form the image of the original picture transmitted. Notice that the process at the receiver is the reverse of that at the transmitter.

Notice the similarity between this and the sound broadcasting system at (A). In fact, the transmitting equipment exclusive of the scanning and photoelectric cell units, and the receiving equipment exclusive of the light producing and re-assembling device are almost of exactly the same types as those used for regular sound-radio communication—differing only in the several design details required for handling a rather wide modulating-frequency range. Now perhaps the "mysteries" of television are beginning to fade away somewhat from the mind of the reader! We will now study the problems involved in conversion of the reflected light rays from an object into corresponding electrical impulses at the transmitter, and the conversion of these back into the complete scenes at the receiver.

586. Persistence of vision in television: If it was desired to transmit simply "still" pictures by television, the problem would be greatly simplified. Actually however, the pictures of moving objects must also be transmitted and reproduced. Since changing scenes are also dealt with in the ordinary motion picture, let us see how the problem is solved there. This will shed some light on our problems in television transmission and reception. Let us first consider a very important characteristic of the human eye.

When light enters the normal eye it is focused on to the retina by the eye-lens. This retina is coated with a material known as the *visual purple*, in which are embedded the so-called *rods* and *cones* at the nerve ends. According to one theory, when light falls upon the visual-purple, a photoelectric action takes place, and electrons are freed much as they are in a photoelectric cell. These freed electrons set up currents in the visual-purple which are detected by the rods and cones. These in turn set up electric currents in the nerves that carry them to the brain and produce the sensation of sight. The exact action in the brain is still unknown. The nerves are the circuits that carry the message to the brain. The eye interprets different wavelengths or frequencies as color. Notice the remarkable similarity between this system and an ordinary vacuum tube radio receiver with its tuning circuits.

One exceedingly important characteristic of the eye, is that it does not respond at once to any change in light intensity, but has a lag of about 1/10 of a second and retains an impression for this definite period. Due to this, it is possible to produce the sensation of continuous motion by viewing a moving object successively at intervals of 1/10 second or less.

This is called *persistence of vision*, and is made use of in the projection of motion pictures. On the other hand, an impression must affect the eye for a certain definite minimum of time, depending upon the intensity of the light, or it will not register on the consciousness at all. To see any moving picture or scene by this method then, the eye must see each scene for a period long enough to awake the consciousness (at least one five-hundred thousandth part of a second if strongly illuminated), and must follow one another at least 1/10 of a second apart. In the projection of motion pictures, the film consists of a series of individual pictures which pass down in front of the light source at a speed of about 16 per second. Each scene or "frame" is jerked down in front of the lens by a special intermittent-motion mechanism, remains stationary there for a short period, then the blade of a rotating shutter comes around and shuts off the light from the scene while the film is being jerked down to the next frame, etc. In other words, each image of the picture flashed on the screen, persists on the retina of the eye for the full time during which the light is cut off, the next *frame* or picture is jerked into place in front of the lens, and the following picture flashes on the screen, etc.

The absolute darkness which exists when the shutter cuts off the light during each jerk of the film is not noticed at all, and the sensation of a continuously moving scene is impressed on the brain. This might be termed, "deceiving the eye".

All television methods thus far developed make use of this action of "deceiving the eye". An electrical impression of the entire scene to be transmitted, (the scene is actually sliced into thin strips as we shall see), is taken, transmitted, and reproduced on the screen at the receiving end almost simultaneously 20 times every second in most systems in use at present. In this way the entire picture is reproduced on the receiving screen 20 times every second, each view differing slightly from the previous one due to the movements of the object televised, and the persistence of vision of the eye makes it appear as a continuously moving picture in exactly the same way as in the case of cinema or motion pictures.

587. How the picture may be sliced into elements: In the motion picture, the entire scene is present on the small picture or "frame" on the film in front of the lens at any instant, and is flashed on to the screen as one complete single picture or impulse. In television, it has not been found possible to transmit the whole scene at once in a single impulse (20 times a second), because no system or device for recording and reproducing the individual light and dark elements of the picture all together in this way, has yet been developed. Instead, each 1/20 of a second the "scanning" device scans the entire scene in narrow "strips" or "slices" starting at the top and working down toward the bottom (see Fig. 448). The "light" and "dark" impulses constituting each strip are transmitted progressively and these light impulses and strips are re-constructed in proper order on the screen at the receiver, persistence of vision again aiding us in making the individual strips appear as a single composite picture.

Experiment: Many simple experiments may be performed to illustrate the persistence of vision. If the glowing end of a match is twirled around, the glowing spot changes its position so rapidly that the persistence of vision of the eye makes it appear to be a bright ring of light. Draw a fish on one side of a white card and a gold fish globe on the other directly in back. Now fasten a string to two opposite edges of the card and twist or twirl it rapidly by blowing on it so as to make it rotate. The fish will appear to be in the globe.

Just how a picture may be broken up into tiny elements and still appear like a solid picture to the eye, may be appreciated by examining closely with the eye alone, or with a magnifying glass, any half-tone reproduction in this book or in a magazine. It will be seen that what ordinarily appears to be a uniform picture, really is made up of a large number of tiny dots of ink of various sizes and shapes. Fig. 447 is reproduced here especially for a study of this. When a half-tone cut is made, the subject is photographed through a screen consisting of a transparent substance with opaque lines ruled closely on it to form tiny squares. The half-tone cut which is made, also contains these tiny squares, and the tiny square impressions really constitute the reproductions. It will be seen from the illustration at the left, which is made through an exceptionally coarse screen especially for this study, that in the light portion of the picture, these tiny spots of ink are very small. In the darker parts on the hair, coat, vest, and necktie, they are very much larger, and in some places run so close together as to merge into one another. As shown by these illustrations made through screens of different coarseness, the general effect produced by

Fig. 447—The detail of the reproduced picture depends upon the number of picture elements used per unit area. At the left is a half-tone reproduction made up of individual dots of ink (picture elements) spaced 50 to the inch. There are 2,500 such elements per square inch in this. At the center is the same illustration made up of individual dots of ink spaced much closer i.e., 85 per inch. At the right there are 120 dots to the inch. Notice the poor detail of the picture at the left as compared to that on the right.

the entire assembly of tiny dots depends on how fine-grained a structure is used. The picture at the left, which seems rather coarse and lacks detail, was made through a screen having 50 horizontal and 50 vertical lines to the inch, i.e., 50×50 or 2,500 squares or elements per square inch. For the center picture, an 85 line screen was employed. This gives 7225 squares or elements per square inch. That at the right was made with a 120-line screen giving 14,400 elements per square inch. If you stand off with your eyes about 12 inches from the book you will see that the squares in the one at the left are plainly visible, those in the middle are just barely visible, and those at the right cannot be distinguished. Notice how the *detail* of the picture is lost when the tiny picture elements are coarse. For ordinary reproduction, a picture composed of some 17,000 dots to the square inch, (130 rows per inch), leaves little to be desired in the way of detail. The usual newspaper reproductions contain 4,225 dots per square inch (65 rows per inch). A picture composed of some 400 dots per square inch (20 rows per inch), is barely passable even when viewed at a distance of 18 inches or so. In the present television systems using scanning disks, 60 lines or elements per inch are employed.

It is evident from this discussion of half-tone reproductions, that in television, it is really not necessary to transmit and reproduce the entire scene as a single unit each 1/20 of a second. We may split up the scene viewed by the television transmitter, into elementary dots, transmit electrical vibrations corresponding to the brightness or darkness of each individual dot, and reproduce the dots in the same relative order and position at the receiving end. Then our received picture will be made up of a number of dots similar to a half-tone, and if the elements are small enough it will be acceptable. This system has actually been used by Dr. Ives at the Bell Telephone Laboratories, but since a separate circuit was necessary for each element or dot (2,500 circuits in all in this particular apparatus), the system was very complicated and commercially impractical.

588. Division of the scene into strips for television (scanning): In most television systems now in use, the scene is not scanned in the form of dots but in *strips*, by a suitable *scanning device* in the transmitter. At the receiver, these strips of the scene are reproduced in proper order to form the complete scene. The principle of strip-scanning may be understood from a study of Fig. 448. At the left, we have a simple scene or picture to be transmitted. This consists of light and dark areas. Suppose we view this picture through the small square opening shown at the upper left-hand corner of the picture, and that this opening is moved horizontally to the right in the direction of the arrow. We will then view or *scan* the top strip number 1. We now move this square peep hole down a distance equal to the height of this strip, and again move it across the picture from left to right scanning another strip number 2. This will appear as top strip number 2 shown at the right. This operation may be repeated until the entire picture has been scanned or divided into strips which will appear successively as numbered at the right. It is seen, that if all the individual strips at the right were assembled close together, they would form the original picture. Now suppose it were possible for us to scan *all* of these strips in this picture in less than 1/10 of a second. We would not see them as individual strips, because the persistence of vision would cause us to retain the impression of the first strip and the succeeding ones up to the time when the last one was scanned. Therefore, we would see the entire picture as a unit. This is the basis of the television systems now in use. We have considered here, a "still" picture. Suppose the scene were continuously changing? In that case if we scanned the entire picture in at least 1/10 of a second, we would be scanning the entire picture 10 times or more every second, which is sufficiently fast to just enable the persistence of vision to retain the impression of one picture until the next one has been received. The eye would then receive the impression of motion of the scanned objects just as in the case of the motion picture. In practice it is desirable to scan the pictures more rapidly than this, 20 times per second more being used in most television units at the present time.

In actual television scanning, the scanning strips are very much narrower than shown in Fig. 448, 60 lines or strips to the inch now being common in disc scanning systems. Of course the greater the number of scanning strips, the greater the detail of the picture. Considering any one of these very narrow strips, it is found to be composed of a succession of parts which vary in the amount of light and shade, or in the amount of light reflected at the various points by the image.

The actual total area scanned is called a "frame". Thus in Fig. 448, the entire picture at the left would compose a frame.

589. The use of the photoelectric cell: Now that we have considered a method of breaking our picture or scene up into a number of fine elementary strips, the next problem is to convert the successive light and dark variations in each strip scanned, into corresponding variations in an electric current. This extremely delicate and important operation is performed by the photoelectric cell which we have already studied in Chapter 32; or some other form of suitable light-sensitive cell.

If we arrange in some way for the light reflected from each elementary area in every strip of the scene scanned to fall upon the sensitive surface of a light-sensitive cell, the cell will respond to the variations in the intensity of the light, and may be arranged to produce corresponding variations in the voltage or current of an electric circuit. For instance, if the reflected light coming through the moving square peephole at the left of Fig. 448 were focussed on to a photoelectric cell, it is evident that each light and dark area of each strip scanned, would cause a corresponding variation in the cell current. When a light area was scanned the cell current would increase, when a dark area was being scanned, the cell current would decrease. The variations in the cell current for the bottom strip at the left, would appear somewhat as shown below it, O-O being the axis line for the cell current. Thus the light-sensitive cell in the television system corresponds to the microphone in the sound-broadcasting system, in that it produces the variations in the current. The variations in the cell current are amplified by a very high-gain multi-stage resistance-coupled amplifier of the general form shown at the left of Fig. 438A. This must be designed to amplify uniformly, an unusually wide band of frequencies, and all circuits must be laid out carefully and shielded to prevent feedback.

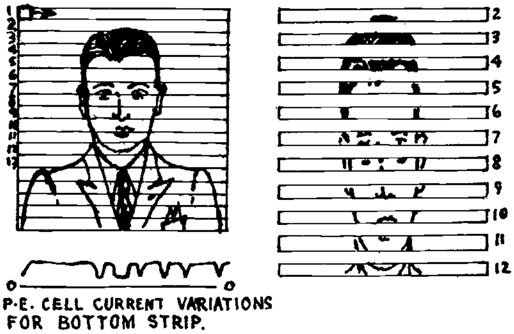


Fig. 448—Strip scanning. The scene is rapidly scanned in very narrow horizontal strips. The variations in the light and shade in each strip are converted into corresponding electrical impulses by the photoelectric cell. These electrical impulses are transmitted. At the receiving station they are re-converted back into varying light intensities which are reconstructed in strips somewhat as shown at the right. This is done rapidly so as to appear as a complete scene to the eye. Of course the strips actually overlap slightly.

590. Transmission frequency band required: Let us see just how wide the frequency band will be for standard 60 lines per frame—20 frames per second scanning, assuming the picture to be but 1-inch square. We will assume that the detail of the picture horizontally, is to be as good as that vertically. The worst possible case would then be when there is a variation in light intensity for every 1/60 of an inch horizontally along a scanned strip. This means that the picture elements are so irregular, that a partial light or dark portion occurs in every 1/60 of an inch along the horizontal strip. There will then be 30 impulses produced during the scanning of a *single strip*, since it takes one complete light variation from light to dark to light through two elements, to correspond to a complete a-c cycle. Therefore, 60×30 or 1800 impulses are produced during a single scanning of the *entire picture*. Since it is completely scanned 20 times every second, there will be $1800 \times 20 = 36,000$ impulses in the photoelectric cell circuit every second for this condition. Building high-gain amplifiers to amplify uniformly a band of frequencies up to 36,000 cycles is no simple task, and the resistance-coupled type amplifier is the only type which can be designed to do this. The lowest frequency of this picture frequency is 20 cycles. The amount of distortion present in transformer-coupled a-f amplifiers, while not serious in ordinary sound broadcasting, makes them absolutely unsuited for television work A special resistance-coupled amplifier which will amplify uniformly all frequencies from 15 to 30,000 cycles is shown at the right of Fig. 438A. This circuit should be studied carefully at this point.

The varying output of the photoelectric cell is amplified and made to modulate the high-frequency carrier current in the usual way. Since each television station transmits a carrier frequency and a rather wide sideband, about 36 kc on each side of the carrier frequency in the case here considered, or a total sideband of 72 kc, television stations have been assigned to transmit on the short waves between 100 and 150 meters in the United States, in order to avoid conjestion. At the present time, each station is allowed a transmission channel of 100 kc. Compare this with the 10 kc channels assigned to sound broadcasting stations. Also, since television signals are transmitted by short waves, the ordinary broadcast band receiver used for sound programs is not suitable for television reception. It is not suitable anyway, because the transformer-coupled audio amplifiers used in these receivers distort entirely too much to permit of their use for amplifying television signals.

591. The scanning disc: To carry out the process of "strip scanning" we have been considering, some form of scanning device for rapidly scanning successive strips of the scene must be employed. Perhaps the simplest and most widely used form of scanning device now used in one form or another by practically all television transmitters and receivers, (excepting those employing the cathode ray principle), is the Nipkow scanning disc, invented in 1884, and shown in its most elementary form at the left of Fig. 449. This is an ordinary circular disc containing a series of small holes (or lenses), arranged in the form of a spiral (or several spirals).

Each of these holes is as far from the following one as the width W of the picture to be reproduced at the scanning disk at the receiving end, so that only one hole is actually scanning the scene at a time. The "pitch" or distance of the center of each hole from the center of the disc, differs from that of the next by the diameter of the hole itself—which is the height of the strip scanned. Round holes are shown in this disc. In practice, it is preferable to make the holes square or rectangular to permit more light to pass through to the photoelectric cell, and the holes are arranged so that the strips they scan, slightly overlap each other. This reduces the tendency to produce "lines" or "streaks" across the received picture where one scanned strip would just meet the one above and below it. As the disc rotates, one hole after another sweeps over the field of view of the scene—each hole scanning a slightly curved strip, as shown in the enlarged section at the right of Fig. 449. Since each hole is nearer to the center of the disc than the preceeding one, it scans a strip next to the one scanned just before it. In this way, the entire scene is scanned completely 20 times every second. The visual slicing up of the scene during the scanning action is indicated in the enlarged view at the right, by the curved lines which represent the boundaries of the strips scanned. The manner in which the photoelectric--cell current

might vary due to the variations of light impressed on it during the scanning of some one strip, is shown below. In the illustration at the right, the picture is scanned in 39 narrow strips (39 lines).

As we shall see later other forms of discs with two or three sets of holes may also be used. Also the disc may take the form of a belt or drum. The cathode ray system of scanning and reproduction is so radically different from the ordinary disc scanning system that it will be considered separately later.

592. Disc scanning methods: There are three methods of using the disc for scanning the scene to be transmitted. These are, *film pickup,*

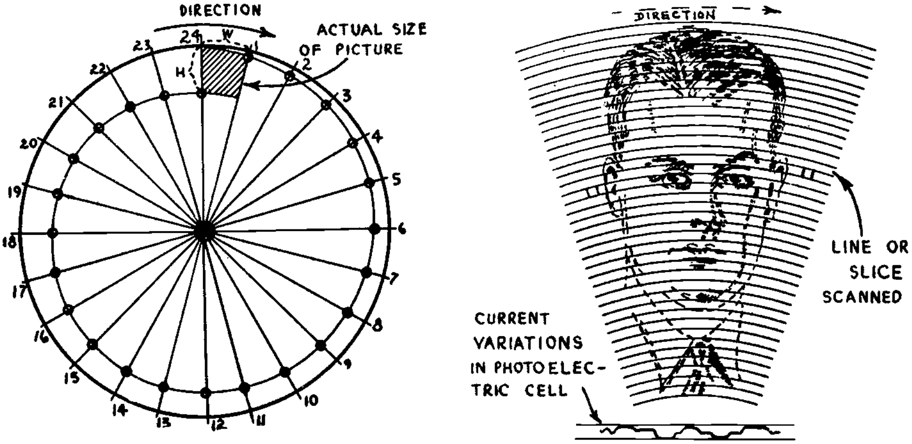


Fig. 449—Left: Layout of the holes in spiral form in a circular 24-line scanning disc. The shaded area represents the size of the reproduced picture at the receiving station.

Right: How a scene is scanned over curved strip paths by a circular scanning disc. This is an enlarged view, and is drawn for 39-line scanning, i.e., there are 39 scanning strips for the entire scene. Every time a black part of the scene is viewed by the photoelectric cell, the cell current drops. The variations in the cell current during the scanning of one particular strip of the picture on the right are shown at the lower right.

direct pickup, and *indirect pickup.* Pickup from a moving picture film has become popular, since the film is taken under ideal conditions and it presents a very small area to be scanned, an area which can be brightly illuminated with much more light than can be comfortably thrown on a person sitting in front of a television camera.

The direct pickup method uses what might be termed a "television camera". It is a scanning arrangement, photoelectric cell and cell amplifier mounted on a strong tripod with a very fast lens picking up the light reflected from the illuminated object to be televised. The rapidly moving holes in the scanning disc allow one pencil or strip of this light at a time to pass through to an ultra-sensitive photoelectric cell mounted behind the disc. The current variations in the photoelectric cell, caused by the light and dark variations in the light projected on it, are transformed into similar voltage variations, and amplified by the amplifier mounted at that point. This builds them up to a sufficient strength to be sent to the radio transmitter itself, where they may be amplified further, and made to modulate the carrier current of the station in the regular way. This system is shown at the left of Fig. 450.

This method is most successful for outdoor work, since there is plenty of light available. For indoor work, however, it requires very intense artificial lighting which is extremely trying on the artists performing before the televisor. The intense heat produced by the battery of lights employed for the floodlighting of the performer is rather uncomfortable.

This problem has led to the development of the indirect pickup method, which is now widely used. This is commonly called the "flying spot" method.

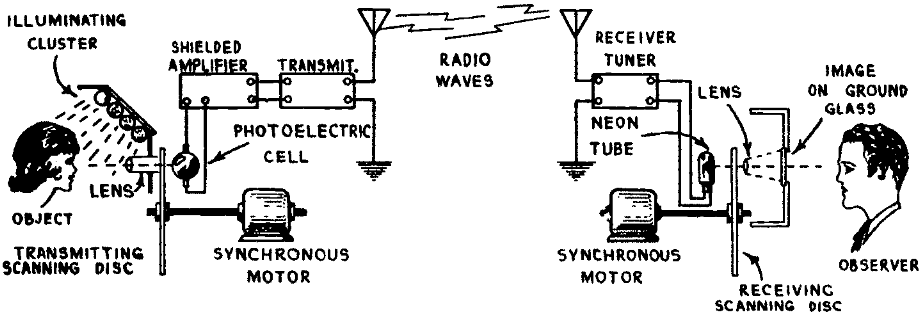


Fig. 450—Television transmitting and receiving system using the scanning disc method. The direct pickup system is used in the transmitter at the left. Light reflected from the strongly illuminated subject is picked up by a suitable lens system and directed through the whirling holes in the scanning disc and focussed on to the sensitive material in the photoelectric cell.

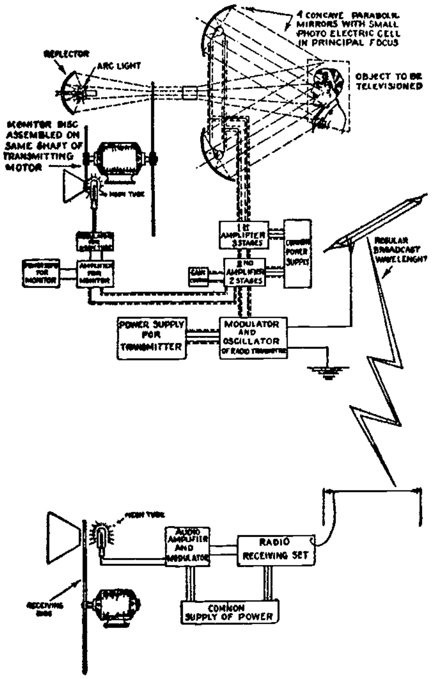
In this system, the scanner comprises a powerful arc lamp fitted with a scanning disc driven by an a-c synchronous motor, and a battery of lenses of different focal lengths so as to provide different sizes of fields. The assembly is mounted on a swivel base similar to that of the usual barber's chair as shown at the left of Fig. 451, so as to permit of aiming the beam at the subject. By swinging any desired lens into posi-

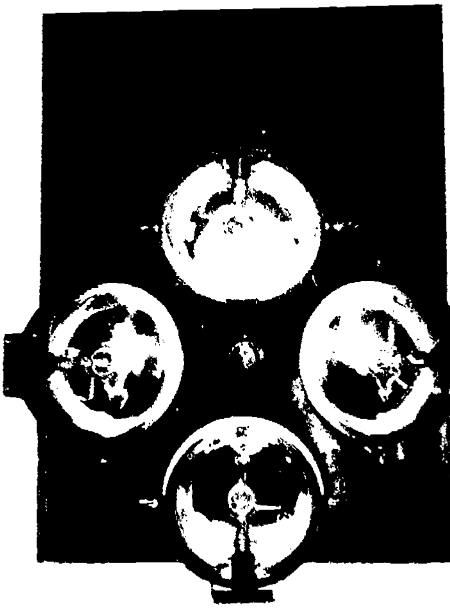
Courtesy The Jenkins Television Corp.

Fig. 451—Left: A flying-spot television camera. Three of the possible five lenses are mounted on the circular scanning disc housing, the desired lens being moved into position by the handle on the outer rim of the housing. The entire camera may be moved vertically by means of the foot pedal on the base. The operator is holding the wheel which tilts the camera vertically.
Right: The interior of a studio from which both sound and television signals are being transmitted. The sound is picked up by the microphone in the foreground. The reflected light from the flying-spot is being picked up by the photoelectric cells in the rectangular metal boxes at the left and right.

tion, through the convenient turret mounting, the scanner can be made to handle close-ups, or half-length and full-length subjects, without moving the relative positions of scanner and subject. The operator stands alongside the scanner which he manipulates during the actual pick-up of a program, following the studio action through a glass window.

When the disc is turned, the light passing through the holes makes successive trips across the subject being televised, so that in one complete turn, every part of the subject has been passed over by a light spot. The subject has been completely scanned. The tiny spot of light that sweeps the subject line by line is reflected in





Courtesy Pilot Radio & Tube Corp.

Fig. 452—Left: Flying-spot transmission system, and the receiver. The reflected light rays from the pencil of light moving across the subject, act on the photoelectric cells. Right: The arrangement of 4 photoelectric cells in the principal focus of the silvered reflector in back of each one, for increased light pickup, for the arrangement at the left.

varying degree, depending on whether it falls on a light or a dark portion of face, body, or clothes. The reflected light is intercepted by a battery of photoelectric cells, generally arranged in two groups placed in front and slightly to each side of the subject as shown at the right of Fig. 451. The photoelectric cells translate the varying light values into corresponding electrical values which, greatly amplified by means of amplifiers placed directly behind the photoelectric cells in the same casing, are sent by wire to the modulator of the transmitter, after passing through the monitoring board. In the control room immediately off the studio and separated from it by glass windows, the control operators follow the pick-up by means of a master radiovisor monitor mounted on the switchboard. Glancing through a peep-hole, the operator sees the television picture exactly as it is being transmitted to the "lookers-in". The degree of gain can be varied so as to provide the necessary brilliancy and contrast in the pictures. Also, by means of the large glass windows looking out into the studio, the control operators can signal the studio announcer about any necessary changes in the placement of subject and equipment. The spots of light sweep over the subject so rapidly that the eye cannot follow them, and the subject really appears to be illuminated by a steady light.

A schematic diagram of a complete transmitting and receiving system of this type is shown at the left of Fig. 452. The light source behind the scanning disc projects a flying spot or pencil of light on to the subject being televised. The light reflected from this subject acts on the photoelectric cells which are here shown placed in the principal focus of parabolic mirrors for greater collection and concentration of the reflected light rays. A photoelectric cell pick-up assembly of this type is shown at the right. A small photoelectric cell is placed at the principal focus of each of the four silvered parabolic reflectors.

593. Synchronized television and sound transmission: In cases where synchronized sound and television programs are transmitted, the studio also includes one or more microphones suitably placed. A studio of this kind is shown at the right of Fig. 451.

The artist is facing the flying spot beam as well as a microphone which may be just beyond the vision of the pick-up apparatus. Inasmuch as the voice or the music, as the case may be, is picked up simultaneously with the accompanying image, and since electricity and radio waves travel with virtually no delay, the two signals remain in step. There is no synchronizing problem in the radio talkies, or combined sight and sound broadcasting. Of course the combination of sight and sound broadcasting calls for two separate and distinct channels, including separate pick-ups, amplifiers, control room equipment, and transmitting stations, for the present at least. Likewise, two separate and distinct receivers are required at the receiving end, one to pick up the sound signals, and the other to pick up the television signals. When the sound accompaniment is handled by the usual broadcast station, a broadcast receiver may be employed in quite the conventional manner. It is only necessary to know what broadcasting station is handling the sound for a given television station. If the sound accompaniment is through a short-wave transmitter, then, obviously, a short-wave receiver is required.

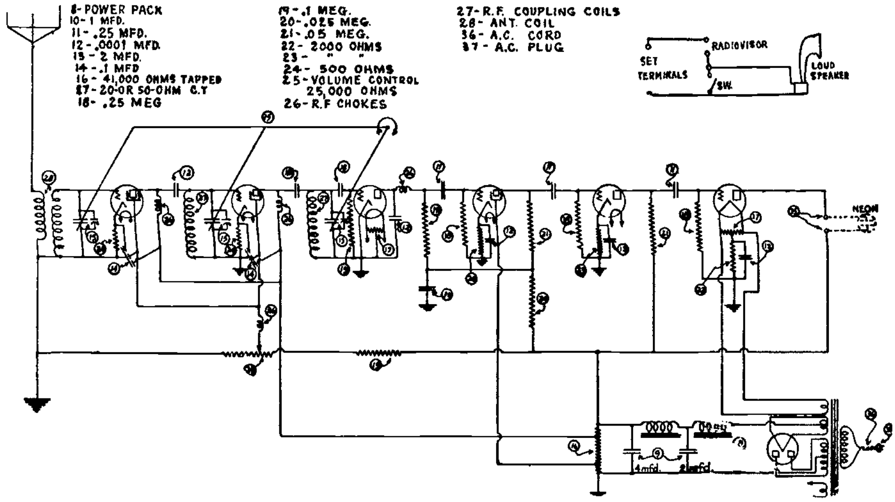
594. General television tuner and amplifier receiving system: At the receiving station, the incoming television signals must be received, tuned from those of other stations, amplified, demodulated and finally led to a device capable of changing the electric impulses back into correspondingly varying pulses of light. Finally these individual varying pulses of light must be rearranged to form the complete picture.

Television transmission is now being conducted with short waves. We found in Article 590 that a wide transmission frequency band is required for present forms of television transmission in which a Nipkow disc is employed. Therefore the television receiver must receive a band of frequencies many thousand cycles wider than the 10 kc band commonly employed in sound broadcasting. This means that the receiver's r-f tuning stages must tune broadly, broad enough to receive about four adjacent broadcast programs at once, if it were used on the broadcast bands. Of course a more selective receiver could be used for television reception, but since the upper sideband frequencies would be suppressed, there would be a sacrifice in the detail of the received picture, when the disc system is used.

The ordinary broadcast band receiver is not suitable for television reception because television transmission is being carried on with short waves from 100 to 150 meters and a short wave receiver is necessary. Even if a short wave adapter or converter is used with the broadcast receiver, reception will not be satisfactory because the audio amplifiers in broadcast band receivers designed for sound programs only, distort far too much for satisfactory amplification of television signals. Furthermore, the sound which accompanies the television is broadcast on the regular broadcast band; so to get both sight and sound two receivers are required, and the regular broadcast receiver is necessary for the sound reception.

The first requirement of a television receiver then, is that it tune to the carrier frequencies or wavelengths on which the television signals are being broadcast (100 to 150 meters in the U. S.), and that it tune fairly broadly. This means that very little or no regeneration can be employed, since regeneration sharpens the tuning so much that sidebands are cut, and objectionable distortion takes place. The sensitivity must be built up by straight radio-frequency amplification.

The second requisite is to have an audio amplifier that will operate satisfactorily over the required wide range of light-impulse frequencies—



Courtesy The Jenkins Television Corp.

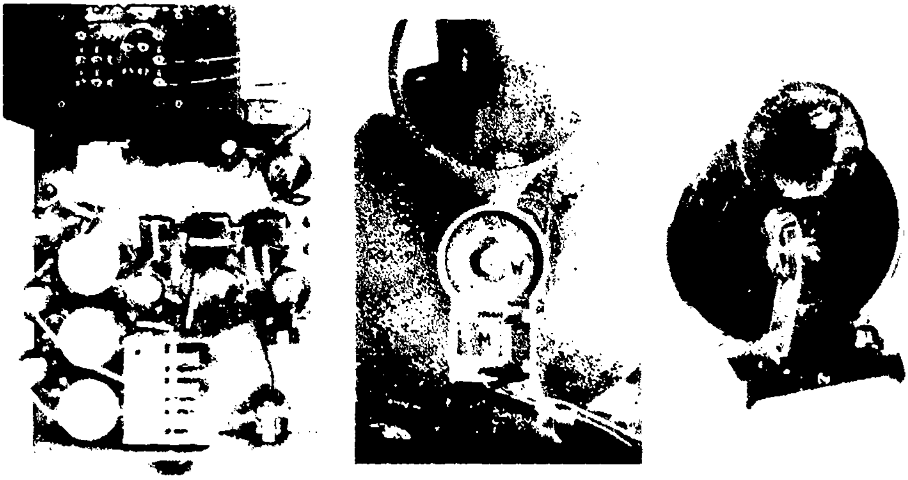
Fig. 453—A complete a-c operated short wave television signal receiver consisting of 2 stages of screen grid t-r-f amplification, detector, and 3 stages of resistance coupled audio amplification designed to produce uniform amplification. For listening to the synchronizing signal, the alternate loud speaker connection at the upper right may be employed. (See left of Fig. 454.)

up to about 43 kc. The lowest light-impulse frequency is determined by the number of scanning holes passing over the object being televised every second. In a standard 60 line per frame—20 frame per second system, this would be equal to the picture frequency—or 20 cycles. The audio amplifier, therefore, must operate over a range of from about 20 to 36,000 cycles (for a 1×1 inch picture). Resistance coupling offers the only practical form of coupling for an audio amplifier which is to amplify this range of frequencies at all uniformly. (See the amplifier circuit at the right of Fig. 438A.)

If "bias" or plate-current detection is used, it is necessary to employ an "even" number of a-f stages and, since four stages would be too unstable, we must make provision for a higher level of output from the detector tube and drop one a-f stage. The reason is, that in passing through a vacuum tube, the signal is shifted in phase by

180 degrees. This corresponds to a complete reversal of the picture—"maximum" light intensity becoming "minimum"—and a "negative" picture results. The audio-frequency component, therefore, must pass through an even number of such reversals, if a positive picture is to result. In "grid-leak" detection the rectification takes place in the grid circuit and one such displacement occurs before the a-f amplifier is reached. With "bias" or "plate circuit" detection this does not occur and, in consequence, we employ an even number of audio-frequency stages.

The output must be powerful enough to operate the neon lamp used to change the electrical pulsations to light variations. The neon lamp must be large enough to give a clear image. A type '45 output tube or larger has been found satisfactory for home use. The circuit diagram



Courtesy The Jenkins Television Corp.

Fig. 454—Left: A top view of the chassis of the receiver whose circuit diagram is shown in Fig. 453.
Center: The "phonic wheel" synchronizer attached to a radiovisor. This depends upon the predominant scanning frequency present in the television signal.
Right: Jenkins stripped televisor with magnifying lens. The driving motor is in the center in front of the disc. The neon tube is just behind the magnifying lens.

of a complete short wave a-c operated television receiver designed especially for the purpose is shown in Fig. 453.

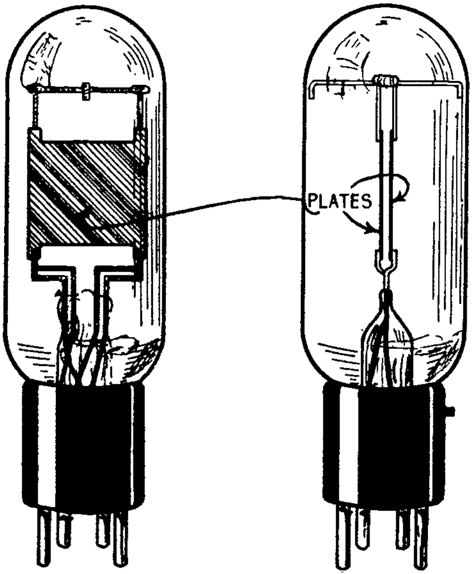
The tuned r-f amplifier consists of two screen grid stages operating with three tuned circuits, using a gang condenser controlled by a single tuning knob. The three tuned circuits serve efficiently to separate the desired station from the unwanted ones, while the two screen-grid r-f tubes provide amplification sufficient to give a good picture signal when the received wave has a field strength as low as 15 microvolts-per-meter. It has been found inadvisable to provide any greater sensitivity than this value, as the background level of static and other electrical disturbances causes distortion to appear in a picture when signals weaker than 15 microvolts-per-meter are received.

The r-f amplifier, while eliminating unwanted stations, amplifies the side-band frequencies as well as the carrier frequencies, and there is no discrimination which would result in loss of picture detail.

The third unit is a simple grid leak and condenser detector, which separates the latent pictorial values from the signal and passes them along to the audio amplifier for further amplification.

The audio amplifier is resistance-capacity coupled, consisting of three stages. The first tube is a screen-grid type, and the second a standard three-element type, both being of the separate-heater type. The third stage is an output stage of the '45 type which delivers power to the neon lamp terminals. Thus it is seen that the general circuit arrangement of a television receiver follows standard sound broadcast receiver practice. However, the values of the coupling resistors, blocking condensers, etc., in the audio amplifier have been selected particularly to produce undistorted amplification over the large band of picture element frequencies (these are audio frequencies) to be received. A top view of the chassis of this receiver is shown at the left of Fig. 454. A push-pull output stage may also be used in television receivers.

595. The radiovisor: The television receiver provides the necessary signal output, but not the desired pictures. It may be compared to a sound broadcast receiver without a loudspeaker. A *radiovisor* or



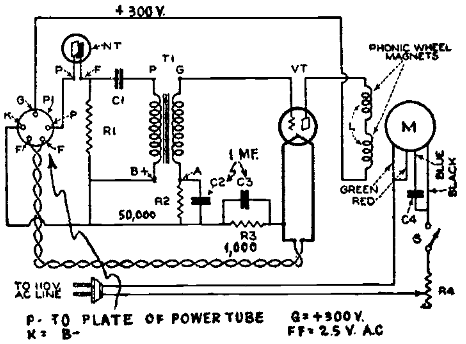


Fig. 455—Left: Front and side views of a neon tube showing the rectangular plates and the gap between them. These connect to the P and the diagonally opposite F prong.

Right: The complete circuit of the synchronization amplifier tube VT and phonic wheel synchronizer magnet coils LL used in the phonic wheel type synchronizer employed in several television receiving systems.

picture-weaving device is necessary. The usual radiovisor comprises a scanning disc, a driving motor, a television neon lamp, perhaps an optical system for enlarging the pictures, and control switches and speed adjustments. A complete radiovisor of this type is shown at the right of Fig. 454.

596. The neon tube: In order to receive television pictures by present methods, there is required a source of light which is capable of changing its brilliancy almost instantly with rapid changes of potential in the receiver. This light reproduces the individual impulses being transmitted, and its position in the circuit is comparable to that of a loud speaker in a broadcast receiver. Up to the present time, the most widely used source of light in radiovisors employing scanning discs, has been the neon tube, although this device leaves much to be desired in the way of an intense light source which will not tire the eyes.

A typical gas-discharge tube of the neon type used in television work is shown at the left of Fig. 455. It consists of two flat metal plate elements insulated and mounted parallel to each other, a small distance apart. The tube is filled with neon gas (the same gas used in the pink glow advertising signs), and may be mounted on a standard 4-prong tube base as shown. One plate connects to the "P" prong and the other connects to the diagonally opposite "F" prong. When a potential difference of sufficient value is applied to the plates the neon gas around the plates become ionized and the plates appear to glow with a pinkish color, the brilliance of the light emitted being proportional to the potential difference between the plates. If a neon tube should be connected to the loud-speaker terminals of a broadcast receiver, it will convert the varying audio-frequency output voltage variations, into corresponding light impulses which are really too fast to be perceived as such by the eye. However, the increase in the light when loud notes are played, is easily seen.

In television, the purpose of the neon tube is to glow with as bright a light as possible but to change its brilliance in accordance with the current through it, or in other words to "modulate" its light as the picture signal is fed to it. The familiar type of incandescent lamp (heated filament) would be entirely unsatisfactory for this purpose as it requires too great a length of time for a change in current to produce a corresponding change in the intensity of the light. The rapid current impulses in television work require that the light-impulse device have no "time-lag." The neon tube meets this requirement perfectly, its light fluctuating rapidly with the incoming signal. It is possible to concentrate the light produced by the neon tube, by adapting a "crater" form for the electrodes. This form has become very popular.

The connection of the neon tube to the output terminals of the television receiver depends upon the type of output tube used in the receiver, and the impedance of the neon tube, for a proper impedance match must be observed for efficient energy transfer and to prevent distortion in the output amplifier tube. In the circuit shown in Fig. 453, the neon tube supplied is designed to be connected directly in the plate circuit of the output tube as shown. If the neon tube has a rather low impedance, say around 1,200 ohms, it should be connected to the output tube by a proper impedance-matching transformer, or by a typical 30 henry choke coil—2 mf. condenser output coupling such as is sometimes employed for loud speakers. Considerable research work is being carried on with light sources of various kinds and it is not at all improbable that an entirely new form of light source will soon be developed to replace the neon tube.

597. The receiver's disc: The neon tube or other television lamp employed, increases and decreases in brilliancy instantly in response to changes in the incoming modulation, growing brighter at the instants when more light reaches the photoelectric cell in the transmitter, and dimmer when the light to the photoelectric cell decreases. In front of the television lamp is a scanning disc *exactly similar* to that used at the transmitter. The observer looks through the rapidly moving holes in the disc, at the neon lamp, as shown at the right of Fig. 450. The transmitting and receiving discs are exactly alike as regards size, shape and layout of the holes. They are driven at exactly the same speed, and are exactly *synchronized*, that is, every hole in one disc is at the same place at each instant as the corresponding hole in the other disc. Each hole in the receiving disc traces a pencil of light *of varying intensity* across the viewing screen. Since these pencils of light traced on the screen, successively one below the other, come so rapidly, the persistence of vision of the observer makes the series of light changes appear to be arranged on the screen in the same order as are the corresponding degrees of illumination on the object being scanned at the transmitter. The rapid changes in the intensity and position of the light-impulses appear to the observer as a picture. If the object moves, the picture at the receiving end appears to move also. In most radiovisors, a magnifying lens is employed to magnify the size of the image produced, although there is a limit to the amount of magnification which can be employed, due to the fact that the imperfections are magnified just as much as the picture. The radiovisor shown at the right of Fig. 454 shows a magnifying lens in place in front of the scanning disc. This enables a 7 inch picture to be reproduced with this particular equipment.

598. Synchronizing the discs: It is evident that successful television requires the lights and shadows produced at the receiver to be in exact step with the lights and shadows affecting the photoelectric cell or other light-sensitive device at the transmitter. If the scanning disc method is employed, it is essential that the disc at the receiver rotate in synchronism with, and at exactly the same speed as that at the transmitter, so that the pictures will correspond in position on the screen at any instant.

In addition to causing the scanning and receiving discs to operate at the same speed, it is also necessary that any spot scanned on the object be reproduced at the receiver screen at exactly the same instant. If the two discs are not in exact synchronism there will be no picture, or only part of a picture. For instance, if the receiving disc were running at the same speed as the transmitting disc, but was one-half revolution ahead of it, then the picture would have dropped halfway down the screen. Slowing up the receiving disc would make the picture rise on the screen. Speeding up the receiving disc would make the image drop further.

The so-called *synchronous* type of a-c electric motor is used to drive the discs, since it maintains its speed constant with the frequency of the current of the a-c line. Most other types of motors are subject to speed variations when the line voltage changes ever so slightly.

In the Jenkins televisor shown in Fig. 454, the driving force for the disc is furnished by a synchronous-type Faraday eddy-current motor comprising four electromagnets acting on a copper disc fastened to the scanning disc which is mounted on a ball-bearing shaft. The details of this are shown in the illustration at the right. Synchronism is obtained by means of a toothed rotor that rotates between a pair of magnets energized by the 60-cycle current. The radiovisor will keep in step only with stations on the same power system. However, due to the close regulation of frequency which is maintained today in most power systems, it is feasible to maintain approximate synchronism on signals from a station outside the power system employed by using a simple manually operated speed control.

Where fully automatic synchronization is desired on signals from stations outside the local power system zone, a simple synchronizing device usually of the *phonic wheel* type is added in some systems. This unit comprises a laminated 60-tooth rotor (for 60 line scanning) which fits on the motor shaft, together with an electromagnet M, fed by the 1200-cycle component filtered out of the intercepted carrier wave. The toothed wheel and electromagnet are shown in the illustration at the center of Fig. 454. The 1200-cycle is a dominant frequency in the common 60-line 20 pictures per second signal ($60 \times 20 = 1200$). The receiver is provided with an additional tube to amplify this 1200-cycle component, which is fed to the magnet windings.

If the speed of the receiving disc is a bit too slow, the pull of the magnets M due to the signal in the output of the extra amplifier tube at the end of each scanning line will pull the disc into step by the action of the magnet poles on the teeth of the toothed wheel W. If, on the other hand, the speed of the disc is inclined to be a bit too fast, the pull of the magnets will act as a magnetic brake which will slow up the speed of the motor sufficiently to keep it in step with the transmitter. A circuit diagram of this simple synchronizing system as used in the Hollis Baird television receivers is shown at the right of Fig. 455. NT is the neon tube in the plate circuit of the receiver output tube, T, is a coupling audio transformer and VT is the amplifier tube for the 1,200 cycle component. M is the motor and L is the phonic wheel magnet.

The number of teeth in the phonic wheel W and the spacing between the poles of the synchronizing magnets is determined by the number of lines being transmitted per picture. For a 48-line picture, a 48-toothed wheel must be used. For a 60-line picture, a 60-toothed wheel is employed. It will be noted that while the usual 60-cycle current is used to keep the radiovisor approximately in step with the intercepted signal, the 1200-cycle synchronizer adds the necessary acceleration or braking effect so as to complete the synchronization. With this automatic synchronizer, it is claimed to be possible to hold the signals from stations several hundred miles distant in perfect step for an entire evening. Other synchronizing systems have been developed, but lack of space prevents including a description of them here.

599. Operating a disc-type television receiver: To tune in pictures with television receivers of the general type shown in Fig. 453 and 454, the receiver switch is snapped on and its dial is tuned to the desired signals. By means of an external loud-speaker which may be connected to the receiver output by the switching arrangement shown at the upper right of Fig. 453, the characteristic buzz-saw signals of the television transmitter are detected and tuned to loudest volume. The switch is then thrown so that the loudspeaker is replaced by the television lamp of the radiovisor. The motor of the radiovisor is then turned on, and the tiny pink spot of the neon tube as seen through the scanning disc, becomes a line, then a number of lines and finally a glowing screen as the scanning disc gets up to step. The screen then becomes spotted with shadows which are at first meaningless but they gradually weave themselves into pictures as the scanning disc attains the synchronous speed.

600. Various types of scanning discs: There are several commercial variations of the simple scanning disc shown in Fig. 449, all de-

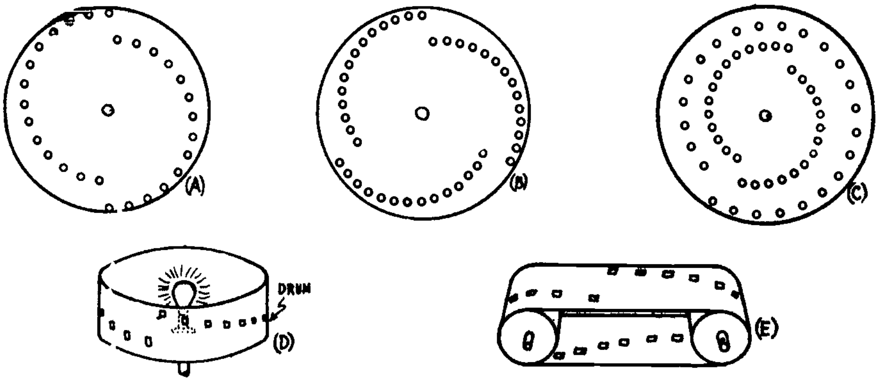


Fig. 456—(A) Flat disc with two sets of scanning holes.
(B) Flat disc with three sets of scanning holes.
(C) Single disc with 2 sets of holes arranged to receive signals from stations employing 2 different numbers of lines per picture.
(D) A scanning drum with the holes arranged in spiral form.
(E) A flexible scanning belt.

signed as improvements over this form. It is possible to arrange the holes in two or more spirals as shown in Fig. 456, with a consequent reduction in the speed at which the disc must rotate.

At (A), the disc has two spirals, each of which completely scans the image. A disc of this kind need only rotate at half the speed required for the single-spiral disc. At (B) is a disc with three spirals, which need rotate at but ⅓ the speed of a disc with one spiral. A single disc may operate with either of two numbers of lines per frame, if built as at (C), with the holes for one number on a single spiral all the way around the disc and holes for a smaller number of lines arranged in two spirals, each extending half way around the disc.

In addition to the flat discs which have been illustrated, others made in the form of a drum with the holes spirally arranged in the circumference and with the source of light at the center, are shown at (D). A drum scanner is used both in the Hollis Baird receiving systems and in some models of the Jenkins system, on account of their compactness. A travelling belt as shown at (E), with holes arranged spirally has also been used for scanning.

Other interesting scanning systems have been developed; notably that developed by Dr. Alexanderson, in which a Karolus or Kerr cell is used to change the plane of polarization of the light beam going through it by means of an electrostatic field produced by very high voltage; that of John L. Baird, which uses a radially slotted disc in combination with a spirally slotted disc and cellular tubes; and that of Jenkins, in which lenses are used in the disc instead of holes, and the direction of the scanning light rays are directed up and down vertically by the action of a prismatic disc. However, in each case the resultant action of scanning is substantially the same as has been described for the simple disc.

601. The mechanical vs. the cathode-ray television systems: The television systems thus far described make use of mechanical parts which are moved for the control of light beams. These parts have weight and therefore have corresponding inertia and momentum which of course limits the speed of the actions in which they take part. Also, in the systems in which scanning discs are employed, the problem of getting sufficient light through the rapidly moving holes in the disc has been a very important one. If the holes are made small so as to obtain good picture detail, the light passing through is very limited. If they are made large to allow more light to pass through, the picture detail diminishes. Also a wide frequency band is required for transmission if good picture detail is required.

Two schools of television are assuming form out of the various lines of experimental work which have been pursued in this art during the last few years. These are, that in which *mechanical scanning* is employed and that employing *electrical scanning*. The scanning disc or drum is the heart of the mechanical system, while the scanning in the electrical system is accomplished by means of the *cathode-ray* tube.

602. The cathode-ray tube: The general form of cathode-ray tube used for oscillographs and in the cathode-ray television system, contains three essential parts; a thin "stream" or "pencil" of electrons travelling at very high velocity, a fluorescent "target" or luminous screen for these electrons to strike against, and some mechanism for "deflecting" the path of the electron pencil in any direction. The illustrations in Figs. 456B and 457 show two common simple forms of this type of tube used in commercial electrical work. The tube shown at (B) of Fig. 458 shows a special form designed by Farnsworth for use in his cathode-ray television system. We will first proceed with a study of the principle of the operation of the general form of cathode-ray tube, shown in Figs. 456A, 456B, and 457.

The unit consists of an elongated glass tube with a flat end as shown, from which all the air has been thoroughly pumped out. At one end is a heated filament or cathode of coated tungsten (C at left of Fig. 456A), which emits a liberal stream of electrons, precisely as electrons are liberated by the hot cathode of the ordinary form of vacuum tube used in radio receivers. Near this cathode is a metal plate P which is maintained at a "positive" potential with respect to the cathode so that it will attract the emitted electrons strongly toward it at high velocity. In the center of this plate is a fine hole as shown. Many of these electrons moving at very high velocity toward the plate, will pass right through this fine hole and continue on their way as a thin pencil of electrons moving at high velocity (a *cathode ray*), down the entire length of the tube. This may be compared to a ray of sunshine entering a room through a small hole in a window shutter.

At the inside of the flattened end S of the tube, is a screen or "target" of fluorescent materials (zinc silicate in the form of the powdered mineral "willemite" is often used, sometimes in combination with calcium tungstate), which shines brightly at the point where the cathode ray or stream of electrons strikes it. Thus, the point where the ray strikes the screen is made visible by a bright spot of light. This is shown in the view at the left of Fig. 456A.

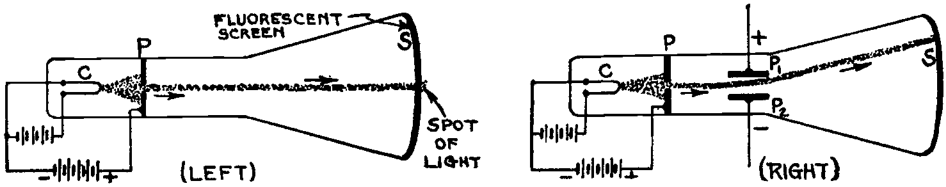
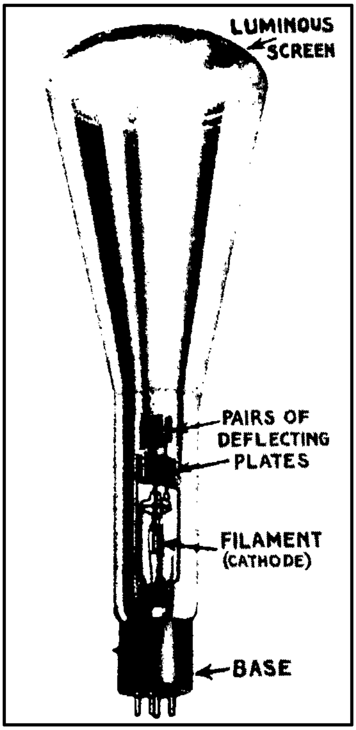


Fig. 456A—Left: A simple cathode-ray tube in which the electrons emitted from the heated filament C are attracted by the positive plate P and shot through a hole through its center. They travel to the fluorescent screen S which they strike against and produce light.
Right: In this cathode ray tube, two deflecting plates P_1 and P_2 have been added. (See Fig. 456B)

The stream of electrons can be deflected from its straight path by either an *electrostatic* field or a *magnetic* field. If the former method is to be employed, another pair of electrodes in the form of two plates P_1 and P_2 is introduced into the neck of the tube as shown in the view at the right of Fig. 456A, so that the stream of electrons passes through the space between them. If now, any voltage or difference of potential is applied between the plates, so that one is made "positive" with respect to the other, the electrons of the ray, being negative charges, will be drawn toward the positive plate during their passage between the plates. (The electrons are not actually attracted sufficiently to make them actually go to the positive plate.) The result of this deflection is that the electron pencil or stream is bent as shown at (B) so that it strikes the screen at a different spot. If the stream is deflected from the position shown at the left to that at the right by the application of an increasing positive potential on one of the plates, the spot of light will trace a line along the screen. Similarly, a magnetic field applied by a magnet or a coil of wire could be employed to deflect the electron stream. A cathode-ray tube with deflecting coils is shown at the left of Fig. 457. The amount of deflection of the stream and spot of light depends upon the strength of the applied electrostatic or magnetic field. Furthermore, since the electron stream is almost without mass and sluggishness, it can follow even very rapid variations in the applied field. This makes it useful in television work where it is made to move in accordance with the rapid impulses comprising the television signal.

The simple tube shown at the left and right of Fig. 456A provides a means for deflecting the spot of light in one direction or another (depending on which of the plates is made "positive"), along a straight line. By introducing another pair of parallel plates placed at right angles to the first pair, and so that the electron stream can pass between both, as shown clearly in the actual tube illustrated in Fig. 456B, it is possible to deflect the spot of light in a direction at right angles to the deflection produced by the first pair of plates. Now if suitable individually-varying potentials are applied to both pairs of plates simultaneously, the electron stream may be deflected in any desired direction. The spot of light will travel over the surface of the fluorescent plate, tracing figures of various shapes, depending on the particular variations of these potentials. If one points the lighted bulb of a small pocket flashlight toward his eyes and rapidly moves the flashlight so as to describe various figures, he will have some idea of the movements of the spot of light in the cathode-ray tube.

It is evident, that by applying deflecting impulses of proper frequency and intensity, the spot of light may be made to deflect in any direction across the surface of the screen. For instance one pair of plates can be made to deflect the spot back and forth "across" the screen thus tracing "lines of light," while the other set can be made to alter the position of each line with respect to the next, thus imitating the successive "line" of "strip-scanning" action obtained by means of the common mechanical scanning disc described in Arts. 588 to 592. In this way, images may be traced out by the moving spot of light if proper signal voltages are applied to the two sets of plates. The "lights" and "shadows" in the images thus created, may be produced by properly varying the luminous intensity of the fluorescent spot of light. This luminosity may be controlled by the electron stream density—which may be varied at will by rapidly varying the potential of the plate P having the hole in it, thus varying the attractive force tending to make the electrons move toward the plate. This of course varies the number which reach it, shoot through the hole, and finally reach the screen, to produce light.

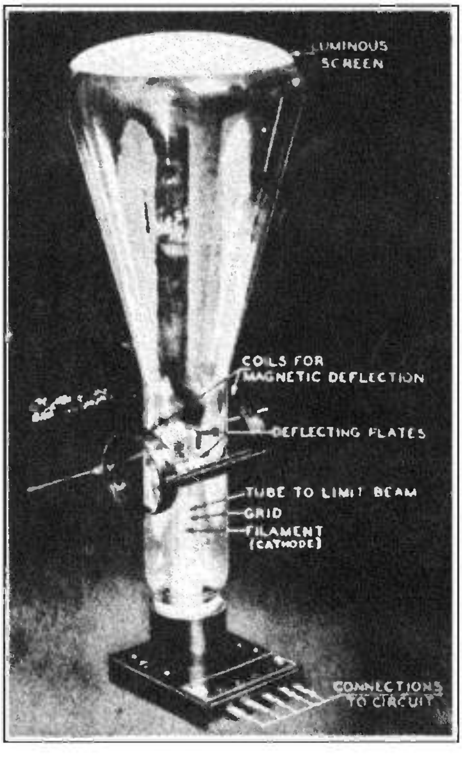


Courtesy Bell Telephone Labs.

Fig. 456B—A cathode ray tube of the form shown in Fig. 456A. This tube has two pairs of deflecting plates. Each pair is mounted at right angles to the others.

The reader will perhaps realize now why the cathode-ray tube has been looked to as the means for solving the problem of eliminating mechanical scanning discs in the television system. The television signals are applied to the electrodes on the tube in the proper manner so as to cause the correct movement and variation in the brilliance of the spot of light which traces out the images to be received, much the same as a scanning disc does. Of course there are obstacles which must be overcome before this system can be reduced to a practical workable basis. The size of the image is limited to a great extent by the actual practical dimensions of the luminous surface in the tube and the practical amount of deflection of the electron stream which can be produced. Magnifying lenses can be used to magnify the image of course, but there is a limit to this imposed by the fact that the imperfections are also magnified. The "detail" of the image is dependent on how tiny a spot of bright luminosity can be created on the surface, for this determines the number of "lines" per inch. Another obstacle to be overcome, is the fact that present forms of cathode-ray tubes require rather high plate voltage to produce satisfactory operation and images of sufficient brightness to be seen at a distance in daylight. However, it is hoped that these obstacles will be overcome shortly. While the simple type of cathode-ray tube described here is modified somewhat when used for television, the operating principles involved are similar. A special form of tube construction which has been developed for television work will now be studied.

603. The Farnsworth cathode-ray system: A cathode-ray television system which contains many features which indicate that it may be



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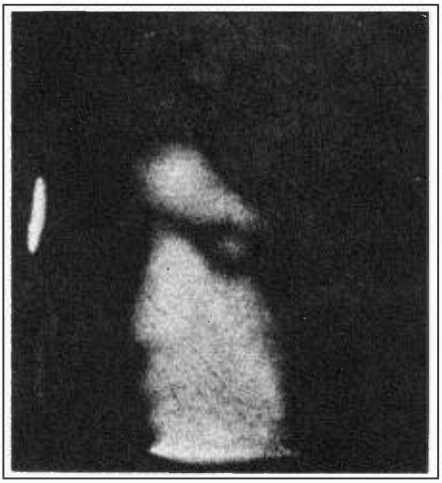


Courtesy Radio News Magazine

Fig. 457—Left: A cathode-ray tube with deflecting plates inside, and magnetic coils outside to control the movement of the electron pencil as it writes on the luminous screen at the end of the tube.

Right: Unretouched photograph of a television image of 20,000 elements, transmitted by the Farnsworth television system. The screen effect shown here is the result of the half-tone process and did not appear in the original photographic print.

developed into a successful commercial form, has been developed by Mr. Philo J. Farnsworth. In this system, the scene at the transmitter is scanned with a cathode-ray beam, no disks or other moving mechanical parts being used. A cathode-ray beam is also used to re-construct the picture at the receiver. The cathode-ray in the receiving tube and that in the transmitter are kept in exact step by means of a control current which is transmitted along with the currents which reproduce the moving picture. It is claimed that a 400-line picture can be transmitted in a 10 kc channel by this system. Compare this with the 36 kc channel required for 60-line, 20 picture transmission by the disc scanning method. A reproduction of an unretouched photograph of an image transmitted by means of cathode rays over the Farnsworth system is shown at the right of Fig. 457. The screen effect shown here is the result of the half-tone process and did not appear in the photographic print from which this illustration was made.

The author is indebted to Mr. A. H. Halloran and to the editors of Radio News Magazine for permission to reprint the illustrations and description of a specialized limited case which has been set up to facilitate an explanation of this system. While it does not define the entire procedure of the Farnsworth system, for exact details are not available at this writing, it does give some idea of the system.

A simplified circuit diagram of the system is shown at (A) of Fig. 458. "An optical image of a moving object 5 is focused through a lens 3 on to a silvered mirror

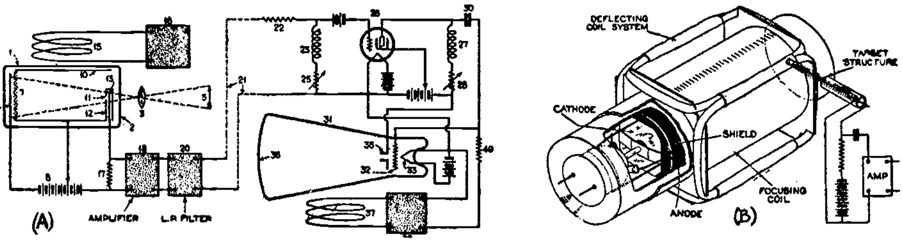


Fig. 458—(A) The simplified schematic layout of the Farnsworth system for narrow-band transmission of moving television pictures. The portion to the left of the dotted connecting lines is the transmitter, while the receiver is to the right.
(B) A perspective view of the "Dissector Tube" employed in this system, showing the design details.

6, this being coated with a material which emits electrons when exposed to light. These parts constitute a sensitive photo-cell of a vacuum type, enclosed in a cylindrical glass tube 1. The mirror 6 is the cathode. Closely adjacent and parallel to it is an anode 7, which is maintained 500-volts positive with reference to 6, by means of a direct-current source 8. The anode consists of a finely-woven wire cloth through whose interstices the liberated electrons are projected into the equi-potential space formed by the shield 10.

Sweeping across the equi-potential space are two electromagnetic fields which are set up by a-c of "saw-tooth" wave-form flowing in two sets of coils placed at right angles around the tube. When one set of coils, diagrammatically represented by 15, is supplied with a 16-cycle current from an oscillator 16, it causes a magnetic field to sweep vertically across the tube 16 times per second. When the other set of coils, which is not shown in the diagram but which can be seen in the perspective view at (B) is supplied with a 3000-cycle current, a magnetic field sweeps horizontally across the tube 3000 times per second. Their resultant effect upon the electrons in the equi-potential space is to form them into a cathode ray image which successively issues from each tiny element of picture area. This cathode ray is then magnetically focused through the small aperture 11 onto the target or electron collector 13.

Hereon is produced a random series of electrical pulses, each having a square front wave $(200)^2 \times 16 \div 2 = 320{,}000$ cycles in width. Each pulse corresponds to an instantaneous change in light intensity in each element of area which is successively scanned by the cathode ray. The variations in light intensity are thus converted into corresponding variations in current intensity. These current pulses are passed through a 5-stage admittance-neutralized amplifier (18) which is capable of passing a 600-kilocycle wave-band, with a practically straight frequency characteristic..

Neglecting for the moment the filter 20 and the intervening network 21-40, and assuming that a 320-kilocycle distortionless channel were available to transmit the amplified current through the receiver, let us see what happens. The receiver is another cathode-ray tube through which sweep two sets of magnetic fields, one vertically and the other horizontally. The currents to establish these fields are 16-cycle and 3000-cycle "saw-tooth" components of the 320-kilocycle band. Because of their peculiar shape they are readily extracted from among the other frequencies and are used to locally generate or amplify, through oscillators 38, sufficient current to induce the required magnetic fields which cause a cathode ray to sweep across a fluorescent screen 36, thus reproducing a moving picture in exact synchronism with the original moving object 5.

In this vacuum tube, or oscillator, the electron-emitting element is a hot filament 33. The emitted electrons are attracted to and projected through the aperture of a plate 35, the number of projected electrons being controlled by the current pulses on the grid 32. The intensity of these current pulses, it will be remembered, depends upon the intensity of the light which initiates them. Consequently as they emerge from the plate into the space through which the two magnetic fields are sweeping, they are formed into a cathode ray which rapidly scans the area of the fluorescent screen 36, thereby forming the moving picture.

But our assumption of a 320-kilocycle distortionless channel is not justified for either radio or wire transmission. In the entire 960-kilocycle spectrum used by American broadcasters of speech and music, there are only three such channels possible. So the greatest problem in television, and the one which Mr. Farnsworth is probably the first to solve in a practical manner, is how to utilize a narrow channel for the production of a moving picture which has sufficient clearness and detail.

The manner in which he accomplishes this seemingly impossible feat is an interesting story in itself, entirely aside from his remarkable success with the cathode-ray tube. His work is based upon a painstaking study of the Fourier integral theorem, one of the most complex and baffling of all mathematical conceptions. In his study of this theorem he discovered an error and in its correction realized the possibility of suppressing all frequencies beyond the limits of a very narrow band, and then to supply the missing frequencies from derived components of the distorted pulse which is received.

As it would take an accomplished mathematician to understand Mr. Farnsworth's analysis, no attempt will be made to present it here mathematically. Yet it is possible to give an interpretation which can be understood by any student familiar with trigonometry.

Mr. Farnsworth starts with the fact that the abrupt changes in light intensity during the scanning of a picture cause corresponding abrupt changes in the pulses of electric current into which the picture is converted by the scanning process. Each signal wave is characterized by an abrupt square front which suddenly increases from zero to a maximum value, or likewise suddenly decreases from a maximum to zero, in an instant of time. These are the changes that correspond to an instantaneous change from black to white, or vice versa, in a picture. For less intense changes in light intensity, there are less intense changes in current. But always each change is characterized by a vertical wave-front.

But the straight wave-front becomes distorted in the electrical system and also in the transmitter aperture, so that the pulse which arrives at the receiver has a sloping wave-front. It causes a badly blurred picture. Only by filling in the gap of missing frequencies can the oblique front be changed to a vertical front and the blurred picture converted into one whose details are clear and distinct.

This filling-in can be done in various ways. The general idea can be understood by considering one method which happens to be applicable to the wire transmission of a moving picture. This method uses a low-pass filter in the transmitter, as shown at 20. Incidentally it is of interest to know that a band-pass filter, calculated to pass frequencies in the neighborhood of 2100 kilocycles, would enable the pulses to be radiated directly, without the necessity of modulating a separate carrier.

Connected in series with the line is a resistor 22 which feeds a shunt circuit consisting of an inductance 23 and a variable resistor 25. The resistive impedance of 22 is of sufficiently high value to control the current independently of the effect of the inductive impedance 23. The flow of current I through 25 causes a voltage drop e = IR and through inductance 23 a voltage drop e′ which is proportional to the rate of change of current I. It thus becomes the first derivative of I.

The sum of the two voltages e + e′ is impressed upon the grid of a vacuum tube which has a high output resistance. Its plate current, which is an amplification of I and I′, in flowing through resistor 28 causes a voltage drop e″ which is proportional to I and I′. The same currents in inductance 27 cause a voltage drop proportional to their rates of change, thus producing the differentiated currents I′ and I″, which are fed into the condenser 30 which stores or integrates the pulses fed to it, converting part of the second derivative back to the first derivative and part of the first back to the fundamental.

The pulses which are fed to the grid 32 control the intensity of the cathode ray which creates the picture, as already explained. Resistors 25 and 28 are variable, so that the values of the several components can be adjusted until the picture has the best appearance.

It should be remembered that this example merely defines one case of Mr. Farnsworth's invention. His entire idea cannot be fully understood without greater recourse to mathematics than is here possible. But it is hoped that this qualitative analysis of how the warp and woof of the moving picture is first formed by a cathode ray, then cut into a mere scrap of the original, and finally patched so as to reproduce the original pattern, may pave the way for an understanding of the quantitative analysis that will probably be available as soon as the transmitted pictures are ready for reception in the home."

604. Future of television: Present methods for transmission and reception of scenes are by no means perfect. They have very definite limitations, and it is entirely possible that practical television of the future will operate on entirely different principles. The cathode-ray system is practically the only radically new system which has been developed along lines totally different from those already in use. At the time of this writing, the merits of this system have not yet been proved on a commercial basis, and construction and operation data are lacking, only meagre details filtering out from the laboratories in which it is being developed and perfected. Obviously no definite opinions can yet be formed regarding it. It does possess many interesting and unusual features however, and something may come of it.

The circuits and equipment shown in this chapter were included to give the reader an insight into how the television transmission and receiving problem is being attacked and worked out. It is probable that if commercial television ever becomes a practical reality and is perfected to the point where it has entertainment and educational value, the apparatus used may differ in design or even in principle from that described. Although some of the most able scientists in the world are working on the problem, the difficulties involved in making television really practical are tremendous. However, we should not be too pessimistic about the outcome, for in this day of invention and research, the impossibility of yesterday becomes the actual reality of today. Many workers have directed their research to the possibility of transmitting the television programs over the existing telephone or electric light circuit wires in the large cities, rather than attempt to transmit by radio. In this way wide transmission frequency channels could be employed. Just what possibilities this method has to offer still remains to be seen.

REVIEW QUESTIONS

1. What is meant by the term television?
2. What is meant by persistence of vision? How is this utilized in the motion picture; in television? Describe a simple experiment which illustrates persistence of vision.
3. Describe in detail, the principles involved in scanning a scene at the transmitting station by means of a scanning disc. Make all drawings necessary to illustrate your description.
4. Repeat question 3 for the disc in the receiving station.
5. A television system is to be designed to transmit pictures using 48 line—15 frame pictures, 1 inch by 1 inch in size. (a) what must be the speed of rotation of the scanning disc; (b) what audio-frequency range must the receiver handle; (c) draw a sketch showing the layout of the holes on the scanning disc.
6. What is the purpose of the photoelectric cell in television systems?
7. Draw a circuit diagram of a two stage resistance-capacity coupled amplifier for amplifying the output of a photoelectric cell used in a television transmitter.
8. What is the purpose of the neon tube? Explain how it operates.
9. Why are resistance-coupled a-f amplifiers used almost exclusively, in television work?
10. Explain what form of distortion makes a transformer-coupled a-f amplifier unsuited for television work?
11. Why can more distortion be allowed in the a-f amplifiers used in sound amplifier systems, than in television systems?
12. What are the advantages of short wave transmission for television signals?
13. Draw sketches showing three different arrangements of the holes in the scanning discs. What are the advantages of each?
14. State and explain the general advantages which the cathode-ray type of television system has over the type with mechanical scanning discs, etc.
15. State several practical limitations of mechanical scanning disc arrangements.
16. What effect would "static" disturbances due to local electrical interference, thunderstorms, etc., have on the received picture in a television system?
17. Draw the necessary sketches and explain the operation of an ordinary form of cathode-ray tube.
18. Explain in a general way just what purpose a cathode-ray tube can be used to serve in a television system. What are some of its desirable features for this work?

CHAPTER 34

THE ANTENNA AND GROUND

THE ANTENNA SYSTEM — WHY THE ANTENNA IS USED — TYPES OF ANTENNAS — THE RECEIVING ANTENNA INSTALLATION — ANTENNA LENGTH — AERIAL WIRE — ERECTING AND INSULATING THE AERIAL WIRES — THE LEAD-IN WIRE — SHIELDED LEAD-IN — ENTERING THE BUILDING — THE GROUND CONNECTION — THE LIGHTNING ARRESTER — LIGHT SOCKET AND INDOOR ANTENNAS — COUNTERPOISE GROUND — SCREEN ANTENNAS — LOOP ANTENNAS — REVIEW QUESTIONS.

605. The antenna system: Before proceeding with a study of antennas, it would be well to briefly review a few points regarding the terms used in antenna circuit nomenclature.

Considering the usual flat-top types of antennas used for receiving, it has become somewhat common for the layman to use the terms *antenna* and *aerial* interchangeably. Accurately speaking, the top or elevated portion of the antenna is the *aerial*; and that portion which completes the electrical connection between the elevated aerial portion and the receiving instruments, is the *lead-in* wire. The *antenna* is the entire system, consisting of the aerial and lead-in wires. The *ground* really constitutes the earth itself, (or a counterpoise ground system), and the wire connecting the receiving instruments with the earth (see Fig. 177). The latter is sometimes called the *ground wire* or *ground lead.*

606. Why the antenna is used: At the radio transmitting station, the antenna system is used to create the electromagnetic radiations popularly known as "radio waves", which travel out into space. Therefore transmitting antenna systems are designed so that a maximum amount of useful radiation is produced by a given expenditure of electrical power in them. At the receiving station, the function of the antenna system is to act as circuit in which the passing electromagnetic radiations from the transmitting stations may induce signal voltages which are as strong as possible. These signal voltages cause corresponding high-frequency alternating signal currents to flow up and down through the circuit between the aerial wire and the ground, which really form the plates of a large condenser (see Figs. 177 and 179).

The resistance of this path through which the signal current must circulate, should be kept as low as possible so that a maximum amount of current will flow, and act on the receiver circuit. This means that all antenna and ground circuit connections should be well made so as to have as low a resistance as possible. Since the action of the transmitting antenna in producing radiations was explained in detail in Chapter 15, and the action of the receiving antenna was explained in detail in Arts. 243, 244 and 247, this will not be considered again here. The reader is urged to review this work briefly at this time to refresh his memory on these points. It will be remembered that the antenna circuit really forms a condenser circuit.

The arbitrarily selected *standard antenna* which is used in radio receiver sensitivity tests and measurements is an antenna of 4 meters effective height, 25 ohms resistance, 200 micro-microfarads capacitance and 20 microhenries inductance. Such an antenna may be easily constructed artificially for test purposes, (except as to height), by connecting the proper values of inductance, resistance and capacitance together.

607. Types of antennas: Many forms of antennas have been devised for transmitting and receiving, each form having a particular

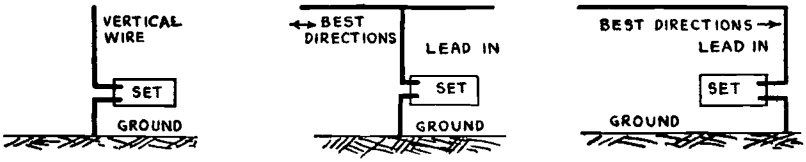


Fig. 460—Left: A vertical antenna.
Center: A T-type antenna with a horizontal top portion.
Right: An inverted L type antenna. This type is used extensively for receiving.

characteristic desirable for some special operating condition. Perhaps the most unusual form is the short doublet type with reflectors shown in Fig. 434, and used in the transmission and reception of quasi-optical rays. The more common forms of antennas used for broadcast-band and ordinary short wave transmission and reception will now be considered.

Fig. 460 shows three common simple forms of antennas. At the left is a simple *vertical wire* type, which transmits and receives equally well in all directions. In the center is a *T-type* antenna. This consists of a vertical lead-in wire attached to the horizontal aerial wire at its center point. Antennas of this type transmit or receive best in the line of direction of the horizontal portion, and equally well in both directions along this line. At the right is an *inverted-L* antenna commonly used for reception on account of the convenience of erecting it, as we shall see. It transmits best from the direction of the lead-in end. For ordinary broadcast band reception, it receives slightly better from the direction of the lead-in, but for short wave reception this directional effect is rather marked especially on some frequencies. This property may be taken advantage of for receiving the signals strongly from stations in some particular direction, by properly laying out the receiving antenna's direction.

A *horizontal-V* type antenna is shown at the left of Fig. 461. This is also used quite extensively for receiving. It transmits and receives best in the direction in which the V points. To the right of this is the *umbrella* type antenna. Since this type has a number of conducting paths in parallel, it has a very low resistance, and it transmits equally well in all directions. It is used somewhat for transmitting, but its rather complicated structure has limited its use for receiving.

Two types of *loop* or *coil* antennas are shown next. The one at the left is a *flat* or *pancake* loop consisting of a number of turns of wire wound in the form of a flat spiral coil and supported on a framework (not shown). The *box type* loop has the wires wound in the form of a rectangular box.

The loop type of antenna is commonly used without a ground connection, since it operates entirely by the inductive action of the electromagnetic fields cutting across the wires of the loop, much the same as the action of the armature wires in an electric generator. Loop antennas are constructed from about 1 ft. square, to loops of large size, perhaps to 10 or 15 feet square depending on the space available. Their signal pickup is rather small, and they are used mainly on account of their sharp directional property of transmitting or receiving best from the two directions along the line of the plane of the loop, and practically zero along the line of direction at right angles to this plane. This makes them extremely useful for radio beacon work, (see Art. 539), for electrical interference locators, for radio direction-finding systems, etc.

608. The receiving-antenna installation: Modern radio receivers are being constructed so sensitive, (i.e. provide so much amplification), that in most cases only a very small antenna system consisting perhaps of 10 or 20 feet of wire strung around the picture molding or baseboard of the room in which the receiver is installed, is required for good local-station reception. However, in many locations it is desirable to erect a larger outdoor antenna in which rather strong signal voltages and currents will be set up.

Any attempts to set down definite, detailed rules for the erection of a receiving antenna would be foolish, since the environment of practically every antenna installation presents different conditions which require

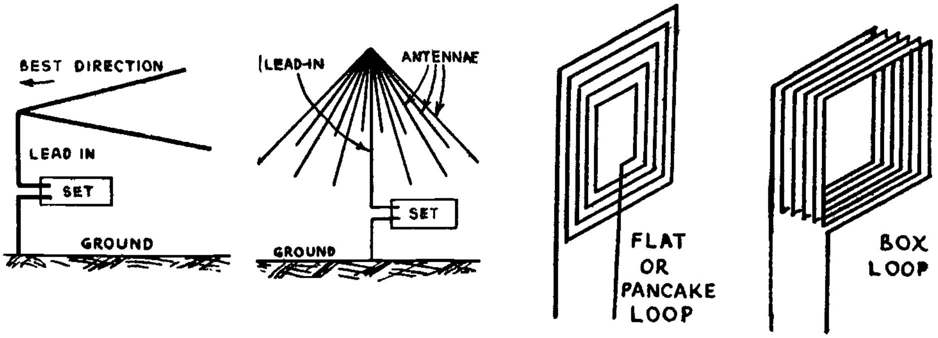


Fig. 461—Left to right; Horizontal V-type; Umbrella type; flat or pancake loop; and box type loop antenna.

that the antenna be designed and erected to conform with them. Thus, it is perfectly easy to specify that an antenna should be erected say 100 feet high and made 100 feet long, but it may not be possible to do this in many installations simply because the surrounding layout of buildings, trees, etc. may not permit it. In crowded locations, such as in city apartment house districts where one encounters countless difficulties in the presence of numerous other antennas, and finds no convenient support for the contemplated one, the best judgment must be exercised. All we can do is study some of the *general* guiding principles which apply to the installation of antennas in most cases.

609. Antenna length: The amount of energy that reaches the average receiving antenna is too small to be measured directly by any practical instrument. The voltages induced in antenna systems are so small that they are usually measured in microvolts (millionths of a volt) (see Art. 228, 347 and 348). Of course the voltage induced by any one station depends not only on the receiving antenna system but also on the power employed by the transmitting station, its distance away, and the transmission conditions. With modern receivers, excellent reception may be obtained with voltages as low as 100 microvolts (.0001 volts) induced in a good antenna circuit.

If we assume that the average height of an outside aerial is about 30 or 40 feet, a total length of wire not exceeding about 60 to 75 feet is all that is necessary or desirable for ordinary broadcast-band reception. In these days of high-power transmitting stations, an aerial of these dimensions provides ample signal pick up in most cases, and much shorter aerials may very often be used. If the antenna system is made too long, the received energy is greater, but since the antenna picks up the signals of the unwanted stations as well as those of the wanted stations, lengthening it may make the unwanted station signals so strong that it may be difficult to tune them out, i.e., the selectivity decreases. For short wave reception a shorter antenna system having a total length of from about 20 to 40 feet is usually suitable.

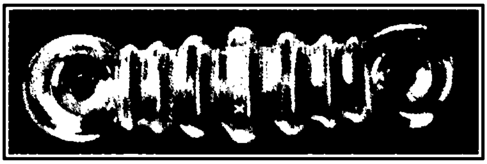
610. Aerial wire: The resistance of the entire antenna and ground system should be kept as low as possible. Number 12 or 14 gauge copper wire is best for *aerial* wire, as it has good conductivity, joints in it can easily be soldered, and it is mechanically strong. Due to some "skin effect", especially at high frequencies, the oscillating currents set up in the antenna circuit may travel along the surface of the wire (see Fig. 291). Therefore, the greatest possible surface should be offered for the flow of current. A wire consisting of 7 twisted strands of No. 22 gauge copper wire offers a larger surface than a single strand of approximately equal cross-section area. For this reason, 7/22 wire, as this stranded wire is called, is used extensively for receiving aerials. It also has great tensile strength. Fancy forms of wire are not necessary. Owing to the rapid oxidation of the wire, which occurs in the smoky atmosphere of cities, the use of *enameled covered* 7/22 wire is often advised but is not really essential. As we shall see, it is very convenient to make the aerial and lead-in of a single piece of wire. Antenna wire is sold in convenient 100-foot rolls for this purpose, (see Fig. 462).

611. Erecting and insulating the aerial wire: The aerial wire should be erected as far away from nearby electric light or power wires as possible. If it is practical, it should be run in a direction at right angles from such wires, also those of any nearby trolley lines, electric railroads, etc., from which electrical disturbances might be picked up. In this case the lead-in should be taken off the end of the aerial *furthest* from the source of the disturbance.

The antenna system should also be kept away from large metallic roofs, metal gutters or leaders, steel framework or metal lath of buildings, large trees, etc., since these grounded objects absorb the radio energy and leave little for the antenna. If it is found necessary to run any part of the antenna system over a metal roof, it should be kept at least 8 or 10 feet above it. The aerial wire must be supported at each end. It may be supported by metal or wooden masts, chimneys, trees, etc., but in every case it should be insulated from the supporting objects at each end by suitable insulators, to prevent leakage of the received energy to the earth instead of allowing it to perform its useful function in the radio receiver. If a tree is used as a support, the insulator should be fastened to a wire running to the tree, so that it is kept at least 5 feet from the end of the nearby foliage and branches.

Aerial wire insulators made of Pyrex glass, porcelain, etc., are usually made with an eye or hole at each end for easy fastening of the wire. They are also of ribbed construction in order to increase the length of

Courtesy Cornish Wire Co.



Courtesy Corning Glass Co.

Fig. 462—Left: A complete receiving antenna kit containing all the material necessary for the erection of a complete antenna-ground system.
Right: A Pyrex glass antenna insulator. Notice the eye at each end, and the ribbed construction to reduce leakage of the weak signal energy from one end to the other over the surface of the insulator in wet weather.

the surface-leakage path from one end to the other. A Pyrex glass insulator of this type is shown at the right of Fig. 462. Notice the eye at each end, and the ribs.

Fig. 463 shows a typical inverted-L antenna installation from a house to a pole erected a short distance away. An additional pole is shown erected on the house (this is not absolutely necessary but helps to elevate the aerial wire). Additional brackets with porcelain knob-type insulators are used to keep the lead-in wire a foot or two away from the side of the building.

The horizontal aerial wire portion is insulated at each end by the insulators shown. It is not necessary or desirable to cut the aerial wire at insulator "A" and join the lead-in wire to it. The lead-in and aerial should both be part of the same single piece of wire. This obviates the necessity for making and soldering a joint at this point. The convenience of this will be appreciated by those readers who have at some time or another tried to keep a soldering iron sufficiently hot until they were able to get to the roof and in position to solder an aerial joint. The detail drawing at the upper right hand corner, shows how the continuous aerial lead-in wire may be fastened to the insulator by a separate fastening wire about 18 inches long. This is drawn through the eye of the insulator to its mid-point; then each end is twisted tightly around the aerial-lead-in wire as shown. The latter wire will not be able to slide or pull out. Due to the changes in temperature at different seasons of the year, the aerial wire expands and contracts. During the summer it expands, and if it is long it may sag considerably. This expansion and contraction can be taken up automatically by one of the spring-tension aerial wire adjusters made for this purpose. This is usually put between one of the insulators and the guy-wire aerial support. The spring has sufficient tension to just take up the slack in the aerial wire at all times.

612. The lead-in wire: The lead-in wire should be kept at least 6 inches away from all buildings, trees, or other obstructions. It should never be allowed to touch the metal cornice or leader at the edge of the roof, for these are grounded. The lead-in may be kept at a distance of 1 foot or more from the building by means of brackets and "porcelain knob" insulators as shown in Fig. 463. Insulators of this type are

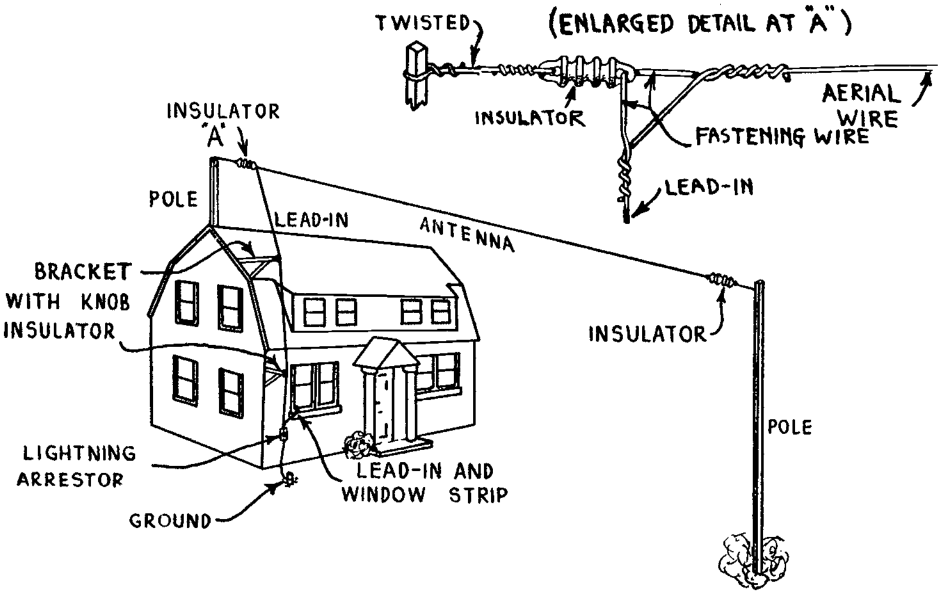


Fig. 463—Installation of a complete inverted-L antenna system on a house. The method of making the continuous aerial lead-in installation at the house end is shown in the detail drawing at the upper right.

shown at the extreme left of the illustration at the left of Fig. 462. Long "stand-off" insulators may also be used for this purpose.

613. Shielded lead-in: In many installations as in apartment houses, hotels, etc., it is necessary to install the aerial wire a considerable distance above or away from the receiver. The long *lead-in* wire of course acts just like the aerial in picking up radio signals, and also in having electrical impulses induced in it by any electrical appliances used in the building. Elevator motors and switching devices, relay contacts on electric refrigerators, etc., may induce considerable disturbing voltages in it, so that reception becomes extremely noisy. In cases of this kind the lead-in wire can consist of *shielded wire*, (see Art. 513).

This may take the form of rubber-insulated copper wire, surrounded by a lead covering or by a braided copper shielding, as shown at (A) of Fig. 464. The outside shielding covering is connected to ground either at lower end, or preferably at several intervals along its length. The wire from the radio receiver to the ground connection may also be shielded in this way if it is long. The aerial wire portion of the antenna system will then be the only part picking up signals and electrical disturbances. Of course shielded wire should not be used for this part, for then no signals would be picked up.

Since the shielded lead-in adds considerable capacitance to the antenna circuit it may throw out the tracking of the antenna tuned stage in a single-dial receiver used with it, and necessitate re-alignment of the first tuning section of the gang condenser in the receiver (see Arts. 632 to 639).

614. Entering the building: Two methods of bringing the lead-in wire into the building are commonly employed. The simplest way is to bring it in through a window nearest to the receiver, using a special flat, flexible, insulated window lead-in strip for this purpose.

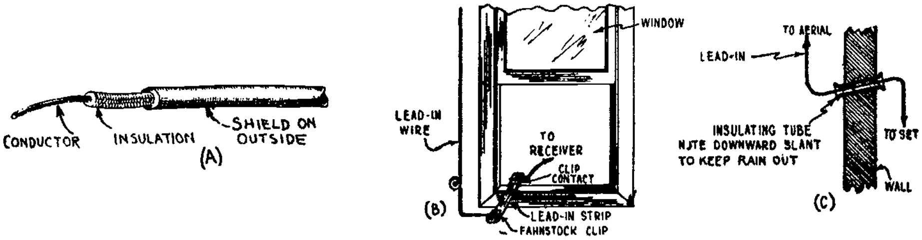


Fig. 464—(A) Shielded lead-in wire used to prevent pickup of electrical disturbances by the lead-in wire.
(B) A window lead-in strip in place between the window and the sill.
(C) A porcelain tube lead-in bushing installed in a wall.

These strips consist of a flat conductor about ½ inch wide, covered with an insulating covering, and provided with a terminal at each end. The strip is placed so the window closes on it, as shown at (B) of Fig. 464, being bent to conform with the shape of window jamb. The end of the lead-in wire connects to the outside terminal, and the wire running to the radio receiver connects to the other terminal. Although clip connections are usually provided on these strips, the wires should be soldered to them, for otherwise they will soon corrode and poor connections result. The strip should have a good waterproof insulating covering. A lead-in strip of this kind is shown directly up front in the left illustration of Fig. 462. A rubber-covered wire of about No. 14 gauge is run from the window lead-in strip to the radio receiver. It may be fastened along the groove or top of the baseboard of the room, with small staples.

In the other method of carrying the lead-in circuit into the building, a hollow porcelain tube bushing similar to the type used in "cleat and tube" electric wiring, is inserted into a hole drilled through the wall, as shown at (C) of Fig. 464. The tube should slope downward to the outside, so that rain running down from the lead-in wire will not run through the tube, into the building. Of course the installation of this tube is very difficult in cases where the wall is made of brick, etc., so the window lead-in strip is more commonly used.

615. The ground connection: The ground connecting wire from the radio receiver to the ground connection should be not smaller than No. 14 gauge. The ground connection should provide an electrical connection of as low a resistance as possible to the earth, since the earth acts as one of the plates of the large condenser formed by the antenna system, and the *full* signal current in the antenna system must flow through the contact during each half cycle. The importance of a good low-resistance contact to the earth cannot be too strongly emphasized. Of course, if a "counterpoise ground" is employed, no "earth" connection is required (see Art. 243).

A water pipe which forms part of a water supply system installed in the earth, usually makes an excellent ground, since it makes intimate contact with the earth for a long distance. Water-pipe grounds are approved by the Board of Fire Underwriters, as they are far more efficient than the average artificial or home-made ground connections. The connection of the ground wire from the receiver, to the

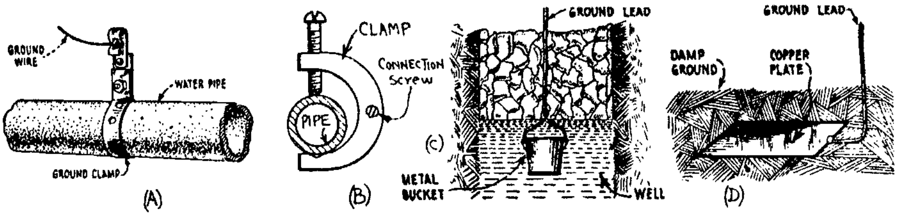


Fig. 465—(A) A strap-type ground clamp in place on a water pipe.
(B) A C-clamp type ground clamp in place on a water pipe.
(C) Using a metal bucket in a well as a ground.
(D) A copper plate at least 2 ft. square buried in moist earth makes a good ground.

water pipe should be made by means of a suitable metal "ground clamp" designed especially for the purpose. Merely wrapping the bare wire around the pipe does not make a good ground connection, for the wire will quickly corrode, and a poor contact will result. A ground wire connected to a simple strap-type ground clamp installed on a pipe, is shown at (A) of Fig. 465. In order to make certain of good contact, the pipe should first be cleaned thoroughly by filing off any rust or paint with a file or sandpaper. The strap of the clamp should then be tightened around the pipe. The ground wire should be wound around the screw, and the nut tightened down on the wire. A C-clamp type ground clamp is shown at (B). It is not necessary to clean the pipe first when this is used, since the hardened steel point of the tightening screw and the clamp, bite into the metal of the pipe, and make good contact.

Where a water pipe is not conveniently handy for use as a ground connection, such articles as a radiator, large copper plate or a bucket buried in a well as at (C) of Fig. 465, or a copper plate about 2 feet square buried in moist earth as shown at (D) can be used. Gas pipes should *never* be used for ground connections. A counterpoise ground (see Art. 618) can also be used.

In general, the more well-grounded objects one can connect the ground lead of a receiving set to, the better will be the reception—perhaps not noticeable on local station reception, but certainly noticeable during distant station reception, since the resistance of the antenna-ground path for the signal current is lowered.

616. The lightning arrester: An essential part of any outdoor antenna installation is the so-called *lightning arrester.* The rules of the

Board of Fire Underwriters require that an approved form of lightning arrester always be employed.

The lightning arrester is connected directly from the antenna lead-in wire to the ground, shunting the radio receiver. The lightning arrester in its simplest form as shown at the left of Fig. 466, consists simply of two metal electrodes which are spaced a few thousandths of an inch apart, (either in air or in a vacuum), so that the ordinary low-voltage radio signals cannot jump across this gap to the ground. Therefore, so far as the radio signals are concerned, it presents an *open circuit,* so the signal currents take their usual path from the lead-in wire through the antenna coil of the receiver coil down to the ground. Therefore, the arrester does not affect the radio reception. It takes about 500 volts to break down the air-gap or vacuum-gap in an arrester. However, if high potentials should be induced in the aerial by discharges

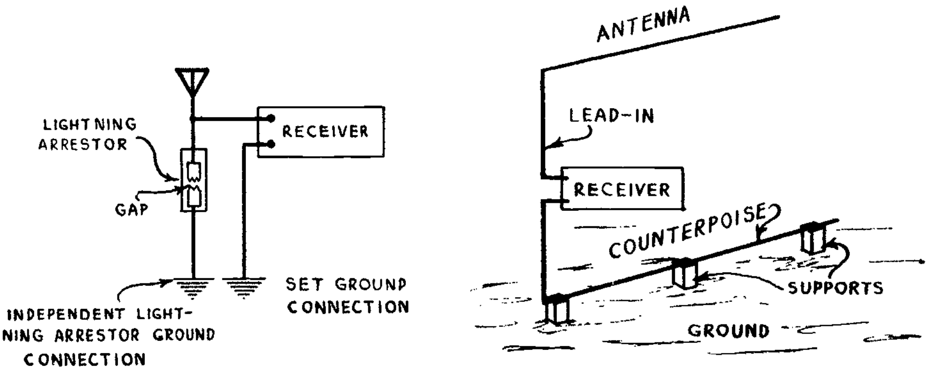


Fig. 466—Left: How a lightning arrester is connected in a receiving system.
Right: How a counterpoise ground is installed. The anten·a and counterpoise wires form the 2 plates of a large condenser—just as the antenna and earth do in the ordinary antenna-earth system.

of lightning in the vicinity, the voltage is high enough to jump across the small air-gap in the arrester and complete the path directly to the ground, instead of flowing through the larger opposition offered by the inductive action of the primary winding of the antenna-coupling transformer in the receiver. Small sparks may actually be seen jumping across the gap in an arrester on a stormy day. Thus the purpose of the arrester is to drain off the charge on the aerial continuously, to prevent the formation of high potentials. If a direct bolt of lightning should strike the aerial, the intense current flowing through it and the arrester to ground, would in all probability melt the rather fine aerial and lead-in wires. If one thinks for a moment and considers the millions and millions of radio receiving antennas erected all over the world, and how unfrequently any are struck by lightning, all fear of the lightning bogey should vanish. In cities where tall buildings with steel frameworks are erected, there are so many paths offered for the grounding of static discharges that lightning seldom strikes an aerial. In country regions—especially in mountainous localities, the danger from lightning is more serious, since less tall objects are available as paths for the lightning discharges to ground, and low buildings and aerials are often struck.

The lightning arrester is usually enclosed in a porcelain case and may be screwed directly to the outside of the building at the window where the lead-in wire is brought into the building, see Fig. 463. One end should be connected to a ½ inch iron pipe driven at least 3 feet or more into the ground, directly under the window. It is absolutely essential to use this separate outdoor ground for the lightning arrester so as to keep the path of all possible lightning discharges *outside* of the building. The wire should be fastened to the pipe by an ordinary ground clamp. The copper connecting-wire may be bare, but should be of a size not smaller than 14 gauge wire. It should run in as nearly a straight direct line as possible, to the ground pipe.

617. Light-socket and indoor antennas: In many cases, as in large apartment houses, etc., it may not be practical or desirable to erect an outside antenna for radio reception. An indoor antenna consisting of a single wire laid in the top channel or groove of the picture molding of one or two rooms, or strung up in an attic, is often used as an indoor antenna. Of course the radiations penetrate through the walls of the building and act on the antenna. In buildings in which metal lath is used in the outside walls, radio reception from an indoor antenna of this kind may not be very successful, since the lath acts as a screen and shields the antenna wire from the radio fields.

In some localities, especially where the electric light circuits are distributed on poles in the streets above the ground, excellent results are often obtained with a *light-socket* antenna, consisting of a plug which is screwed into the light socket. Inside the plug is a small fixed condenser, one terminal of which connects to one side of the lighting circuit, and the other terminal of which is brought out to a terminal on the side of the plug, for connection to the antenna terminal in the receiver. The other side of the line is dead-ended. The condenser acts as a blocking condenser to prevent an actual direct circuit for the line current from the line through the set to the ground. It does allow any r-f radio signals picked up by the electric light wires acting as antennas, to act on the receiver, however. Sometimes, better reception is obtained by reversing the plug in the lighting socket. Some receivers are designed for use with a loop antenna concealed inside the cabinet of the receiver.

618. Counterpoise ground: In places where it is difficult to secure a ground connection at all, as in the case of the installation of radio equipment on automobiles or aircraft (see Arts. 243 & 532), or where it is difficult to secure a ground connection of good conductivity (as where the soil is dry and rocky, and the ground water is at a considerable depth), a *counterpoise ground* can be used. This consists usually of a wire, or system of wires, supported a foot or two above the surface of the ground and insulated from it. The counterpoise should run parallel to the antenna and preferably under it. The receiving set is connected to the regular antenna and counterpoise ground as shown at the right of Fig. 466, no connection to the earth being employed.

The counterpoise may consist of several wires, or a wire screen or net. It merely acts as one plate of the antenna-system condenser, with the aerial and lead-in wires as the other plate. As it has good conductivity, it works better than a high-resistance ground even though its surface area is much smaller.

Counterpoise grounds are used extensively where regular ground connections are difficult or impossible to attain. Thus when operating a portable receiver in an automobile, a short antenna can be installed in the roof of the car, and the frame of the car used as a counterpoise ground (see Art. 532). The rubber tires insulate the frame from the earth. Aeroplanes usually use either a trailing-wire antenna or an antenna mounted on insulated supports above the wings. The wing and fuselage bracing wires, motor frame, etc., are all connected or "bonded" together electrically with wire to form a counterpoise ground.

619. Screen antenna: A simple screen antenna used in some receiver installations, such as on automobiles, in the receiver cabinet in homes in connection with very sensitive receivers, etc., is shown at the left of Fig. 467.

This consists of a copper or brass plate or screen, three or four feet square, which acts as the antenna. A regular ground connection is also used. When a screen of this type is enclosed in the radio receiver cabinet, it has the advantage of making it unnecessary to erect an outside antenna. However, since the energy pickup of the screen is low, a very sensitive receiver must be employed with it.

620. Loop antenna: Loop antennas generally consist of a rectangular or circular coil of from 1 to 15 or 20 turns of insulated wire wound on a supporting framework, as shown at the right of Fig. 461.

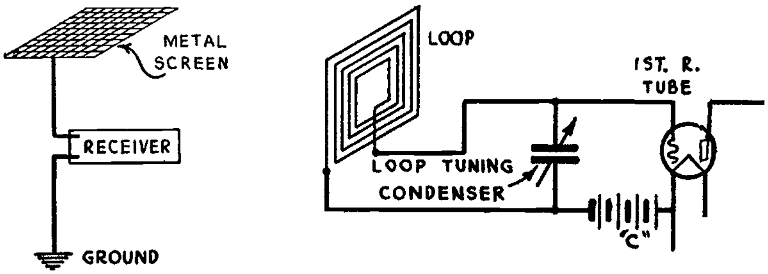


Fig 467—Left: Screen type antenna used extensively in radio installations on automobiles. Right: How a loop antenna may be connected to a receiver; no connection to the earth is necessary. The loop is tuned by the tuning condenser.

This type of antenna operates solely by the inductive action of the magnetic field sent out by the broadcast station. As this field moving at high velocity cuts across the plane of the loop it induces voltage in the wires by electromagnetic induction. (The action is similar to the induction of voltage in the armature wires of a dynamo.)

If the loop is turned so the field strikes along the direction of its plane, the induced voltage in the various turns are in such directions as to add to each other, thus giving maximum response. The voltage is induced due to the fact that by the time the field has travelled from one side of the loop to the other side, it has advanced through a part of its cycle, and so the phase-relation of the induced voltages in both sides of the loops differ. If the loop is turned so its plane is at right angles to the advancing signal field, the voltages in both halves are equal and opposite in direction and hence cancel each other. In this case, there is no response.

Loop antennas have small pick-up unless made of large, unwieldy size. They are usually operated with very sensitive receivers, such as superheterodynes, etc. The loop is usually connected to the first tuning condenser of the receiver for tuning, as shown in Fig. 467. Consequently, the loop should be designed so its inductance will produce resonance over the entire wave band it is desired to receive, when worked with the particular tuning condenser to be used. The directional effects of loop antennas find very important use in radio direction finders and beam compasses. When maximum response from the beacon transmitting station is heard, the plane of the loop is pointing directly to the transmitting antenna.

REVIEW QUESTIONS

1. What is the purpose of the antenna in a radio transmitting station? Explain how it performs this function.
2. What is the purpose of the antenna in a radio receiving station? Explain how it performs this function.
3. Explain and show by means of a sketch, how an elevated antenna and the earth form a condenser. By means of arrows, indicate on this sketch the path of the signal currents in the entire antenna system.
4. Mark the following parts on the above sketch; (a) the aerial; (b) the lead-in; (c) the ground wire; (d) the earth.
5. Upon what factors does the capacitance of the condensers formed by the aerial, lead-in, and earth depend? Explain!
6. Explain in detail how signal voltages and currents are set up in an ordinary inverted-L type antenna.
7. Draw sketches of 4 types of antennas, and explain the construction of each.
8. Draw a sketch and explain step by step, how to erect a horizontal-L antenna, and ground system complete with a lightning arrester. Show the primary winding of the antenna coupling coil in the radio receiver, connected properly in the circuit.
9. Describe the construction, and explain the operation of a lightning arrester. Why doesn't the signal current leak through the arrester to ground just as the static disturbances do?
10. Why are insulators used on antennas? What desirable properties should antenna insulators have? Explain why ribbing the surface increases the resistance to surface-leakage.
11. Explain why a low-resistance ground connection is important for good reception. What steps should be taken to make the ground system of low resistance?
12. What is a counterpoise ground? What are its advantages? Why is it used in automobile radio installations?
13. Describe a common form of lightning arrester, and show how it should be connected to a receiving antenna.
14. What is a loop antenna? Explain its principle of operation.
15. In which direction does a loop antenna receive best? Why?
16. May rubber-covered copper wire be used as aerial wire? Why?
17. What benefits are secured by shielding the antenna lead-in wire?
18. Describe the construction of a light-socket antenna plug. How does this operate?
19. Why is a separate ground required for the lightning arrester? How is this secured?
20. What is the purpose of the ground clamp? Draw a sketch of one, of the strap type. Explain how the pipe should be prepared before the ground clamp is put on the pipe.

CHAPTER 35

TESTING AND SERVICING

NEED FOR TESTING — METHODS OF TESTING FOR OPEN CIRCUITS — TESTING FOR SHORT CIRCUITS — TESTING FOR HIGH RESISTANCE GROUNDS — CHECKING RESISTANCE VALUES — TESTING FILTER AND BY-PASS CONDENSERS — CIRCUIT ANALYSIS AND SIMPLIFIED CONTINUITY CIRCUIT DIAGRAMS — R.M.A. RESISTOR AND WIRE-COLOR CODES — ANALYZING THE CIRCUITS OF A RECEIVER WITH SEPARATE INSTRUMENTS — THE SET ANALYZER METHOD OF DIAGNOSING TROUBLE — COMMERCIAL SET TESTERS OR ANALYZERS — ANALYZING TUNING CIRCUITS — USE OF THE OUTPUT METER IN ALIGNING — THE OSCILLATOR CIRCUIT — SIMPLE TEST OSCILLATORS — COMMERCIAL TEST OSCILLATORS — ALIGNING TUNED STAGES IN T.R.F. RECEIVERS — ALIGNING TUNED STAGES IN SUPERHETERODYNES — REVIEW QUESTIONS.

621. Need for testing: Radio equipment of any kind is, in the final analysis, merely a combination of electron streams, wires, inductances, resistances and capacitances, properly constructed and connected together. It seems almost impossible that so many different circuit combinations could be evolved from just these five elements, but it is true nevertheless. Consider any receiver circuit, no matter how complicated—that of Fig. 453 will do. Study and analyze it carefully. Look at every part, and you will find that it consists of either a resistance, an inductance, a capacitance, or an electronic-stream device (vacuum tube) with connecting wires. It is possible for any of these parts to become inoperative due to one cause or another; just as it is possible for wires to come loose, causing open circuits; or insulation to deteriorate, rub, or chafe, causing short-circuits. Vacuum tubes are liable to become inoperative due to a decrease of electron emission caused by all of the active material on the cathode becoming used up—or the filament may burn out. If the general arrangement of radio circuits is known, and a knowledge of the various methods of testing for opens, shorts, etc., is at hand, it is possible with some little experience, to locate trouble of any kind in radio equipment.

Many troubles may arise in radio receivers, and it is necessary to know not only how to repair the trouble but also to test for and locate it first. This requires some knowledge of the various methods of testing circuits and repairing inoperative parts. It is not necessarily true that a part is *defective* just because it fails to operate. It may have been perfectly designed and constructed, but may have been mechanically strained, overheated, or otherwise abused in service, causing it to become *inoperative.*

Properly speaking, a *defective* part is one which has been designed or constructed incorrectly. We will first consider the various simple tests for locating and determining simple troubles such as open-circuits, short-circuits, etc., by means of individual instruments. Later we will consider the use of instruments arranged conveniently in groups, in the form of service kits and set analyzers for facilitating rapid diagnosing and localizing of troubles. The arrangement and operation of the various instruments in set testers and analyzers can be much more easily understood and intelligently applied, if the fundamental principles of testing with individual instruments are thoroughly mastered first.

While it is not possible to present a thorough course on testing and servicing of radio equipment in the small space available here, we can set down the fundamental principles which will enable the student to understand the basic ideas involved in this work. After all, since all makes of radio equipment employ somewhat different arrangements of parts and special circuit kinks here and there, considerable practical experience in servicing many models and makes of receivers is necessary before anyone can attack servicing problems in an efficient straightforward manner. But the construction of radio equipment has become so interlinked with basic electrical circuits and principles, that no intelligent service work can possibly be carried out on modern radio equipment without a thorough knowledge of the basic principles. While service work is carried on in practice by diagnosing the trouble first, and then localizing it down to the particular inoperative unit by means of continuity tests, etc., for our purpose it will be best to consider the latter tests first, and proceed to simple trouble-diagnosing later. Since all receivers are composed of a combination of the five basic types of parts already referred to, we will begin our study by considering how each of these may be tested separately. It is assumed that the reader is thoroughly familiar with the construction and operation of electrical measuring instruments as described in Chapter 13. This is essential before proceeding with this study.

622. Methods of testing for open circuits: Any circuit which does not form a complete path for the flow of current is called an *open circuit.* Consider (A) of Fig. 468. This shows a simple circuit consisting of a battery and a resistor, R.

Since the resistor, the connecting wires, and the battery form a complete path for the flow of the battery current we have a *closed circuit.* If a current-indicating device—such as an ammeter or milliammeter of proper range depending on the amount of current flowing—were connected in series with the circuit, it would indicate the number of amperes or milliamperes of current flowing. If a voltmeter were connected across the resistor R as shown, it would indicate the "fall of potential" or "voltage drop" across the resistor, i.e., the amount of voltage or electrical pushing force required to cause the electrons or current to flow through the resistor against its opposition or resistance. Now refer to (B) which shows the same resistor and the same battery, but due to some reason, the resistance wire of which the resistor is constructed has broken or become "open" at point X. Evidently, no current can now flow through the resistor, i.e., the circuit is "open". This will be indicated by the fact that the ammeter does not register at all now. However, the voltmeter will now register the full e. m. f. of the battery, since it is now directly across the battery terminals. Suppose the resistor were perfect but a break occurred in one of the connecting wires. Evidently, the same condition of an "open circuit" would result, no current would flow, and the current-indicating meter would read zero.

An inductance coil "L" of any kind, such as the primary or secondary winding of an r-f or a-f transformer, a power transformer, a choke coil, etc., also normally presents a closed circuit to the flow of current, as shown at (C). If the wire breaks or a connection opens, an open circuit results, and the current stops flowing. The current-indicating meter then does not register when connected in series with the circuit.

In the case of a condenser C, as shown at (D), since the dielectric insulates one plate from the other, no current will flow through it if a direct current voltage is applied, i.e., so far as d-c is concerned, the condenser normally presents an open circuit and the ammeter will not read if the condenser is perfect. (In the case of electrolytic condensers a small "leakage current" would flow through on this test.) If an a-c voltage were applied to the condenser instead, an a-c current would flow in the external circuit between the plates, this current depending on the value of the voltage applied, and the capacitance of the condenser.

A circuit such as that of a resistor, inductance, or wiring, may also be tested for open circuits or continuity by means of a source of voltage such as a small 4½ volt C battery, and a suitable voltmeter—preferably of the high-resistance type. The

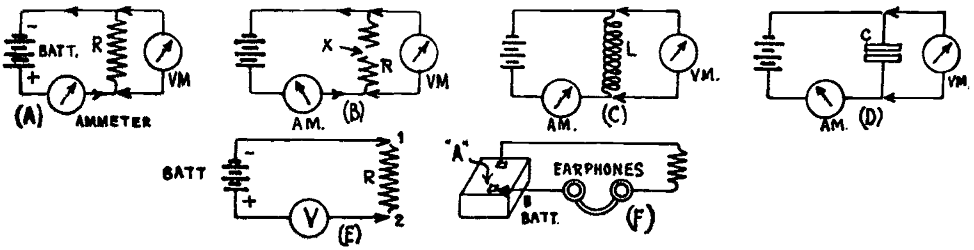


Fig. 468—Various methods of testing for circuit continuity—or "open circuits." (A), (B), (C) and (D) are by means of a battery and meters. (E) is by means of a voltmeter and battery, (ohmmeter). (F) is by means of a battery and earphones.

voltmeter, and resistor or inductance winding to be tested for continuity, are connected in series with each other and across the battery as shown at (E). If the two terminals 1 and 2 are touched together, the voltmeter will register the full voltage of the battery. If they are connected across the resistor, the voltmeter will still read if the resistor presents a continuous path for the flow of current. The voltmeter reading may be lower than before, depending on the value of the resistor being tested. If an *open circuit* exists in the resistor being tested, the voltmeter will not indicate.

It will be recognized that the arrangement at (E) really constitutes the ohmmeter circuit which we studied in Article 217. Commercial ohmmeters, one type of which is shown in Fig. 155, are very handy for testing for open circuits. If the circuit is closed, the ohmmeter indicates the resistance of the circuit. If it is "open", the ohmmeter reads "infinite" resistance—or the highest resistance on its scale.

Another simple method of testing for open circuits, without the use of measuring instruments, is to employ a battery—preferably a 45 volt "B" battery—and a pair of earphones as shown at (F). Every time the terminal "A" is *touched to the battery terminal*, a loud click is heard in the earphones if the circuit being tested is "closed". If the circuit is "open", no click at all (or a very faint one), will be heard. When testing condensers, a very faint click will be heard if the condenser is perfect. One disadvantage of this method is that when testing very high resistances for continuity, a very faint click may be heard even if the circuit through the resistor is continuous, since the resistor limits the current through the earphones. This should be remembered.

From the foregoing, it will be seen that any resistor, inductor, or wire circuit may be tested for "continuity of circuit" or "open circuit" by means of a source of voltage and either an ammeter (or milliammeter), a voltmeter, or a pair of earphones. Where two or more devices are connected in parallel and it is desired to test each one for open circuit, they should all be disconnected and each tested separately, for if they were all left connected, even though one had an open circuit it would not show up in the test, for current would still be flowing through the others. If several devices are in series, the test arrangement shown at (B) is handy. When connected successively across each one, the voltmeter will quickly indicate which of the devices is open. It will show a reading equal to the battery voltage when connected across the device which has the open circuit.

623. Testing for short circuits: A *short circuit* may be defined as an accidental low resistance connection between the two sides of a circuit, such that the current from the source is thereby allowed to return to the source without passing (or only part of it passing) through the device or devices through which it is intended to flow.

Let us refer to the simple circuit at (A) of Fig. 469. This shows a battery supplying current to the filament of a vacuum tube, filament rheostat R being used in the circuit to adjust the current to the proper value for the tube. A voltmeter connected across the filament as shown, indicates the full voltage across it. Now suppose that the two supply wires should for some reason become connected together at some point, as shown at (B). This might be due to the insulation being worn down to the bare wires, or some other cause. It is evident that the current from the source no longer flows through the resistance of the filament, for it can now take a path of less resistance directly across the short-circuit point, and back to the source, as shown by the arrows. This short circuit path is shown by the heavy lines. This represents a *short-circuited condition.* A short circuit will be indicated by the fact that an excessive current flows through the wires from the voltage source, (if the source of the

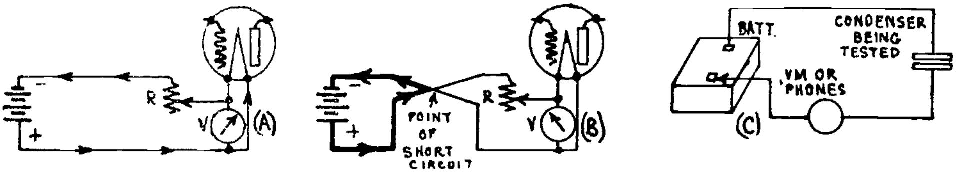


Fig. 469—Methods of testing for short circuits. (A), A normal filament circuit. (B), A short circuit in the filament circuit. The heavy lines indicate the path of the current. The voltmeter reading drops to zero. (C) Testing for a short circuit between the plates of a condenser.

voltage is able to maintain this heavy current flow), since the resistance of the current path is now very low. Also, a voltmeter connected *across* the device which is intended to receive the current, either reads zero or else reads very much lower than its normal value, since the resistance of the short circuit path is very much less than the normal resistance of the device, and therefore the voltage drop across it is also very low. This may be used as a test for determining short circuits in resistors, inductances or wire circuits.

A short circuit between the plates of a condenser may be determined by connecting it to a source of voltage such as a battery, in series with either a voltmeter or a pair of earphones as shown at (C). If a short circuit exists between the plates, a flow of current across them will be indicated by the deflection of the voltmeter, or by the strong clicks heard in the earphones every time terminal "A" is touched to the battery terminal. If the condenser is O. K., only very faint clicks will be heard, due to the "charging" of the condenser. Of course an ohmmeter may also be used for testing for short circuits, since when it is connected directly across the terminals of the device or circuit to be tested, it will indicate *zero* or at least a low resistance value if a short circuit exists in its dielectric, (see Fig. 155).

When testing for possible short circuits existing in any circuit having several devices connected in parallel, they should first be disconnected from each other and each one tested separately.

624. Testing for high-resistance grounds: In many instances an actual short circuit may not occur between the two sides of a circuit, but instead, a rather high-resistance leakage path, which could not be correctly termed a "short circuit", might occur between them. This is usually called a "high resistance ground", and may be due to deterioration of the insulation between circuits, to abrasion of the insulation, to poor grade of insulating material employed, etc. High-resistance grounds are probably best tested for by means of an ohmmeter, since then the actual resistance of the leakage path, even if it is high, will be indicated.

625. Checking resistance values: When testing a receiver for defects, it is often necessary and desirable to check the resistance values of the resistors, or other parts. This may be done by the *volt-meter-ammeter method* for low resistances, described in detail in Articles 215 and 216; by the ohmmeter method described in Article 217; or by the Wheatstone bridge method described in Article 218. These methods should be reviewed at this time. Of course, some idea of the resistance which the device to be checked should have, should be known, if its condition is to be judged at all. The ohmmeter method is the quickest and most satisfactory one for radio service work.

626. Testing filter and by-pass condensers: Filter and by-pass condensers used in radio receivers are usually sealed in Bakelite, metal,

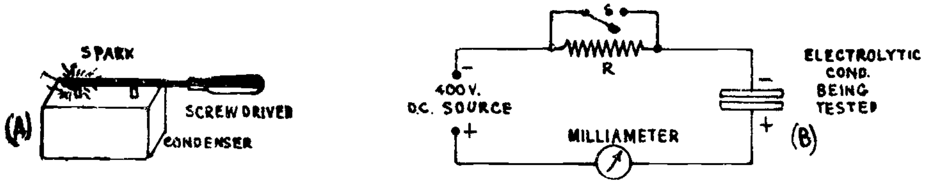


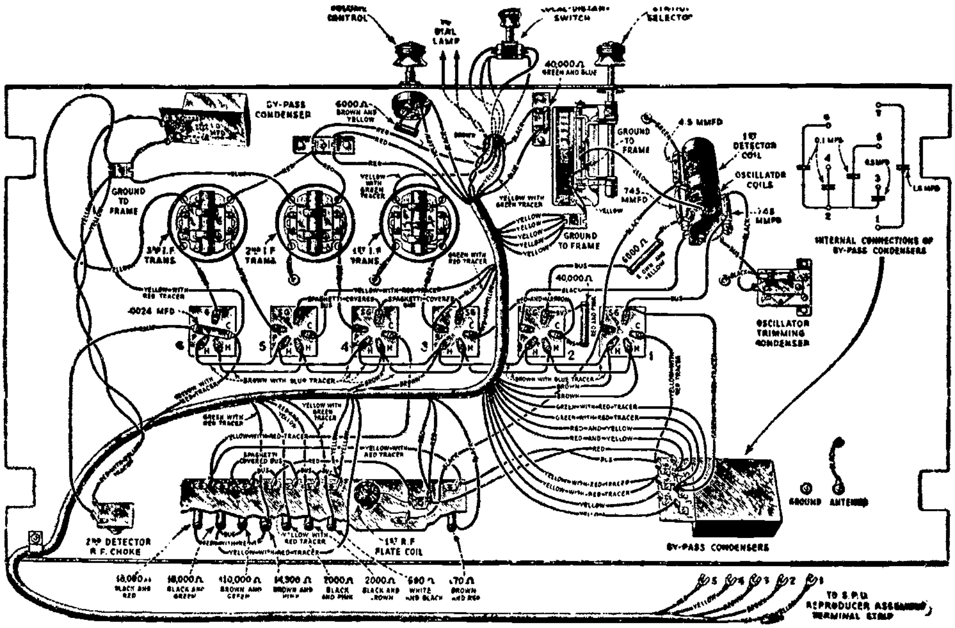
Fig. 470—(A) Testing a condenser for short circuits by charging it with a d-c voltage source and then shorting its terminals.
(B) Testing an electrolytic condenser by measuring its leakage current.

or cardboard containers. The condensers may be in the form of separate units or may be grouped together in one container in the form of a "condenser block" as shown in Fig. 93. In most cases, the condensers in blocks have a common terminal as shown in the diagram in Fig. 93, but in many instances they have separate terminals brought out.

Although open circuits sometimes occur in paper-type condensers due to the metal terminal tab pulling away from the tinfoil plates, this trouble is rare. The usual trouble is due to a short circuit caused by breakdown of the dielectric between the plates. Of course this applies only to condensers of the tinfoil-paper (or mica) type. Electrolytic condensers are "self-healing", that is, if the dielectric film breaks down due to the application of too high a voltage, it re-forms if the high voltage is removed within a reasonable time, and becomes as good as new again.

Tinfoil-paper filter condensers may be tested for breakdown by several methods. One of the simplest, is to disconnect the condenser from the circuit and apply from 90 to 200 volts d-c directly to its terminals, by means of a "B" battery, or d-c electric light line, etc., and then noting whether it holds the charge. Immediately after charging, the charging source is disconnected, and short circuiting the condenser terminals with a screwdriver should produce a flash, the size of the flash depending on the capacitance of the condenser, and the voltage used for charging. This is shown at (A) of Fig. 470. If the condenser has a short circuit between its plates, no charge will be stored by them, and no flash will be produced. This type of condenser may also be tested by means of the battery and voltmeter or earphone method described for (C) of Fig. 469.

Electrolytic condensers may become inoperative due to drying out of the electrolyte, or chemical changes taking place in it. A condenser of this type may be tested by connecting it directly to a source of d-c voltage (about 400 volts d-c for a condenser rated at 450 volts d-c, and measuring the leakage current flowing through it, by means of a suitable milliammeter as shown at (B) of Fig. 470. Electrolytic condensers of different manufacture differ as to the leakage current, but some idea of the value to be expected may be obtained from the following figures for two typical condensers of this type tested with 400 volts d-c. For a 10-mf. condenser the leakage current did not exceed about 2.4 milliamperes. For a 4-mf. condenser, it did not exceed about 1.0 milliamperes. Care should be taken to connect the condenser to the

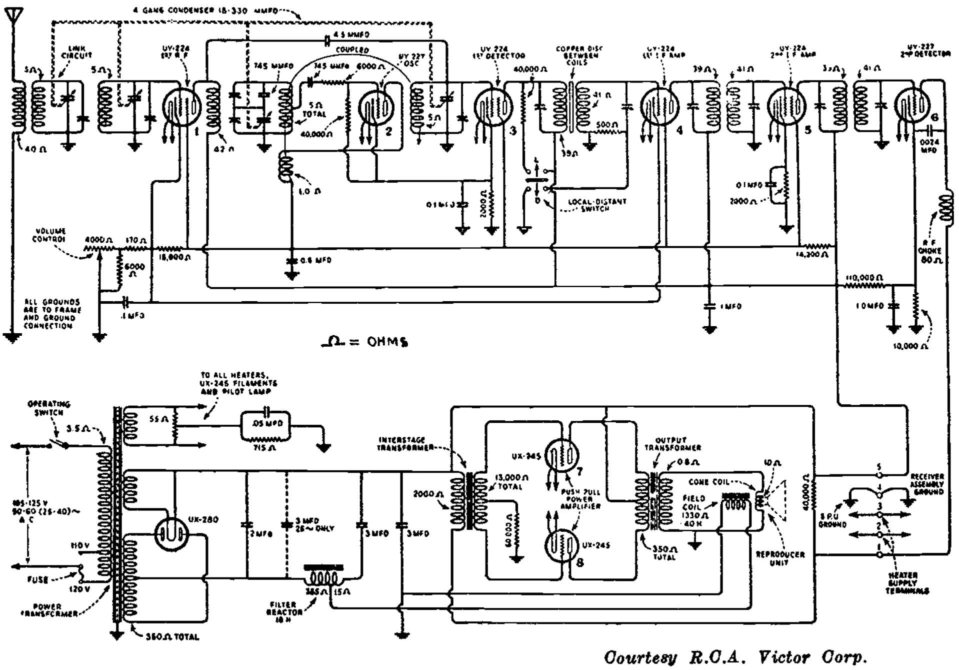


Courtesy R.C.A. Victor Corp.

Fig. 471—How the wiring and parts arrangement under the chassis of a typical radio receiver may look. This appears rather jumbled and complicated, but careful tracing of the various circuits enables one to draw the simple schematic circuit diagram for it as shown in Fig. 472.

line terminals with the proper polarity, i.e., the *positive* terminal of the line should be connected to the *positive* terminal of the electrolytic condenser. Also, to prevent burnout of the milliammeter if the condenser should by chance happen to be short circuited, a protective resistor R, of a value depending on the voltage of the testing source and the range of the milliammeter used, should be connected in series with the circuit at the start, when the voltage is applied. Switch S should be open. If no excessive current reading results, it may be assumed that no short-circuit exists in the condenser and the switch S may be closed. This shorts the protective resistor out of the circuit, and the leakage current reading may now be taken.

627. Circuit analysis and simplified continuity circuit diagrams: In many cases, tests must be made on a radio receiver for which no schematic circuit diagram is readily available, and with which the person who is to test it, is not familiar. By examining the parts and wiring it is usually a simple matter to determine in general what type of circuit is used in the receiver, i.e., whether it is some form of t-r-f, or a superheterodyne receiver. An inspection of the number of tuned circuits and the number and types of tubes used, will also give some information. Beyond this, nothing may be known about it. If the bottom of the chassis is inspected, a mass of parts and wire somewhat as shown in Fig. 471, may greet the eyes. To the inexperienced novice, such an array appears rather complicated, puzzling, and usually very discouraging. After some practice in tracing circuits however, such things need not be at all troublesome, provided the person has a good working knowledge of the fundamental receiver circuits, such as has been presented in this text. Another



Courtesy R.C.A. Victor Corp.

Fig. 472—The schematic circuit diagram of the receiver shown in Fig. 471 (with the power supply unit added.) This is drawn by tracing the individual filament, cathode, grid, and plate circuits of the various tubes and setting them down in the form of a diagram in systematic order. Compare the simplicity of this diagram with Fig. 471.

requisite is the ability to take a complicated appearing circuit and part arrangement, trace the main individual filament, cathode, grid, and plate circuits, and set each one down in simplified schematic form on paper, to form a schematic circuit diagram of the type used throughout this book—which is easy to follow, and tells at a glance, just what the individual circuit connections are.

For instance, careful inspection of the receiver chassis, shown in Fig. 471, (the power supply unit is separate and need not be considered here for our purpose), will reveal immediately that there are three intermediate-frequency transformers mounted in shielding cans at the upper left hand corner of the chassis. These are of the general type shown in Fig. 285. This immediately tells us that the receiver employs a superheterodyne circuit. Inspection of the type of power tubes and loud speaker used also tells us something about the possible power supply unit arrangement. Inspection of the tuning condenser tells us how many tuned circuits are used. Inspection of the types of tubes employed and their sequence in the circuit also tells us a great deal about the circuit, and enables us to start drawing our simple schematic circuit diagram by setting down the proper symbols of the tubes in their proper order, as shown in Fig. 472.

We may start with the filament terminals of the tubes, and trace all the filament connections. If they are all connected in the usual parallel arrangement, they can be drawn in the simple schematic form as shown. Next we can trace through the cathode circuits of the tubes, one at a time and draw each one in on the circuit diagram. It will be found that all cathode circuits eventually end up at B—. Next, we can trace the plate circuits, back from the plate terminal of each tube. Next, may come the screen grid circuits and finally, the grid circuits. The power supply unit wiring may be tackled next, or in some cases it may be preferable to finish this first. In this way, a careful step-by-step analysis of the entire receiver may be made, and set down in the form of a simple schematic circuit diagram easy to follow. The complete circuit of the receiver chassis shown in Fig. 471, has been traced in this way and is drawn in simple *schematic* form in Fig. 472, together with the power supply and loud speaker unit which is constructed separately from the chassis of Fig. 471. Notice the simplicity of this diagram and the ease with which any circuit in it may be traced. Most receivers are wired with wires of different colors and code markings to facilitate tracing the circuits. Of course, the resistance values, etc. marked on this diagram, would not be known, but they could be measured if desired. Many of the manufacturers of the R. M. A. group have adopted the standard resistor color code markings for identifying the resistors used in their receivers. The combination of the color marked on the main body of the resistor, that marked on a narrow ring of the body, and that marked on the end, gives the value of the resistance. This is considered in detail in Article 628.

It is true that many commercial receivers are constructed with many of the parts sealed up in groups, in cans which are filled with pitch, wax, or some other moisture-excluding compound, and are therefore not very well adapted to tracing of the connections such as has been outlined here. This condition is one which must be accepted in many cases. Tracing of as much of the circuit wiring as is accessible, will often help some. If more knowledge of the circuit is required, the schematic circuit diagram must be obtained either from the manufacture of the receiver, or from some other source, such as one of the radio service manuals which contain the circuit diagrams for most of the receivers manufactured. One of these books is almost a necessity in service work. In many instances, these service manuals also specify the voltage readings which should be obtained at various points in the circuit when the receiver is in proper working order. This information is very helpful.

628. R. M. A. resistor and wire-color code: The standard resistor color-code marking which has been approved by the Radio Manufacturers Association in the United States, is used on the resistors in the recent models of receivers which are manufactured by companies which are members of this association. It enables one to tell at a glance just what the resistance value of a resistor is, by inspecting the code color markings on it.

The code identifies resistors by means of 3 colors, known as "body," "tip" and "dot" colors. The *Body Color* is the main color of the resistor and represents the first figure of the resistance value. The *Tip Color* is the color of the end of the resistor and represents the second figure of the resistance value. The *Dot Color* (sometimes a narrow band is used instead of a dot) indicates the number of ciphers following the first two figures.

Example: A resistor has a Red Body—(2); a Green Tip —(5); and an Orange Dot or Band—(000).

Answer: The resistor value is 25,000 ohms.

The figures represented by the various colors are given in the following table:

1st Figure (Body Color)	2nd Figure (Tip Color)	(Dot or narrow Band Color)
0—Black	0—Black	None —Black
1—Brown	1—Brown	0 —Brown
2—Red	2—Red	00 —Red
3—Orange	3—Orange	000 —Orange
4—Yellow	4—Yellow	0000 —Yellow
5—Green	5—Green	00000 —Green
6—Blue	6—Blue	000000—Blue
7—Violet	7—Violet	
8—Gray	8—Gray	
9—White	9—White	

It should be borne in mind that this code applies only to the newer model receivers that are now appearing on the market. It will be a safe practice on all older model receivers to refer to the manufacturer's service notes for the color code used on the earlier model sets.

—WIRE COLOR CODE—

A standard color code has also been approved by the National Electrical Manufacturers Association for the wires used in wiring up the receiver. As is the case with the resistor code markings, this particular wire-marking code is not standard on all receivers, but is being used in the latest receivers manufactured by manufacturer members of the N. E. M. A. The wire color code follows:

For conductors that are individual to one circuit only: "A+," Yellow; "A—," Black with Yellow tracer; "B+" Max., Red; "B+" Int., Maroon and Red; "B+" Det., Maroon; "B—" Black with Red tracer; "C+," Green; "C—(low), Black and Green; "C—" (max.), Black with Green tracer; Loud Speaker (high side), Brown; Loud Speaker (low side), Black with Brown tracer.

629. Analyzing the circuits of a receiver with separate instruments: In testing any receiver for the cause of trouble which may be making it totally inoperative, or else operating unsatisfactorily, a considerable amount of information may be obtained by first testing the individual tubes for either "mutual conductance" or "emission". In many instances, this will reveal one or more of the tubes to have become inoperative, in which case it is only necessary to replace the tube in order to get the set working satisfactorily

If the tubes all check up properly, the voltages which actually exist at their various prongs when they are in place in the receiver, may be checked next with a suitable voltmeter.

This procedure is called *diagnosing* or *analyzing* the receiver, and usually enables one to determine in just which circuit the trouble lies, for trouble occurring in any circuit associated with a tube will usually cause a change in the voltage existing at the tube prong connected to that circuit. After the circuit in which the trouble lies has been located in this way, the particular unit which is inoperative, may be located definitely by applying the proper separate continuity tests and resistance measurements which we have already studied (in Arts. 622 to 627), to the idividual parts in that particular circuit. Thus, there are really two main steps to radio receiver servicing, first the *diagnosing* or *analyzing*, and then the trouble *localizing*, *identification*, and *correction*.

Each tube has either three, four, or five individual external circuits, depending on its type. If it is a direct-heater type three-electrode tube, it has a filament, a grid, and a plate circuit. If it is a separate-heater type three-electrode tube, it has a filament, cathode, grid and a plate circuit. If it is a separate-heater type screen grid or pentode tube, it has a filament, cathode, control-grid, plate and screen grid circuit. Keeping this in mind, it is possible to analyze the various circuits of a receiver by testing the voltages existing at these terminals of the tube sockets. In most modern receivers, it is quite difficult to reach directly, the various coupling transformers, resistors, condensers, etc., in order to make tests. In almost all receivers, the main circuits come more or less directly to the tube socket connections, which are easily reached for test work. Therefore a receiver is usually *analyzed* by measuring the voltages existing at the tube socket terminals. In most cases, this will indicate just which of these circuits the trouble lies in.

To illustrate how these circuits may be analyzed, let us consider the typical screen-grid r-f amplifier stage shown at (A) of Fig. 473. The method of analyzing the circuits of this tube and stage may be duplicated for any other stage in the receiver. In the grid circuit of the tube we have the secondary of the preceding r-f transformer with the tuning condenser C_1. In the plate circuit is the primary L of the next r-f transformer, one end of the primary being connected to the plate of the tube, the other end connecting to the plate-filter system consisting of the resistance R_1 and the by-pass condenser C_2. The other end of the resistance R_1 connects to that terminal of the plate supply unit which supplies plate voltage to the r-f amplifier tubes.

Of course, in a complete receiver several tubes comprise the radio-frequency amplifier, but the circuits of each individual tube are closely similar to the one shown here. Slight variations from this fundamental circut will be found, but if this normal arrangement is kept in mind it will make circuit testing a simple task.

In order to check the voltages appearing at the various circuits, individual voltmeters may be used. For a-c electric receivers, two voltmeters are all that are required for this work. One handy instrument for this work is a d-c voltmeter having a resistance of 1,000 ohms or more per volt, (see Article 205), and having scales reading 0-10, 0-250, and 0-750 volts. A meter of this type is shown in Fig. 144. Its scope of utility, because of its high "ohms-per-volt" value, is very wide. As a filament voltmeter for d-c tubes, it affords very accurate readings. As a "B"-supply voltage meter, it indicates the true output, because it does not draw enough current to affect the operation of the power unit. As a grid-bias voltmeter, it permits accurate Adjustment of the grid-bias resistor. Its low current consumption, due to its high resistance, does not materially affect the plate current flowing through the biasing resistor.

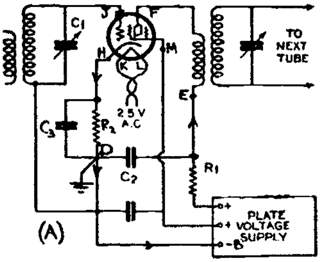
An a-c voltmeter of the general type shown at the right of Fig. 144, and having scales reading 0-4, 0-8, and 0-150 volts, is also very useful. The two lower scales are for reading filament voltages on a-c and rectifier tubes, the 150 volt scale is for checking the a-c electric light line voltage. It is possible and desirable to use a single multi-range copper-oxide rectifier type voltmeter for this purpose (see Art. 214), since it will measure both a-c and d-c voltages accurately. The use of separate instruments is considered here merely to develop the methods of testing and analyzing the circuits. Later, we will see how the *set analyzer* performs all of these functions in a rapid simple way.

To check the filament voltage, the a-c voltmeter is connected across filament terminals K-L. To check the plate voltage, the d-c voltmeter is connected between the point H (cathode) and the point F (plate). (*Note*: All voltages or potentials in a direct-heater type tube are always understood to be referred with respect to the *negative terminal of the filament*. All voltages or potentials in a separate-heater type tube are always understood to be referred with respect to the *cathode*, as the reference terminal (see Art. 270). These are considered as the points of lowest potential in the tube.) If the correct voltage reading is obtained between the cathode and the plate, it indicates that whatever is connected in the plate circuit of the tube (in this case it is the primary winding of a transformer), is not "open". It also indicates that the "B" voltage supply unit is operating satisfactorily. If no voltage reading is obtained between H and F, a test should be made between H and E. If a reading is obtained here, it indicates that an open circuit exists in the primary winding of the transformer. The screen grid circut can be checked by connectng the voltmeter from H to M. The control-grid circuit can be checked by connecting it from H to J. (J is the cap on the tube.) If no reading is obtained here, a test should be made between H and D (D will be usually grounded to the metal chassis). This should indicate the grid-bias voltage if both the grid-bias resistor and its by-pass condenser C_3 are O. K.

This simple test may be repeated at the socket of each tube, until the tube at which the improper voltage exists is located. The individual circuit at which the improper voltage exists can then be traced, and the individual parts in it tested for open or short circuits, etc., by the methods already described. If the plate and grid voltages on all the tubes are found to be low, the circuits of the "B" power supply units may be suspected and should be checked up. Abnormally low output voltage would in all probability be caused by a broken-down filter condenser—necessitating the individual testing of all the filter condensers for shorts.

630. The set analyzer method of diagnosing trouble: The procedure outlined above indicates in a general way how the circuits of each individual tube in a receiver may be analyzed to locate, by means of two simple instruments, the particular circuit in which trouble exists. It has one great drawback in modern test work, however.

When receivers were constructed with all tube sockets mounted on an open baseboard, with every connection easily accessible, this method of testing was simple to



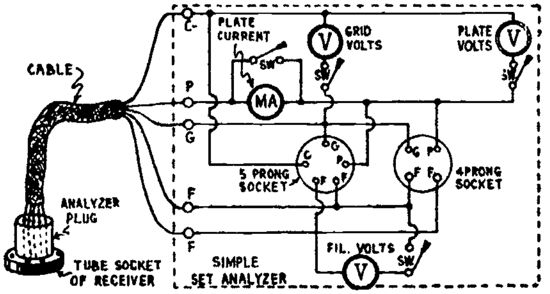


Fig. 473—Left: The individual filament, cathode, control-grid, screen-grid, and plate circuits of a typical screen-grid amplifier tube in a radio receiver. Note that each circuit terminates at the socket and tube.
Right: The elements of a simple set tester or analyzer which permits of rapid testing of the voltages existing at the terminals of any tube socket in the receiver. The analyzer really extends the circuits of the tube socket to a point outside the receiver for convenient testing by means of the various instruments provided. The tube taken from the receiver is plugged into the analyzer tube socket.

apply. Modern receivers are constructed with the tube sockets, resistors, wiring and most condensers, mounted underneath the chassis. Transformers and chokes are mounted in cans. Therefore testing by this method would necessitate the complete removal of the chassis from the cabinet for every service job, and the testing at the tube socket terminals with the set in an inverted position—which is rather awkward, and inconvenient.

The testing manipulations may be greatly facilitated and speeded up, by bringing all of the circuits of the socket of the tube to be tested, to an extra tube socket in which is placed this tube taken from the receiver socket. This extra tube socket is already permanently connected to the testing arrangement, with all meters, switches, etc., arranged to facilitate rapid switching of meters to any circuit, selection of instrument scales, etc. This may be conveniently done by employing a *dummy plug* exactly resembling the base of the vacuum tube, and having prongs arranged in the same order. A wire connects to each prong, and these wires are all brought out, (usually in the form of a cable), to the similar socket in the tester, in which the tube taken from the receiver is placed. The various instruments and switching arrangements for testing are permanently connected in the tester itself, between the "dummy" plug and this socket.

The arrangement of a very simple set analyzer or tester of this kind in which separate meters are used, is shown at (B) of Fig. 473.

A study of this diagram, shows that the set tester or analyzer idea is merely one designed for convenient testing. Instead of bringing the testing instruments to the terminals on the tube socket, which are usually very inconveniently located—and doing all of the testing in the limited cramped quarters in the receiver; we remove the tube from the receiver socket, extend each individual tube circuit out to the tester by means of the plug and cable, and connect the ends of these extended circuits to the tube taken out of the receiver—the testing instruments being automatically connected properly in between—and do our testing conveniently with plenty of room to work in, and with testing instruments and switching arrangements already connected up in the circuit to perform all the required tests simply and quickly. This is the basis of the set analyzer or tester idea. Of course, in order to make intelligent use of tests of this kind, it is necessary to know just what the voltages at the various terminals of each tube socket should be under normal operating conditions. This data is usually furnished by the receiver manufacturer, or may be obtained from service manuals. Most commercial set analyzers and testers are provided with instruction books containing tables showing the correct voltage readings for most of the standard makes of receivers.

A typical table of this kind for an a-c electric receiver, is reproduced below from the instruction book for the Weston Model 566 Type 2 Radio Set Analyzer. Notice that all the important data concerning the receiver is contained in this table.

MAJESTIC—MODEL 20 CHASSIS

Type Tube	Tube Position	"A" Volts	"B" Volts	"C" Volts	Screen Volts	Screen Current	Cath. Volts	Nor'l MA.	Grid Test MA.
'51	1 R.F.	2.3	180	0	90	....	3	5	6.2
'51	1 Det.	2.3	180	0	87	....	8	0.8	1.1
'51	1 I.F.	2.32	150	0	90	....	3	4.0	5.2
'27	Osc.	2.32	90	0	....	....	....	4.0	5.1
'27	2 Det.	2.32	255	10	....	....	21.6	0.8	1.0
'45	1 A.F. } P.P.	2.36	275	45	....	....	....	29.0	33.0
'45	1 A.F. } P.P.	2.36	275	45	....	....	....	29.0	33.0
'80	Rect.	4.8	410	....	....	....	....	40.0	per anode

Line Voltage—117 v. Volume Control set at "Max."

The analyzer is provided with both a 4-prong and a 5-prong socket into which the tube taken from the receiver is placed during the test—depending on its type. Also, the 5-prong plug furnished for plugging into the receiver socket is provided with a removable 4-prong adapter, for use when the circuits leading to a 4-prong tube are to be tested.

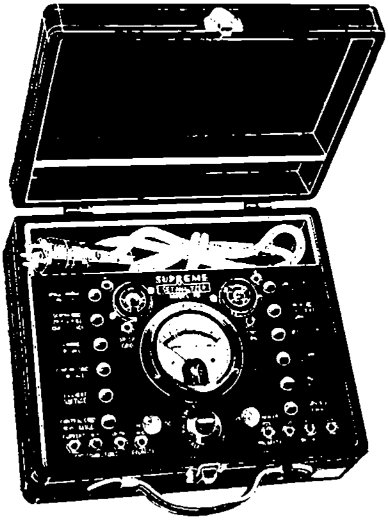
Procedure in analyzing: To start the analysis, the set is turned on and the volume control is set at the "MAX" position. The first electrical check should be made on the power supply unit to determine whether it is supplying the normal voltages to the various circuits of the radio set. If the set is of the battery-operated type, check the voltages of the various batteries, with a voltmeter. If the battery voltages are low, they should be re-charged or replaced. (Note: A 45-volt "B" battery unit should be discarded when its voltage drops to about 30-35 volts, measured while it is being used.)

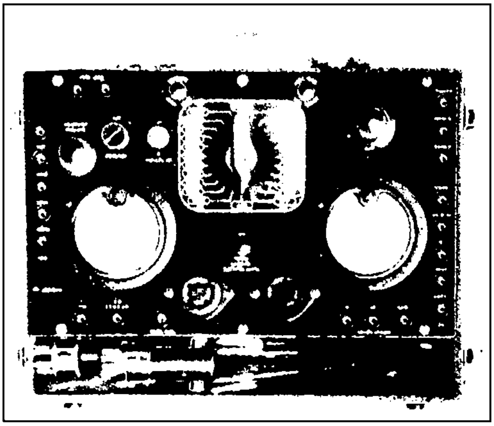
If the receiver is electrically operated, the line voltage should be checked next with a suitable voltmeter. The rectifier tube or tubes should be checked next. The voltages being applied to the rectifier tube plates by the power transformer should be checked next.

After the source of power to the radio set has been checked in this way, the next procedure is to check the current and voltage supplied to all terminals of each tube in the circuit. The usual practice is to check the tubes in the order in which the signal passes through them, that is, start with the antenna stage and end with the power amplifier or output stage.

Each tube should be removed from its socket in turn, in the above order, placed into the socket of the analyzer, and the plug of the analyzer placed into the same socket of the receiver from which the tube was removed. By pressing the proper buttons and manipulating the proper switches, as explained in detail in the instruction book accompanying the particular analyzer employed, all of the important voltage and current readings existing at each tube socket may be obtained. The number of readings taken is dependent upon the type of tube used. For a complete analysis of the circuits to a 3-element tube, it is necessary to measure the following values: (1) plate voltage, (2) plate current, (3) grid voltage, (4) grid current, (5) filament voltage. Where cathode, screen grid or pentode tube circuits are being analyzed, the following additional measurements should be known: (6) cathode voltage, (7) screen grid voltage, (8) screen grid current. When making these tests on each tube in the receiver, a rough test of its mutual conductance should also be made by the "grid test method" explained in Art. 290. Set analyzers are provided with a "grid test" button for making this test. These readings may be seen in the last two columns in the table on P. 900.

If this analysis of the voltages existing at the terminals of the tubes shows improper voltages to exist at any terminal, all of the parts in that particular circuit should then be tested for continuity, grounds, short-circuits, etc.



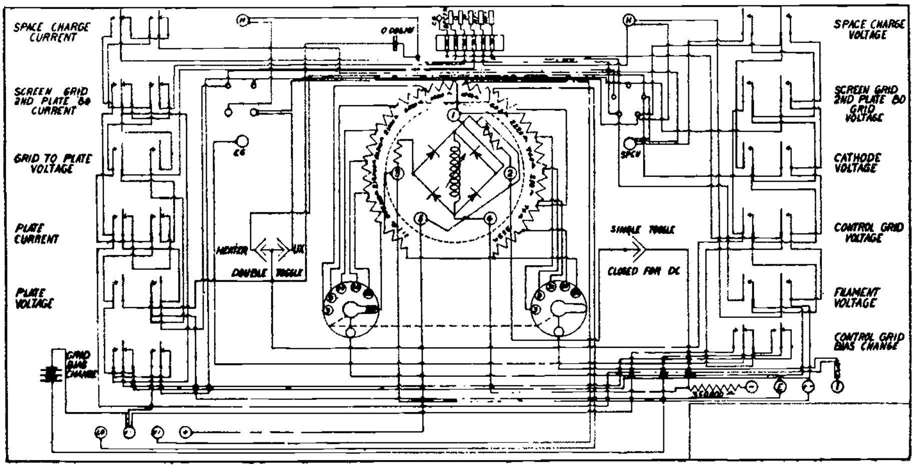


Courtesy Supreme Instruments Corp. *Courtesy Weston Elect. Inst. Co.*

Fig. 474—Left: A typical set tester and analyzer arranged in a portable case. A single copper-oxide type meter and suitable switching arrangement performs all tests. The circuit diagram is shown in Fig. 475. The "dummy-plug" and cable are in the compartment at the rear.
Right: A typical set tester and analyzer with an a-c meter and a d-c meter. The single selector dial at the center controls the switching arrangement for the entire unit. (Weston Model 566 Type 3).

Trouble-localizing: Locating the inoperative part or open connection in a circuit may be accomplished by a simple continuity test, (see Article 622), if the diagnosing process shows the trouble to be due to an open circuit. The simple continuity test is of no value however, when the trouble is due to a short circuit across a device which has a low resistance. In cases of this kind an actual resistance test of each part in the circuit, by low-resistance measuring equipment, is necessary to locate the unit causing the trouble. Of course it is necessary to know the rated resistance value of the unit tested, that is, its ohmic value as specified by the receiver manufacturer. Some manufacturers mark the resistances of the parts directly on the circuit diagrams, as shown in the diagram of Fig. 472. Open circuits are more easily located than short circuits, for the latter do not generally show up in the diagnosis with the set analyzer or voltage test, since they do not materially affect the operating voltages unless the short circuit is *across* the circuit somewhere.

631. Commercial set testers or analyzers: The set analyzer or test circuits we have considered are extremely simple ones. Modern set analyzers are provided with rather complicated switching arrangements and usually contain but one or two meters to be used for all measurements, both a-c- and d-c. These meters are provided with several multiplier resistors and switching arrangements which enable various ranges to be obtained and enable the operator to switch them to the various circuits to measure the voltages and currents. In addition, suitable terminals are provided for the connection of test prods and leads for making individual tests. These include voltage and current tests, continuity tests, resistance measurements, etc. It is not possible to go into the various circuit arrangements and test procedures to be followed with these instruments here.* Complete instructions are furnished with these testers by



Courtesy Supreme Instruments Corp.

Fig. 475—The complete schematic circuit diagram of the set analyzer shown at the left of Fig. 474. Notice the connections of the single copper-oxide meter, and the multiplier resistors at the center. Also notice the various push-button switches at the left and right for connecting the meter to the various circuits of the tube under test.

the manufacturers in each case. Two typical set testers or analyzers which are representative of these devices are shown in Fig. 474.

The set analyzer at the left employs a single meter of the copper-oxide rectifier type (see Article 214), measuring a-c and d-c voltages in six ranges up to 900 volts, and a-c and d-c currents in five ranges up to 300 milliamperes. It may also be used as an output meter (see Fig. 153) in lining up or adjusting the tuning condenser sections in a gang condenser, and adjusting the tuned circuits in the i-f amplifiers of superheterodynes. Terminals are also provided for making external measurements and tests. The complete circuit diagram of this analyzer is shown in Fig. 475. Notice the connections of the copper-oxide type meter and the multiplier resistor system at the center.

The analyzer shown at the right of Fig. 474 contains two meters—one for a-c and one for d-c measurements. The single selector-dial at the center operates a very ingenious switching arrangement which automatically connects the instruments properly in the tube circuit, for any particular test which may be required. Terminals

*For a more detailed and complete treatise on this phase of the subject, see "The Radio Servicing Course" by Alfred A. Ghirardi & Bertram M. Freed. Published by the Radio & Technical Pub. Co., 45 Astor Place, New York City.

are also provided along the left and right edges for making external tests and measurements. Both analyzers are enclosed in suitable portable carrying cases. Notice that each is provided with both a 4-prong and a 5-prong socket into which the tube from the receiver is inserted. The socket used, depends on whether the tube is of the 4 or 5-prong type. Also notice the cable and 5-prong plug in the rear compartment of the tester on the left. The rear compartment of the tester on the right contains, from left to right, two sets of test wires and prods for external testing of circuits and parts, the 5-prong plug for inserting into the receiver socket, and the 4-prong adapter used when circuits to a 4-prong tube are to be tested. Both of the testers shown, are provided with facilities for testing all of the tubes in the receiver, under the voltage conditions which actually exist in the receiver.

632. Aligning tuning circuits: Both the sensitivity and the selectivity of the present-day single-control t-r-f receiver depends particularly upon how well each individual tuned circuit is in resonance with the others at all positions of the tuning dial. In superheterodyne receivers, it is necessary not only to line up the tuning of the t-r-f and oscillator circuits, but it is also necessary to line up the tuning of the usual band-pass i-f tuned circuits all exactly to the band-pass frequency employed in the receiver. Many receivers do not hold their adjustments; in many, the adjustments must be checked up when new tubes are inserted in the receiver. In either case, it is often necessary to align these tuned circuits so that maximum sensitivity and selectivity are obtained.

One way to align these tuned circuits, is to tune in a distant or weak station, and adjust the *trimming* or *compensating* condensers provided. If the receiver employs tuning condensers with a slotted rotor plate in each section, (as shown in Fig. 268 and 269), the individual segments of the slotted plate must be bent in or out at various positions of the tuning dial, until maximum signal strength results in each case, as judged by the ear. This method is tedious and inaccurate, as the ear is not sensitive enough to be able to distinguish between small changes in intensity of the output sound produced by the receiver (see Arts. 421 and 423) while the adjustment is being made, thus leading to inaccurate adjustment.

633. Use of the output meter in aligning: A more suitable and accurate method of judging the output, is to use an "output meter" of the copper-oxide type (see Article 214 and Fig. 153) for indicating the exact value of the output of the receiver while the aligning is being accomplished. This is very much more accurate than the ear. Some output meters are calibrated directly in volts, others are calibrated in milliwatts. The connections for the output meter will be discussed in Art. 638.

634. Need for the "test oscillator": The tuned circuits in receivers can be aligned by adjusting them while listening to the program from a weak station tuned in, but the use of a special miniature broadcasting station or oscillator for this work permits of much more rapid and accurate adjustments. If the program signal from a broadcasting station is used for this purpose, the *input signal strength* and the *loudness* or *modulation* of the program are very likely to vary while the adjustments are being made, thus leading to incorrect adjustment. When a "test oscillator" is employed for this purpose, the coupling to the receiver, strength of input signal, etc., may easily be adjusted for best conditions, and the frequency is easily adjusted to any particular value desired. A *modulated oscillator* must be used for this purpose.

635. The oscillator circuit: We have already studied how a vacuum tube can be made to produce oscillations of almost any frequency by connecting it in a circuit arranged to continuously feed back some of the energy from the plate circuit (see Arts. 308 and 388).

In an oscillating vacuum tube, part of the varying plate energy is fed back to the grid, inducing an alternating voltage in the grid circuit. This is then amplified by the tube. The limit of amplification is reached when the grid voltage builds up to

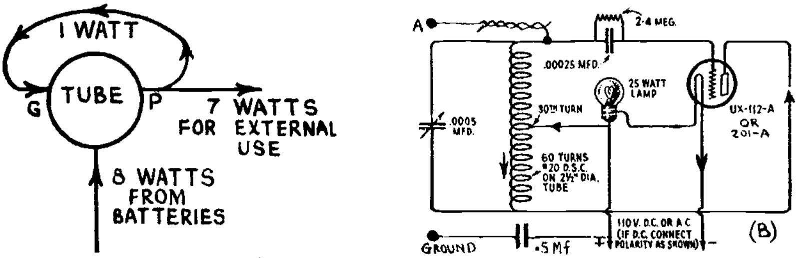


Fig. 476—Left: The action of the oscillator tube.
Right: A simple portable test oscillator designed for the broadcast band. It may be operated from either an a-c or d-c volt electric-light circuit.

a value large enough to swing over the whole length of the characteristic curve of the tube, for at the ends of the curve any increase in grid voltage has little or no effect in increasing the plate current (see D of Fig. 327).

To consider a case with simple figures, if one watt of energy is all that is required in the grid circuit to make up for the various circuit resistance losses, etc., to work the tube to capacity and to set into motion eight watts of energy in the plate circuit, then by suitably coupling an external circuit to the plate circuit we can absorb seven watts from it for any purpose we desire, and feed one watt back to the grid circuit to be used in sustaining the oscillations. (The extra power comes from the "B" voltage supply device.) This is the principle of the usual oscillator, and is shown in an elementary way at the left of Fig. 476. It is evident that the action of a tube as an oscillator really depends upon the "amplifying properties" of the tube.

There are several common oscillator circuits, each one having certain desirable characteristics which make it suitable for a certain use, all working on the principle of feeding energy back from plate to grid. They are named after the men who first developed them.

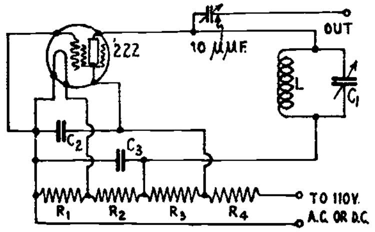
636. Simple test oscillators: A simple, portable, self-modulated oscillator circuit which may be operated directly from either a 110 volt a-c or a d-c electric light line, and which is useful in service work for "aligning" the tuned circuits of single-dial control receivers, is shown at the right of Fig. 476.

The coil-winding and tuning condenser data for the construction of a unit of this type for covering the broadcast band from 500 to 1,500 kc is given on the diagram. The arrows show the direction of the plate current. Feedback occurs due to the magnetic field of the part of the coil in the plate circuit linking with that of the part of the coil in the grid circuit. The gridleak and condenser cause the regular blocking action in the grid circuit which modulates the signal, the frequency of the modulation depending on the values of the condenser and leak employed. The entire unit really comprises a regenerative detector operating with sufficient feedback of energy from the plate to the grid circuits to cause oscillation. This oscillator may also be built in battery-operated form by using a separate "A" battery for the filament circuit, and separate "B" battery for the plate circuit. The A+ and B—, or A— and B—, should *not* be connected together. The wire from the terminal marked "A" is an insulated wire twisted together with the insulated wire connected to the tuning circuit, for a distance of 1 or 2 inches. This provides enough capacity to transfer energy from the oscillator to the receiver. A small midget condenser of about 10 mmf. capacity between these two wires will also serve the same purpose, with the advantage that the coupling may be easily varied. Terminal "A" is to be connected to the "antenna" terminal of the receiver and the "ground" terminal connects to the ground terminal of the receiver. This oscillator could be designed to produce the 175 or 180 kc frequency required for adjusting the band-pass i-f circuits of superheterodynes, by using the proper honeycomb type tuning coils, and tuning condensers of proper capacitance (see honeycomb coil data in Art. 408).

An r-f oscillator, somewhat simpler in general construction, and which will maintain its calibration quite accurately, can be built using the "dynatron" oscillator circuit.

The *dynatron oscillator* uses a screen grid tube operated at such voltages that it is operating at the region below the zero line in the E_p - I_p characteristic curves at the left of Fig. 228. For these values of plate voltages, the secondary emission from the plate (see Article 317 and 318) causes an electron flow in the reverse direction to that normally found in a tube, and oscillations are produced if a tuned circuit is connected in series with the plate, the frequency of these oscillations being determined by the frequency to which the circuit is tuned. Whereas, oscillators using three electrode tubes require coils in both the plate and grid circuits to make them oscillate, the dynatron requires only a single coil. This simplifies the circuit of course, and also makes it easier to use a plug-in coil arrangement for producing oscillations over a wide range of frequencies.

The circuit diagram at the left of Fig. 477 shows a dynatron oscillator arranged to operate directly from the 110 volt line; the voltage may be either a-c or d-c. In the case of d-c voltages, the upper line terminal shown must be the "positive". The necessary potentials for the filament, screen grid and plate (it will be noted in this circuit that the control-grid is tied directly to the filament) are obtained by means of four resistors connected in series across the 110 volt line. Resistance R_4 (50 ohms) serves to reduce the line voltage to about 60 volts for application to the screen grid. R_3 (300 ohms) further reduces the voltage for the plate circuit. R_1 of 1,000 ohms,



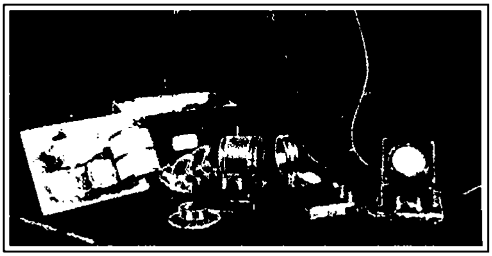


Fig. 477—Left: A simple dynatron oscillator circuit suitable for use as a portable test oscillator. The "constants" of the parts are given in the text.
Right: A dynatron oscillator used in school work for lining up tuning circuits. The tuning coil and condenser are shown mounted on the panel at the left.

and R_2 of 150 ohms, function to supply about 3.3 volts to the filament of the tube. The screen and plate circuits are by-passed to the filament by 1-mf. condensers C_2 and C_3.

If the oscillator is to cover the broadcast band then L and C_1 can be any ordinary coil and condenser designed for use in a broadcast receiver. An old radio-frequency transformer can be used with the primary removed.

When the oscillator is to be used for working on the i-f amplifier of superheterodyne receivers, L can be replaced by a honeycomb coil that will tune to the desired frequency with the condenser C_1. The oscillator can even be used to generate audio frequencies by connecting the primary of an audio transformer in the plate circuit of the tube. By arranging the oscillator to use plug-in coils it will be possible to cover any desired frequency range simply and quickly. If good coils are used the frequency generated by the oscillator will be found to be unusually stable.

637. Commercial test oscillators: A typical complete "modulated" test oscillator with self-contained batteries for its operation, and constructed to be portable, is shown at the left of Fig. 478. The battery compartment is at the left. The oscillator panel and tuning dial are at the center, and the built-in output meter is shown at the right. This makes a complete outfit for checking up the alignment of tuned circuits, for neutralizing receivers, and also for measuring capacity of condensers, inductance of coils, for use as a wavemeter, etc. Its circuit diagram is shown in Fig. 479.

It is completely shielded and has a range from 550 to 1,550 kc for broadcast frequency work, and also a range of 110 to 200 kc for long wave and superheterodyne intermediate-frequency amplifier work.

A positive indication of oscillation is provided by a direct current milliammeter which is normally connected in the grid circuit and serves as a "grid-dip-meter" to

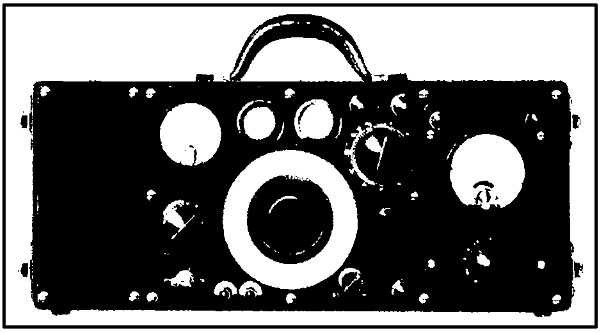


Fig. 478 — Portable modulated battery-operated test oscillator for test work on t-r-f, and superheterodyne receivers, and for tuned circuit aligning. The "grid-dip" resonance indicator is at the upper left; the tuning dial is at the center; an "output meter" is provided at the right. The circuit diagram is shown in Fig. 479. (Weston Model 590.)

Courtesy Weston Elect. Inst. Co.

indicate when the condition of resonance has been reached. It also serves as a guide to show when the oscillator is on.

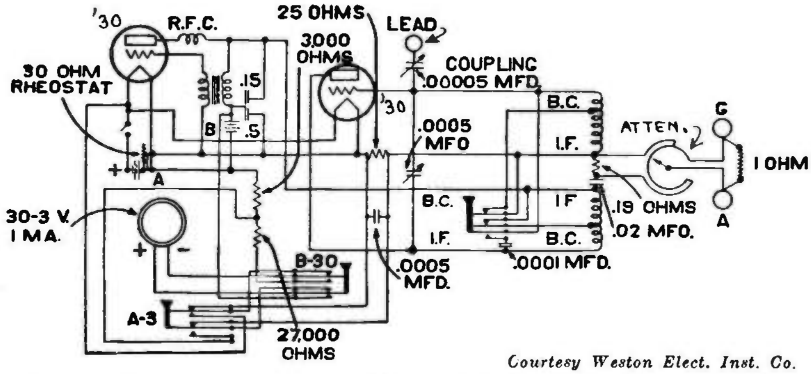
A specially designed attenuator controls the output of the oscillator, which may be varied smoothly and gradually from zero to approximately 5,000 microvolts.

The oscillator uses two '30 type tubes which require a filament current of 60 milliamperes each. With four 1½ V. unit flashlight-type cells, the oscillator will operate satisfactorily for a period of about 20 hours continuously, and much longer when used intermittently.

An external view of another very handy commercial test oscillator is shown at the left of Fig. 480. The metal shield over the oscillator tube is visible directly behind the frequency-adjusting dial. The "signal-strength" or "output control" knob is directly below this. The circuit diagram of this oscillator is shown in Fig. 481.

The oscillator is designed to operate directly from the 110-volt a-c electric light circuit. The r-f signals it produces are automatically modulated *steadily* by the 60-cycle plate-current ripple produced by the a-c power supply employed as the plate voltage source. This modulation causes the output signal of the radio receiver coupled to the oscillator during test, to have an audio-frequency hum corresponding to this modulation frequency. This makes it audible. The grid leak and condenser shown, are not for modulation purposes but are included to provide proper grid-bias for the oscillator tube and to provide protection to the oscillator circuits against possible short-circuits between the grid and plate elements of the oscillator tube. (Notice that the grid-condenser capacity is very large, .02 mf).

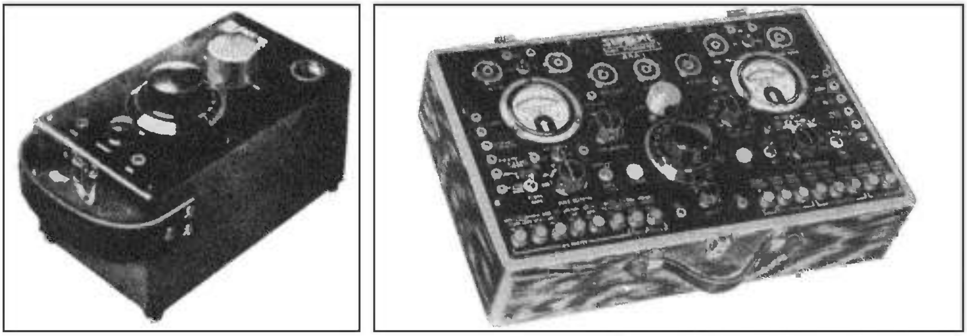
A type '30 tube is employed. The tuning unit consists of a 6,200 microhenry inductance coil tuned by a .0005 mf. variable condenser operated by a vernier dial. These provide a fundamental tuning range of 90 to 250 kc. By utilizing the "harmonic frequencies" generated, the tuning range is spread from 90 to 1500 kc, so the oscillator may be used for aligning the tuned circuits in both r-f and i-f amplifiers. The output signal strength is adjusted by means of potentiometer R_1. This varies the plate



Courtesy Weston Elect. Inst. Co.

Fig. 479—The circuit arrangement employed in the Weston Model 590 test oscillator shown at the left of Fig. 478. A feature of this oscillator is the separate modulator tube at the right. The grid-dip milliammeter provided in the grid circuit of the oscillator to indicate when the tuned circuit being adjusted is tuned exactly to the frequency of the oscillator, is a very helpful feature.

voltage applied to the tube, and so varies the output directly. The full resistance of R. as well as resistance R_2 are always in the circuit in order to reduce the 110 volts of the line down to the 2 volts required for the tube filament. A 6-turn coupling coil L_3 picks up the energy from the tuning coil, and connects to the output circuit. A rather elaborate filter system consisting of two r-f chokes and by-pass condensers

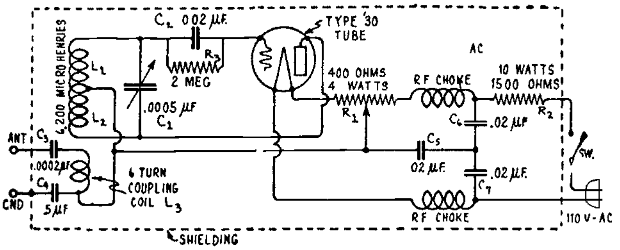


Courtesy Supreme Instruments Corp.

Fig. 480—Left: External view of the a-c operated test oscillator whose circuit diagram is shown in Fig. 481. The entire unit is enclosed in a portable carrying-case. The frequency-adjusting dial is at the center. The leads for connecting to the receiver are not shown here (see Fig. 482 for connections to receiver). (Supreme Model 60)
Right: A complete testing and servicing instrument containing in a single case, a set analyzer, a tube tester, a test oscillator, and an output meter. Simple switching arrangements enable rapid tests to be made. (Model AAA-1 Diagometer).

C_5, C_6 and C_7 prevent any of the r-f energy from feeding back into the electric light circuit and causing disturbances in radio receivers which may be operating from the same lighting circuit.

At the right of Fig. 480 is a very ingenious combination testing and servicing instrument of great usefulness. It contains in its single portable carrying-case, a complete set analyzer and tester, a shielded modulated "test oscillator," an output meter, and a tube tester. Thus it contains within its single case, all of the devices required for rapid intelligent servicing of all forms of radio receivers. Its meter ranges permit measurements as high as 1,200 volts to be made, thus making it useful for



Courtesy Supreme Instruments Corp.

Fig. 481—The circuit arrangement employed in the Supreme Model 60 Test Oscillator shown at the left of Fig. 480. The oscillator tube is purposely made to generate strong "harmonic" frequencies which are utilized to give the oscillator the wide frequency-range of 90 to 1500 kc. with a single tuning condenser and set of tuning coils.

servicing public-address and sound amplifier equipment. The shielded "test oscillator" is calibrated for every frequency between 90 and 1,500 kc.

638. Aligning the tuned circuits in t-r-f receivers: The use of the modulated r-f test oscillator for adjusting the tuned circuits of a single-dial t-r-f receiver so that each tuned circuit is exactly in "resonance" or "tune" with all of the others at any position of the dial, will now be considered. This proceedure is commonly called, "ganging", "aligning" or "synchronizing". The aligning is usually done by adjusting either the small variable compensating condensers connected in parallel with each of the main tuning condenser sections (see Fig. 100), or else by bending in or out slightly, the fan-shaped segments of the end rotor plate of each condenser section in the gang, when such segments are provided, (see Figs. 268 and 269. Study (B) of Fig. 268).

Type of aligning adjustment provided in receiver: Mention must be made at this point of the fact that the older broadcast receivers do not have slotted end-plates provided for the purpose of condenser alignment. In this case, where only separate compensating condensers are provided for each section of the gang condenser (see Fig. 100), the tuning can be lined up *exactly*, only at one point on the dial. This is usually done at the frequency which the receiver is tuned to, when the tuning dial is set at about 50. In these sets, if the volume or tuning is off at each end of the dial, nothing much can be done about it. If several desired stations that come in at either end of the dial are received poorly, the receiver may be balanced so that these stations are received. Then stations at other points on the dial will come in with less volume.

When a fan-cut rotor plate is provided on each section of the gang tuning condenser, the tuning may be aligned *exactly* over the entire tuning range. The method of adjusting such condensers, is explained in detail at about the middle of Art. 373. This should be studied carefully again at this point. Condensers of this type are shown in Figs. 268 and 269.

The exact procedure to follow for aligning the tuned circuits of a single-dial control t-r-f receiver by means of a modulated r-f test oscillator of any of the types described in Arts. 636 and 637, is as follows: (It is assumed of course that the receiver is in satisfactory operating condition.

(a) Connecting the oscillator: Disconnect the "antenna" wire from the "Ant" terminal on the radio receiver chassis, so that broadcast signals will not interfere with the signal to be fed to the receiver by the test oscillator. Connect the "Ant." terminal of the test oscillator to the "Ant." terminal on the receiver (or to a special contact point which is in some cases specified by the receiver manufacturer). Connect the "Gnd." terminal of the test oscillator, to the "Gnd." terminal of the receiver. (Most commercial test oscillators are provided with a special shielded lead for these connections, as shown in Fig. 482. In this case, the inside wire connects the "Ant." terminals of both the receiver and test oscillator together. The outside metal shielding (which is insulated from the inside wire), connects the "Gnd." terminals of both the receiver and the test oscillator together. This shield prevents direct radiation of signal energy from the oscillator connecting wire, and makes it all go through the proper channels and tuning circuits of the receiver.) In most cases, the usual "ground" wire should be left connected to the "Gnd." terminal of the receiver or oscillator during the aligning procedure. The entire aligning setup is shown in Fig. 482.

(b) **Testing the receiver and test oscillator:** To find out whether both the receiver and test oscillator are operating properly, turn on the operating power supply to both the receiver and the test oscillator. Set the oscillator for operation on the broadcast-frequency range. As the radio tubes attain their normal operating temperature, turn the oscillator "output" or "attenuator" control part way up, then set the oscillator tuning-dial at whatever frequency it is desired to start the aligning. Now tune the receiver until the oscillator signal is heard loudest. The volume control of the receiver should be set at "maximum" position. If the signal is too loud, it should be reduced by adjusting the "attenuator" knob on the test oscillator.

(c) **Possible ways of connecting the output meter:** If it is desired to use an "output meter" (see Fig. 153) to indicate when the receiver has been aligned properly so it produces "maximum" signal output for a given signal input fed to it by the test

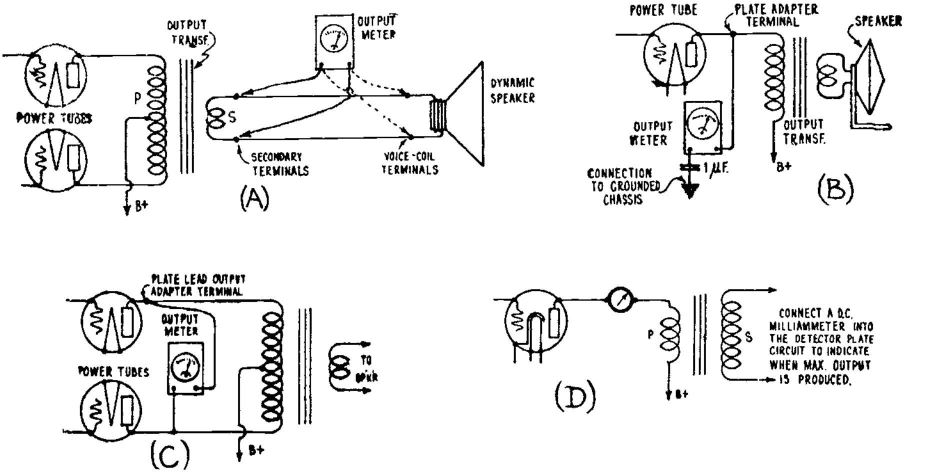


Fig. 481A—(A) The output meter may be connected either across the secondary terminals of the output transformer or across the voice-coil if an electro-dynamic speaker is used in the receiver.
(B) Using a plate-lead output adapter for connecting the output meter across the output if a single power tube is used.
(C) Where push-pull output tubes are used, the output meter may be connected across the plate circuits as shown, by means of plate-lead output adapters.
(D) An 0-5 m.a. d-c milliammeter connected in series with the plate circuit of the detector makes a good output indicator. The indication to be watched for depends on the type of detector employed (see Art. 638 (c)).

oscillator (see Art. 633), turn the power-supply switches "off." The output meter may be connected to the receiver in several ways, depending upon the receiver output stage, and loud speaker arrangements. If the receiver uses an electro-dynamic type of loud speaker, perhaps the most convenient way of connecting the output meter, is directly across the terminals of the voice-coil, or across the secondary terminals of the output transformer, as shown at (A) of Fig. 481A. If these terminals are not easily accessible, or if a magnetic cone or horn type speaker is employed, the output meter should be connected to the plate circuit of the power output tubes in the receiver.

Here again there are two possible cases—either the receiver uses a single output tube or uses two tubes in push-pull. Also, some of the older battery-operated receivers use an output transformer (or output choke-and-condenser filter), between the plate of the power tube and the speaker terminals. Instead of opening up the connections to these inside the receiver, "plate-lead output adapters" may be employed to break into the plate circuit of the power tube without disturbing any connections. Adapters of this kind are provided with most test oscillators.

In the case of receivers using a single power tube, this tube should first be removed from its socket. The plate-lead output adapter is now inserted over the tube prongs, then the tube is put back into the socket (with the "adapter" in place). The other side of the output meter goes to a 1 mf. condenser, the other side of which should be connected or "clipped on to" the "grounded" chassis of the receiver. The connections of the adapter, output meter, and condenser into the power output tube circuit in this case, are shown at (B) of Fig. 481A.

In the case of receivers employing a push pull output stage, one of these adapters should be inserted in each of the push-pull tube sockets, and the output meter connected to the plate terminals of these adapters as shown at (C).

If a regular output meter (see Fig. 153) is not available, a 0-5 d-c milliammeter connected in the detector plate circuit as shown at (D) may be used instead. If no separate milliammeter is at hand, the milliammeter in a set analyzer may be used for this purpose by inserting the plug of the set analyzer into the detector socket and setting the proper switches to read the detector plate current. If this "plate milliammeter" output indicator is used, with receivers using "grid-bias" or "power" detection, the receiver should be aligned so that *maximum* plate current reading is obtained on the meter. With receivers using "grid leak-condenser" detection, the receiver should be aligned so that *minimum* detector plate current reading is obtained, since in this form of detector the plate current is "reduced" by "increased" signal voltage applied to the grid.

Another simple output indicator, which can be applied to superheterodyne receivers, is a low-range high-resistance voltmeter connected between the "cathode" of the second detector tube and the metal "chassis" (B minus). The readings will be affected by the carrier wave only, and are practically independent of the modulation (since the by-pass condenser across the grid-bias resistor here, smooths out the a-f variations of voltage drop across it).

(d) Aligning the tuned circuits in the t-r-f receiver: After the output meter has been properly connected in one of the ways just described, both the test oscillator and the radio receiver should be turned "ON" and the tubes allowed to warm up for a few minutes. Adjust the output meter range-control for a meter deflection at or below two-thirds of the full-scale deflection. The output meter deflections are arbitrary and are watched merely to find out when "maximum" output is being obtained from the receiver.

With the oscillator operating at a definite frequency—preferably at the high-frequency end of the broadcast-band range—adjust the receiver tuning dial until maximum reading is obtained on the output meter. Now vary whatever adjustments are provided on each section of the gang tuning condenser until maximum output is indicated on the meter. The "attenuator" or "signal strength control" of the test oscillator should be adjusted for less output from the oscillator as the output of the set increases. During the meter indications, the oscillator signals should be audible from the loud speaker. Failure to hear the signals which are indicated by the meter, would be an indication of defective output transformer or loud speaker circuits.

If slotted rotor plate adjustments are provided on the tuning condenser, the adjustment of the segment which is just entering into mesh with the stator plates, should be varied in each condenser section (see Art. 373). In most cases, receiver manufacturers supply information as to the exact frequency at which each segment should be adjusted. Usually these fan-shaped rotor end-plates are made with 5 or 6 segments. One prominent manufacturer uses condenser gangs (see Fig 269), which have each end rotor plate cut into 5 segments, and recommends the following frequencies for adjustment: **1120 kc, 840 kc, 700 kc, 600 kc, and 500 kc.** Where no information is at hand, the adjustments should be made at such oscillator frequencies, that *in each case* when the receiver is tuned to the oscillator frequency, the split segment is about half way in mesh with the stator plates. If receivers possessing this desirable construction feature are aligned carefully, the tuning will be lined up properly over the entire scale or tuning range of the receiver.

(e) **End of the aligning:** After completing the adjustments, turn the radio receiver "off", disconnect the oscillator: re-connect the antenna wire to the "ANT." terminal of the receiver; remove the output adapters (if any have been used) and return the power tubes to their own sockets; disconnect the output meter.

Now turn the radio receiver "on" again and test its ability to bring in stations all over the dial. without oscillation and with sharp tuning. This completes the aligning proceedure.

639. Aligning the tuned stages in superheterodynes: In modern single-dial, superheterodyne receivers, the tuning of the tuned radio-frequency circuits and the oscillator circuits is usually accomplished with a gang tuning condenser. These tuned circuits must be "lined up," but this is usually done after the intermediate-frequency stages have first been aligned.

In these sets, the tuned circuits of the primary and secondary windings of the tuned intermediate transformers (see Fig. 283), must first be aligned at whatever intermediate frequency the receiver is designed for. Intermediate frequencies of 170

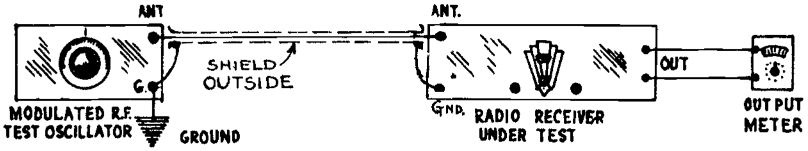


Fig. 482—Test oscillator, radio receiver, and output meter setup for aligning the tuning circuits in a single-control receiver. The oscillator feeds signals of the desired frequency to the receiver. The output meter measures the output of the receiver. The capacity adjustment provided on each section of the gang tuning condenser of the receiver is varied until the output meter indicates that maximum output is being obtained from the receiver. When this is obtained, it indicates that the tuning circuits are properly aligned.

to 180 kc are in common use, although in at least one make of receiver, a frequency as high as 260 kc is used. These stages are adjusted to tune to a definite frequency before leaving the factory, and if for any reason the alignment becomes changed thereafter, the set will not function properly. The general symptoms are, weak reception, broad tuning, and in some cases, poor fidelity. The detailed proceedure to be followed in aligning the intermediate-amplifier tuned circuits will now be considered. It should be remembered that it is not only necessary to align the intermediate stages with each other, but the entire combined i-f amplifier must be tuned accurately to the particular intermediate frequency for which it was designed.

Aligning the intermediate-frequency stages: (a) The oscillator tube in the *receiver* should be removed from its socket and the receiver turned on. The "output meter" or other output indicating device to be used should be properly connected to the receiver as outlined in the section headed "Possible ways of connecting the output meter," in Art. 638.

(b) Now adjust the test oscillator so it is operating at the intermediate frequency specified by the receiver manufacturer (let us assume this is 175 kc). Connect the "Ant" terminal of the oscillator to the "control-grid" terminal (cap) of the *last* i-f tube. Connect the "Gnd" terminal of the test oscillator (usually the "shield" on the previous wire), to the "cathode" terminal of this tube. All the late superheterodyne receivers use screen grid tubes in the intermediate stages. Where 227 type tubes are employed in the i-f stages, as in some of the earlier models, instead of coupling the oscillator to the control-grid cap of the screen grid tube as mentioned, it should be connected to the "grid" terminal of the 227 type tube. This may be done conveniently by removing the tube from its socket, wrapping the "bared" end of the wire tightly around its "grid" prong, and then placing the tube back in its socket (with the wire still making contact with the "grid" prong).

Usually there are two i-f stages, though in many sets only one stage is used. The primary and secondary coil of each stage is tuned by means of a small semi-variable 2-plate condenser of the "postage stamp" type. The interior of a typical intermediate-frequency tuning unit with its shield removed, is shown in Fig. 285. The primary and secondary coils are of the duolateral type mounted on a wooden spacing-bar. The adjustable tuning condensers in the base of the unit, are those which must be adjusted. They are usually constructed so that a screwdriver is all that is required in order to turn the adjusting screw on each one. Therefore, in a two-stage i-f superheterodyne receiver there will be 6 adjustments, and where only one stage is employed, 4 adjustments will be found. The secondary tuning condenser and then the primary condenser of the *last* i-f transformer should be adjusted for maximum output. Next, the test-oscillator coupling lead should be connected to the control-grid cap of the 1st i-f tube, where the receiver has two i-f stages, and adjustment of the condensers in that stage made for maximum output. To tune the 1st i-f transformer, the test-oscillator "Ant" lead is coupled to the control-grid of the 1st detector tube, and the test-oscillator "Gnd" lead is connected to the "cathode" of this tube. The secondary and primary tuning condensers are now adjusted until maximum output is indicated on the output meter.

Adjusting band-pass i-f tuners of the superhet: Some manufacturers have designed the intermediate-frequency stages of their superheterodyne receivers with a band-pass effect so their tuning curve is flat-topped in order to minimize the suppression of sideband frequencies with the resultant poor high-frequency note reproduction. With these i-f amplifiers, no appreciable change in output meter reading should be obtained when the test oscillator frequency is shifted from 171 kc to 179 kc (for a 175 kc amplifier). In other words, any drop which may occur in the output should be the same when the test-oscillator frequency is shifted from 175 kc to 171 kc as it is when it is shifted from 175 kc to 179 kc. This will indicate that the flat-topped portion of the tuning curve of the i-f amplifier is properly centered at 175 kc. The reader should study (C), (D), (E), (F) and (G) of Fig. 257 at this point to properly understand this.

Aligning the oscillator of the superhet: After aligning the i-f stages, the adjustment provided on the receiver oscillator stage tuning condenser section should be adjusted next. This is one of the most important operations in the entire proceedure, and it determines the dial settings at which broadcasting stations are received.

The test oscillator should be connected to the "Ant" and "Gnd" terminals of the receiver exactly as specified for aligning t-r-f receivers, (see Art. 638). The oscillator tube should be in its proper socket in the receiver. Adjust the test oscillator to a frequency near the high-frequency end of the broadcast band. Now vary whatever capacity adjustment is provided on the set oscillator stage tuning condenser section, until maximum output is obtained, as indicated by the output meter. Repeat this at several other frequencies in the broadcast range. This insures that the frequency of the receiver oscillator will always differ from that to which the r-f and first detector tuning circuits are tuned, by a fixed frequency equal to that for which the i-f amplifier is designed,—for any setting of the receiver tuning dial.

In some cases, the receiver pointer dial may have shifted in relation to the condenser shaft. This can be checked and adjusted by noting whether the kilocycle marking on the set dial corresponds with the frequency of the oscillator when the adjustments on the set oscillator condenser are being made.

Aligning the r-f stages of the superhet: The tuned circuits of the radio-frequency stages, (if any are employed), and the first detector stage, are aligned next. With the oscillator still connected as before, those sections of the gang condenser which tune these stages, are aligned in exactly the same way as explained for t-r-f receivers in Art. 638. The test oscillator is operated at several broadcast frequencies,—preferably starting at the high-frequency end of the dial. Proper adjustment is made until maximum output is obtained in each case. This completes the proceedure for aligning all of the tuned circuits of superheterodyne receivers.

REVIEW QUESTIONS

1. What is meant by "continuity" of a circuit?
2. Describe the process of testing a circuit for continuity.
3. Draw a diagram of the plate circuit of a vacuum tube in which the primary of an r-f transformer, and a voltage-dropping resistance are connected in series. A grid-bias resistor is connected between cathode and ground (B minus). Explain how to locate the trouble and determine its nature.
4. A short-circuited primary winding in an audio transformer is suspected as the cause of trouble in the receiver. The resistance of the primary is normally 2,000 ohms. Draw a circuit diagram, and explain how you would test the transformer.
5. How would you check the value of a grid-bias resistor supposed to be of 3,000 ohms resistance?
6. Suppose the by-pass condenser across this grid-bias resistor is of 1 mf. capacity. If this condenser were short-circuited, what effect would it have on the operation of the receiver? How would you test the condenser?
7. What is the first step in servicing an inoperative receiver?
8. Explain how the circuits terminating at a tube socket may be tested by means of separate instruments.
9. What is the advantage of the use of a set analyzer or tester instead of separate meters, for testing receivers?
10. Explain briefly the circuit arrangement and operation of a set analyzer.
11. Draw the circuit diagram of a battery-operated modulated oscillator which may be used for test for testing and lining up the radio-frequency and intermediate-frequency tuned stages of a superheterodyne receiver.
12. Explain how the tuned circuits of a superheterodyne receiver are lined up with a device of this kind. What is the purpose of the output meter used in this work?
13. What does failure to obtain voltage readings at the following points indicate in a receiver; (a) across the filament; (b) from plate to cathode; (c) from cathode to control-grid?
14. Explain in detail how you would proceed to diagnose the trouble and locate it definitely in a 5-tube t-r-f a-c tube electric receiver.
15. Explain the effect of a shorted filter condenser in a power supply unit. If the condenser is one of those in a condenser block, how could it be tested and replaced?
16. Obtain a picture wiring diagram of a simple battery-operated radio receiver, or better still, obtain a complete receiver chassis. Examine the parts and arrangement used in it and tell what type of circuit is employed. Give reasons for your answer.
17. Carefully trace the filament wiring of the receiver of question 16, and draw a complete schematic circuit diagram of it. Draw the diagram neatly and carefully.
18. Now trace all the plate circuits, and draw them in on the diagram.
19. Trace all the grid circuits, and draw them in.
20. Trace all remaining circuits and draw them to complete the diagram.
21. Repeat questions 16 to 20 for a "B" power supply unit.
22. Repeat question 16 for an a-c tube electric receiver.
23. Repeat questions 17 to 20 for this a-c tube electric receiver.
24. What is a 4-gang tuning condenser? What is the object of using "gang" condensers in modern radio receivers?
25. Four sections of a 5-gang tuning condenser in a t-r-f receiver are set at such capacity that they each tune their respective tuning coils to 1000 kc. The fifth section has been jarred out of alignment so that it is tuning its tuning coil to 990 kc at this setting. Explain in detail just what effect this will have on the operation of the receiver. How may it be corrected?

CHAPTER 36

SOUND MOTION PICTURES

GENERAL CONSIDERATIONS — GENERAL METHODS USED — SOUND-ON-DISC RECORDING SYSTEM — SOUND-ON-DISC REPRODUCTION — THE FADER — LOUD SPEAKERS — SPEECH AMPLIFIER — NON-SYNCHRONIZED MUSIC — SOUND-ON-FILM SYSTEM — THE LIGHT VALVE — REPRODUCING — SOUND-ON-FILM MOTION PICTURES — R. C. A. PHOTOPHONE SYSTEM — SPLICING FILM — COMPARISON OF SOUND-ON-FILM AND SOUND-ON-DISC SYSTEMS — REVIEW QUESTIONS.

640. General considerations: The rapid spread of the exhibition of sound motion pictures (commonly called talkies) in theatres, has aroused widespread interest in the methods employed in recording and reproducing the sounds accompanying the picture. The fact that radio equipment in the form of electrical phonograph pickups, photoelectric cells, powerful audio amplifiers and loud speakers are used in this work, makes a discussion of the prinicples involved, and the methods used, very appropriate here.

641. General methods used: There are two fundamental methods which are used in practice to synchronize sound with motion pictures. In the first, a disc record somewhat similar to the home phonograph disc is employed (Vitaphone System). This is commonly known as the *sound-on-disc* system. In the second system, an optical recording on a sound track is imprinted either along the edge of the motion picture film, or in some cases, on a separate film run in synchronism with the picture. The latter method is employed in the Fox Movietone, Phonofilm, and Photophone systems. This is commonly known as the *sound-on-film* system. The Vitaphone and Movietone methods were developed in the Bell Telephone Laboratories, and the Photophone by the Radio Corporation of America. All of these systems are being employed at the present time. They have revolutionized the motion picture industry.

642. Sound-on-disc recording system: The principle of the Vitaphone system, is to make a phonograph record of the sound simultaneously with the taking of the picture, and then play this record with a phonograph pick-up unit fed to amplifiers and loud speakers, while the picture is being projected on the screen. The sound is projected in absolute synchronism with the picture.

When the picture is being filmed, the sound is picked up by several microphones located at advantageous positions in the studio. These feed into the "mixing panel" which is operated by a man located in a special glassed-in "monitor" or "mixing room," overlooking the scene of action (see

Fig. 483). The operator views the stage upon which the action takes place, through several thicknesses of glass to make the "mixer room" absolutely quiet. This is one of the most important parts of the sound apparatus in the entire circuit. The inputs of all the microphones are blended here and the operator can increase or decrease the input of any one microphone at will. Thus he is able to "pull up" or "tone down" the voice of a star, the music from the orchestra, etc.

The director on the floor, controls the recording, etc., by means of a signal box which contains signal lights and push buttons for signalling the

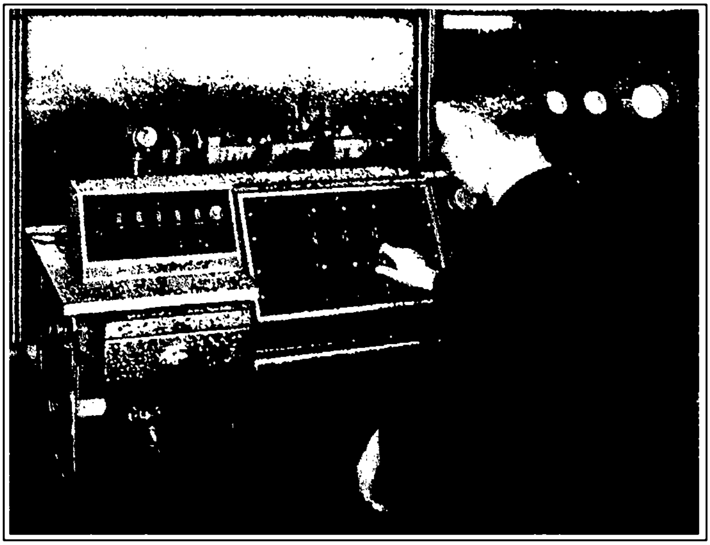


Fig. 483—The "mixer room" of a United Artists sound motion picture studio. Here the output of the various microphones used during the filming of a picture are blended together in the proper proportion by the operator.

various stations concerned in the filming and recording. A scene on a "set" in a sound stage studio just before the scene is "shot", is shown on the left of Fig. 484. All direction is done by motion of the hands or arms. In this picture, all parts of the set are plainly seen. The microphone M is suspended from a boom at the left, almost directly over the star who is seated, and out of visual range of the cameras taking the scene.

Every possible effort is made to prevent the pickup and recording of undesirable noises during the filming of the scene. Arc lights in motion picture filming have given way to huge noiseless incandescent lamps L, as the objectionable sputtering and hissing noises of arc lamps would be recorded along with the rest of the sounds.

The cameras are enclosed in sound-proof housings which may be easily opened to permit access to the mechanism. Two types of these sound deadeners are employed. The type shown at B at the left of Fig. 484 consists of a sound-proof box B as shown. The type shown at the left of Fig. 485 consists of a soft-padding blanket enclosure placed over the entire camera. This is commonly called a "blimp". A box-like housing which encloses cameras for outdoor work is also shown at the right of Fig. 485. This machine contains the camera with its sound proof enclosure at the top. This can be swung in any direction and raised up or down vertically. This machine can move about the stage under its own power, carrying the cameraman and his assistant, when taking scenes of moving objects. In the past, a crew of 3 or 4 "grips" was necessary to keep the camera in motion for such a "shot". The camera mechanism is coupled to an electric driving motor by a noiseless flexible shaft.

The studio in which sound pictures are recorded, must be either sound-proof or acoustically treated, so that sounds from outside cannot penetrate and be picked up

Courtesy Universal Pictures Corp.

Fig. 484—Left: A scene on a sound picture "set." Note the condenser-type microphone M over the seated star. The sound-proof compartment B over the camera is visible. Right: Taking outdoor scenes with the cameras placed in sound-proof enclosures.

by the microphones within the studio, and thus interfere with the sound record being made. The acoustic treatment also prevents reverberations, echos and other objectionable sounds. If the studio were not treated in this way, the rate of sound absorption within the studio would be so low that words spoken in an ordinary tone of voice would be heard for several seconds afterwards, which would mean that the dozen or so syllables following the word in question would blend into the decaying sound of the word, and render understanding extremely difficult.

On the other hand, a sound-recording studio must not be too "dead." It should have some "life" to it. The "life" of a studio is a function of the walls surrounding the studio, the ceiling, the floor, and the number of persons and articles within it. When a sound shot is being made, it is obviously desirable to pick up only the sound pertaining to the action being filmed. All extraneous noises only aid in bringing up the "ground noise", and are therefore a detriment to high-grade recording.

From the monitor room, the signal currents are fed to powerful 4 or 5-stage audio amplifiers which greatly increase their strength. Then the currents are fed to the mechanical recorder which cuts the record. The records used in the Vitaphone system are "laterally" cut, i.e., the groove is of a constant depth and oscillates or undulates laterally about a smooth spiral. The cut is about 0.0025 inches deep and 0.005 inches wide. The space between grooves is about four mils (0.004 inches). The number of grooves per inch varies between 80 and 100 in usual practice. The linear speed of the record past the cutter (or reproducing needle) varies between 70 and 140 feet per minute. Recording is accomplished by a cutting stylus which is made to vibrate in strict accordance with the energizing current. Fig. 486 shows a recording room, in which two "disc recording machines" developed by the Bell Telephone Laboratories are installed. They are constructed to be mechanically rigid, and are arranged to be driven synchronously with the motion picture. The turntables upon which the "wax" record is placed, may be seen at the left of each machine.

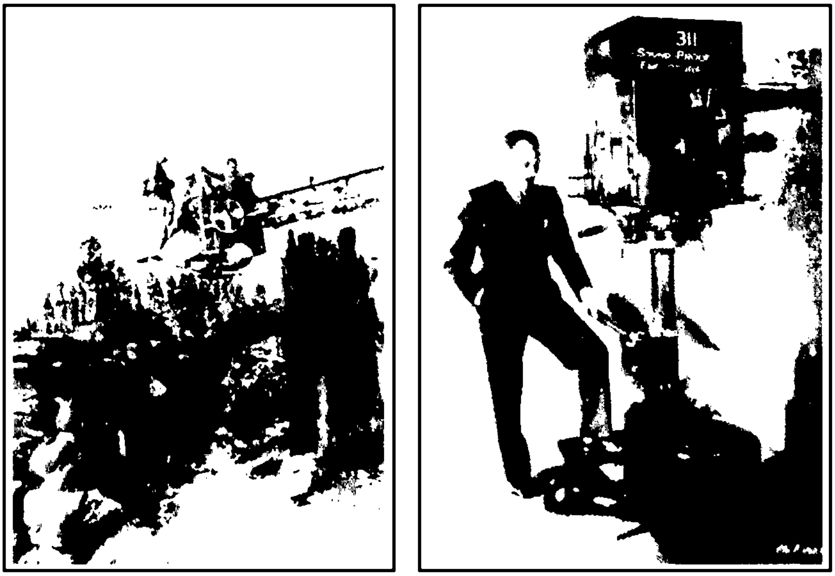
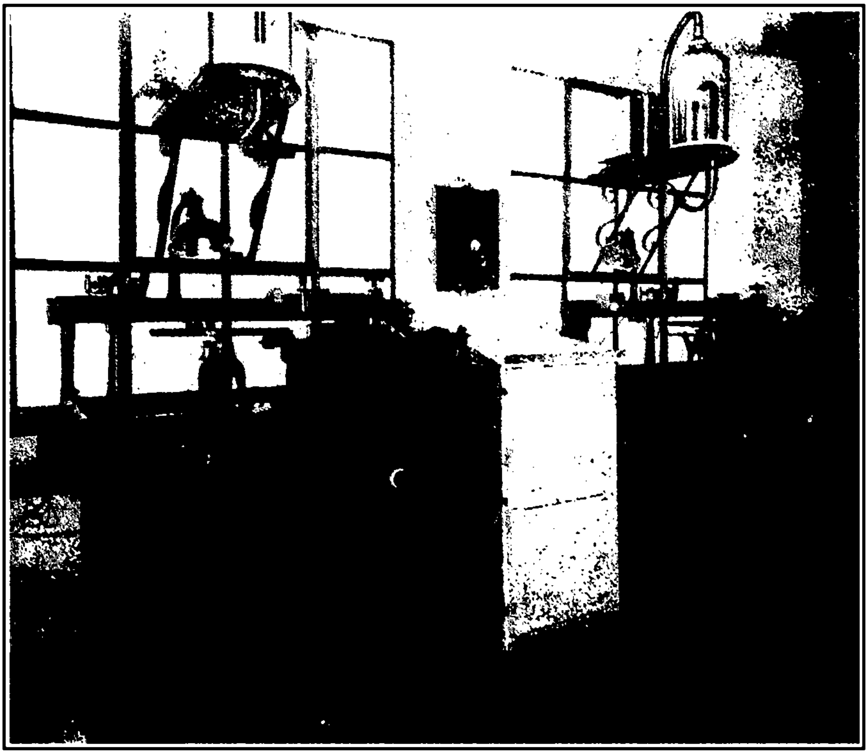


Fig. 485—Left: Cameras mounted on the end of a long crane during the filming of a war scene by Universal Pictures Corp. The cameras are covered with sound-absorbing blankets or "blimps."
Right: A special sound proofed camera used by Paramount Pictures Corp. It is mounted on wheels, and motor driven so it can move about under its own power.

The original disc or "wax" as it is called, is of a special metallic soap from 13 to 17 inches in diameter and about one inch thick. This is given an initial high polish, and is then mounted horizontally on the turntable driven at a uniform rate of speed and synchronized with the film passing through the cameras which are taking the scenes. This synchronization is accomplished by electrical means of a highly technical nature. (For further detailed information on this subject, the reader is referred to the Vol. 7, No. 3 issue of the Bell Laboratories record). The cutting stylus cuts from the center toward the outer edge of the disc. The turntable rotates at about 33 1/3 revolutions per minute, this is nearly ½ the speed at which a home phonograph disc rotates. The sound picture disc is designed to rotate slower so that a longer sound program may be recorded on a single record.

After the wax has been cut, it is of course desirable to be able to "play" it at once in order to detect any flaws. For this purpose, a special reproducer known as the "play-back" is used. This is made extremely



Courtesy Bell Telephone Laboratories

Fig. 486—Disc or "wax" recording machines in the recording room of the United Artists Studio in Hollywood.

light so as to produce no appreciable wear on the relatively soft wax record.

Ordinarily, one machine contains a "play-back" disc which is used by the director to ascertain if his record is as perfect as he wishes it to be, as regards voice and sound. The other disc is the "master disc" from which the reproductions for the final picture are made. This arrangement is very similar to the process of making phonograph records. In some cases, phonograph artists make from six to twenty wax discs before the perfect one is decided upon.

The glass jars above the machines in Fig. 486 form a depository for the wax shavings from the disc being recorded. A suction process is utilized to suck the small wax shavings into the jar. These are emptied when the jar is near the filling point. A microscope is provided with each machine to enable the operator to carefully examine the recordings made.

If the wax is satisfactory it is then dusted with a fine conducting powder, and electroplated to produce a negative copy of the recordings. This is called the "master". By successive electroplating steps, duplicates of the "master" known as "stampers" are obtained, from which large quantities of "positive" playing records can be made. A thousand or more pressings can be made from a single "stamper".

Great success is being attained in the perfection of methods for re-

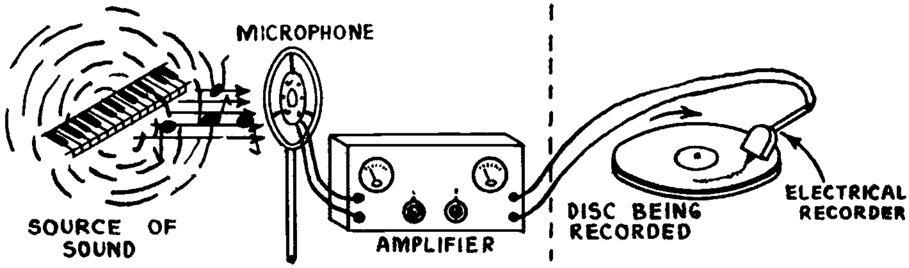


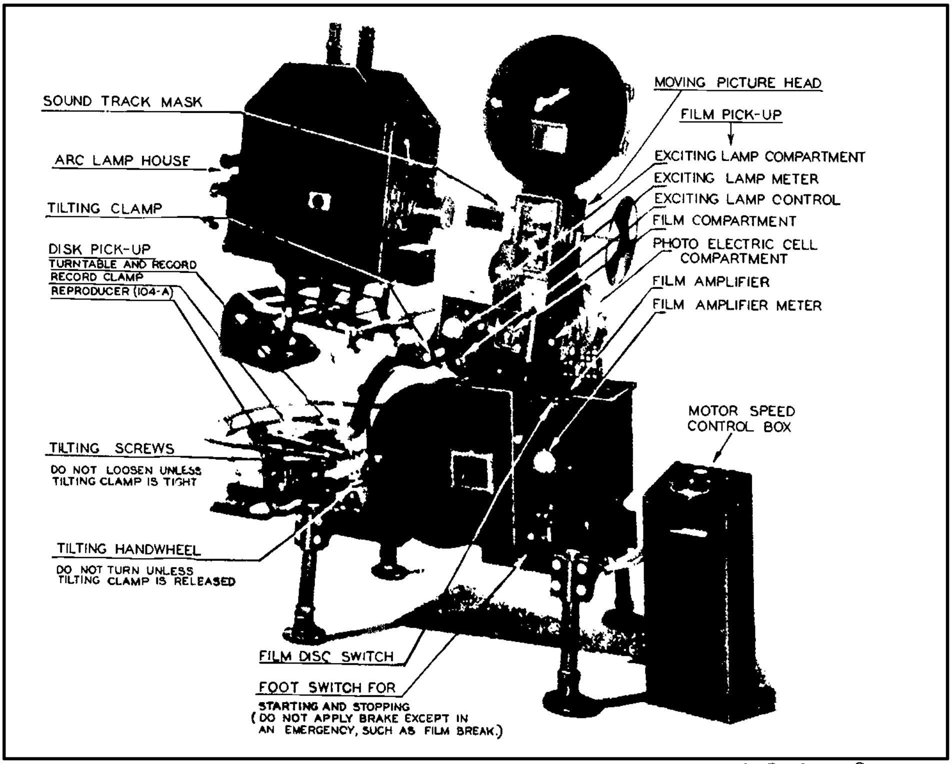
Fig. 487—Sound-on-disc recording system. The sound waves act on the microphone, causing motion of its diaphragm and variations in the current through it. These are amplified by the audio amplifier and actuate the electrical recorder which cuts a spiral groove into the "wax." Tiny wiggles are cut into the groove in accordance with the sound waves. (See left of Fig. 404.)

cording parts of disc records so that the material may be entirely rearranged, portions being deleted or added. This is called "dubbing" the record. This of course is a great advantage for removing objectionable sounds for censorship purposes, etc.

An outline picture of the recording process used in the sound-on-disc system is shown in Fig. 487. The sound waves are impressed on the microphone at the left, which converts them into varying electrical currents. These variations are amplified greatly by the audio amplifier and are then fed to the electrical cutter or recorder which cuts corresponding "wiggles" into the spiral groove on the "wax" disc.

643. Sound-on-disc reproduction: In the sound-on-disc system, the sound records are supplied to the motion picture houses along with the respective motion picture films. One disc is made for each reel of film but a spare disc is supplied with each reel in case of damage, breakage, and so forth. In the projection booth of the theatre, the horizontal turntable is mounted beside each projection machine as shown in Fig. 488. One "frame" at the beginning of the film is marked to go at the starting point. When the film is threaded into the machine the starting point is located at the picture aperture, and the needle of the phonograph pickup (this is called a *reproducer* in sound picture work), is placed in the inside groove of the disc record, at the point marked "start". The disc turntable is rotated by the same electric motor which drives the film through the projector, so that synchronism is maintained between scene and sound throughout the entire showing of the reel of film.

While the film is running at 90 feet per minute, the disc turntable is revolving at 33⅓ r.p.m. The equipment includes a special vacuum tube speed-control system, for keeping the speed of the film and disc constant, so that the film running at the speed of 90 feet per minute keeps



Courtesy Electrical Research Products Corp.

Fig. 488—A motion picture projector equipped for both sound-on-disc and sound-on-film reproduction. For the former the turntable and pick-up (reproducer) shown at the left are employed.

constant within ½ of 1%. The electric motor rotates at exactly 1,200 r.p.m. even though the line voltage may change. This equipment is contained inside of the motor speed-control box shown at the right of Fig. 488. The phonograph pickup unit or "reproducer" is usually of the electromagnetic oil-damped type, of refined design so as to produce good fidelity over a wide frequency band. This type of pickup was described in Article 543. The sound frequencies reproduced by commercial sound picture systems range from about 30 to 6000 cycles per second.

644. The fader: As in the case with the exhibition of ordinary silent motion pictures, two or more projectors must be used alternately

Courtesy Electrical Research Products Corp.

Fig. 489—The method of setting the record at the "starting point" in the sound-on-disc system. The needle of the phonograph pickup unit is placed in the starting mark on the disc.

to present a continuous program. At the end of a record and reel of film, the music and speech coming from one machine must be blended perfectly into that starting from the new one, just as the picture from the

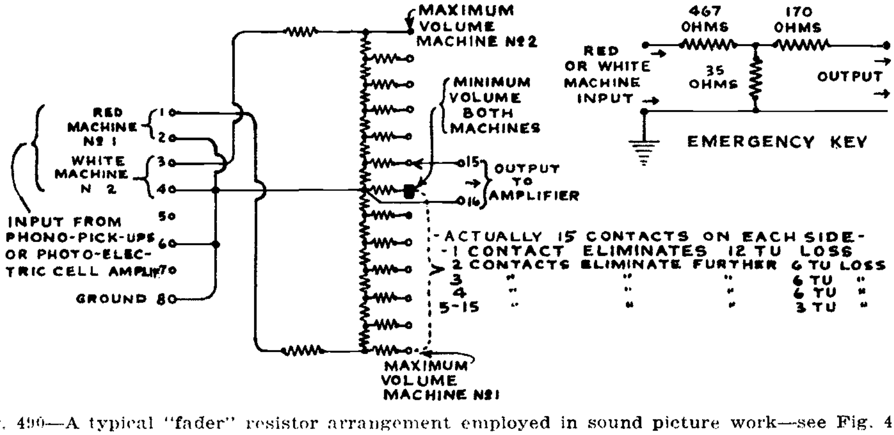


Fig. 490—A typical "fader" resistor arrangement employed in sound picture work—see Fig. 491.

finished reel is faded into that from the next. When a cue spot in the picture flashes on the screen, the operator sets the second machine in motion. Immediately thereafter, the "change-over" is made. This is done on the screen by closing the iris shutter of the expiring projector and instantly opening the shutter of the new machine. The change-over between the two sound records is accomplished by a device known as a "fader".

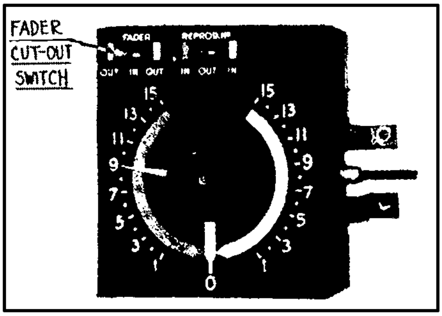


Fig. 491—A typical Fader control cabinet. The Fader control knob may be turned to either side to play from either reproducer. The graduations indicate the volume level position—see Fig. 490.

Courtesy Electrical Research Prod. Corp.

At the end of each sound disc (or sound film) the sound recordings overlap. Then at the beginning of the next one as the starting projector goes into operation, the fader control knob is turned, reducing the output of

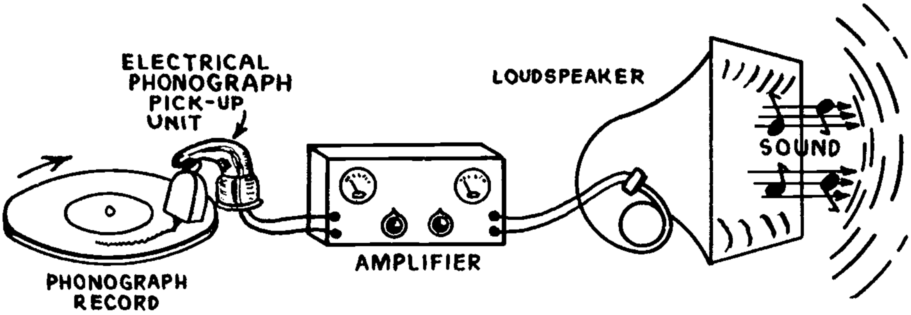


Fig. 493—A simplified diagram of the reproducing arrangement employed in the sound-on-disc system. The wiggles in the spiral groove of the phonograph record cause the needle in the pick-up unit to vibrate. This causes a corresponding varying e.m.f. to be generated in the coil of the pick-up. The variations in the e.m.f are greatly amplified by the powerful amplifier, and are fed to the loud speakers which convert them to corresponding sound waves.

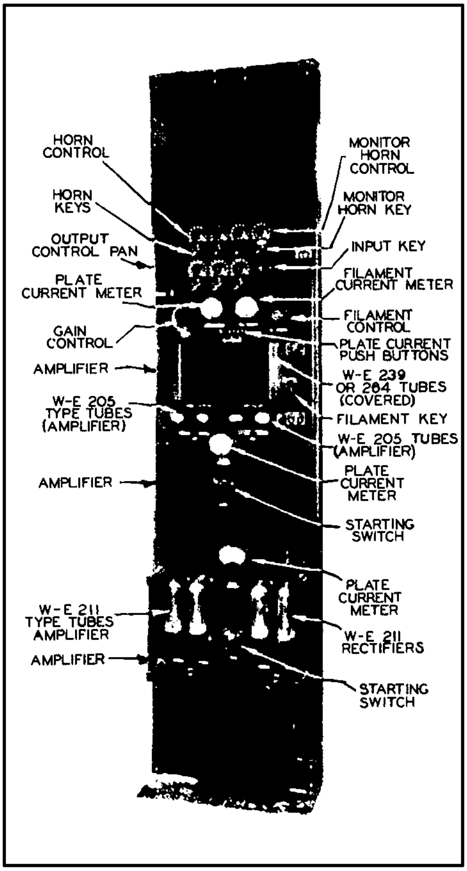
the expiring record gradually to zero and simultaneously increasing the loudness of the sound from the new record to any desired volume.

The fader system commonly used in sound picture work is shown in Fig. 490. Input terminals 1-2 and 3-4 from the machines, are shown at the left. The fader resistor really consists of a potentiometer system.

Terminal 16 is fixed and connects to the center of the resistor. Terminal 15 connects to the moving contact arm which may be moved either up or down from the "minimum volume point" contact. The positions for minimum and maximum volume are shown on the diagram. The front view of the fader control with the knob and indicating dial, is shown in Fig. 491. The changeover from one reel and record to another, is barely perceptible to the audience when done by a skillful operator.

The fader resistor taps are so arranged, that in the lower range used in changing between projectors, the steps are rather large; whereas in the upper range, the volume changes in scarcely perceptible steps. The fader can therefore be used as a volume control, and also for equalizing the volume of sound obtained from different records. As the acoustic characteristics of a theatre, due to its dimensions, architectural features, and especially the size of the audience, varies considerably from time to time, the fader serves also as a convenient means of controlling the volume of the reproduced sound in order to obtain the most natural and pleasing reproduction.

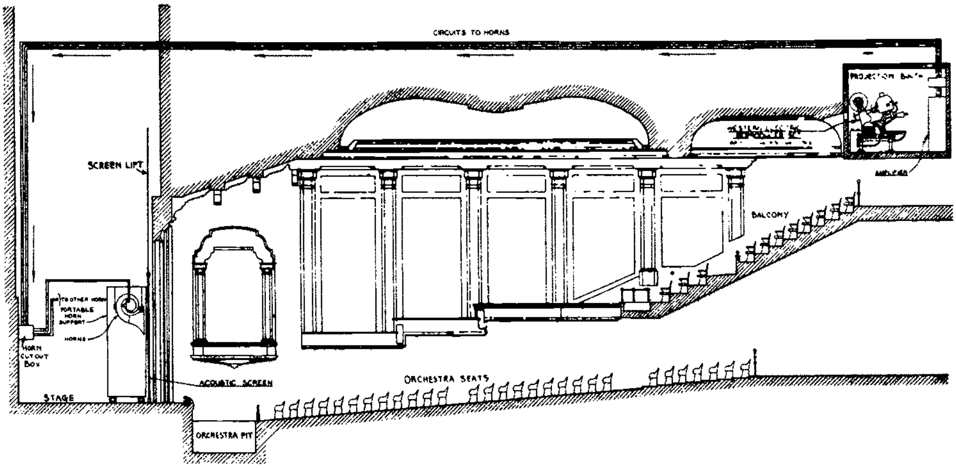
644A. The audio amplifiers: After having been adjusted by the fader, the varying audio voltages go to a series of special amplifiers, where they are enormously amplified. These amplifiers are designed so that all frequencies from about 40 to 10,000 cycles are amplified about equally. The amplifier is usually built in three units. The first consists of a three-stage resistance coupled amplifier using low-power tubes. The second unit consists of a push-pull stage of medium-power tubes heated by alternating current, while the third unit consists of a push-pull stage using high power tubes with filaments energized by alternating current. Plate potentials for all tubes are obtained from rectified alternating current supplied by rectifier tubes, and smoothed out by a suitable filter unit.



Courtesy Electrical Research Prod. Corp.

Fig. 492—A typical rack-and-panel audio amplifier and output control panel employed in sound picture work.

For small theatres, only the first two units are used, while for large theatres one or possibly two of the third type are also used, to obtain sufficient volume of sound for the auditorium without overloading. The three units are capable of multiplying the *energy* of the reproducer nearly one-hundred-million-fold. An amplifier of this type is shown in Fig. 492. The various parts are labeled directly on the illustration. Notice that it is built in standard rack-and-panel form so as to take up a very limited amount of floor space. The output from the last amplifier stage is brought to an output-control panel mounted at the top of the amplifier rack. This consists of an autotransformer having a large number of taps which are connected to a number of dial switches. The loud speakers are connected

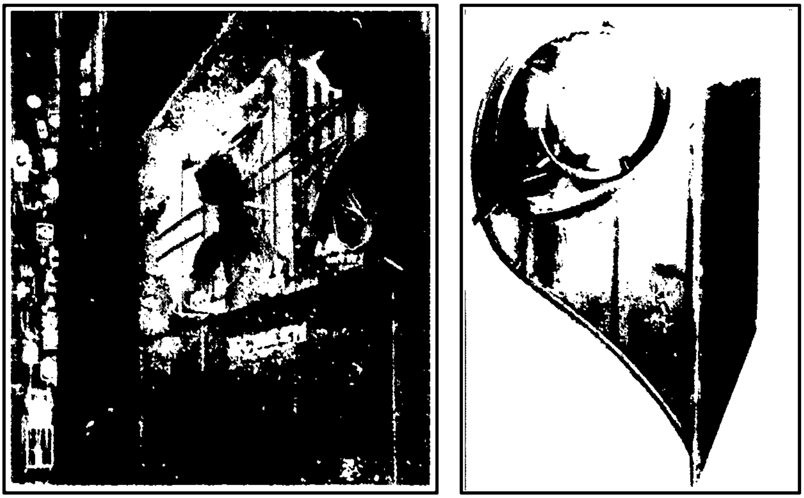


Courtesy Electrical Research Products Corp.

Fig. 494—A longitudinal cross-section view of a typical theatre showing the installation arrangement of the sound equipment. The exponential horns are mounted about 2/3 the way up from the bottom of the screen. The circuits run to the amplifier panel in the projection booth at the upper right.

to these switches, so that the impedance of the amplifier output can be matched to the number of loud speakers it is desired to use at any time. This makes the individual adjustment of volume of any loud speaker possible when necessary. An outline diagram showing the main parts in a sound-on-disc reproducing system is shown in Fig. 493. An electrical phonograph pickup reproducer unit playing from the record at the left, produces varying electric voltages which are amplified by the high-gain audio amplifier system, and then fed to the loud speakers where the sound is reproduced for the audience.

645. The loud speakers: Large exponential horn-type loud speakers with electro-dynamic driving units of the type shown at the left of Fig. 358 and in Fig. 359 have been used almost exclusively in sound motion picture installations on account of their very high efficiency. The loud speakers have been greatly improved and are being designed to take up as little space as possible behind the motion picture screen. In some installations four loud speaker horns are placed at the front of the theatre —two being placed in the orchestra pit and directed more or less toward the balconies, the other two being located behind the upper edge of the screen and directed downward toward the rear floor seats. In recent installations only two speakers are used. These are mounted about 2/3 of the way up from the bottom of the screen as shown in Fig. 494. The actual installation of two of the newer flat-type speakers which are mounted in such a way that they are raised or lowered as a unit with the motion picture screen, are shown at the left of Fig. 495. Notice the bracing to



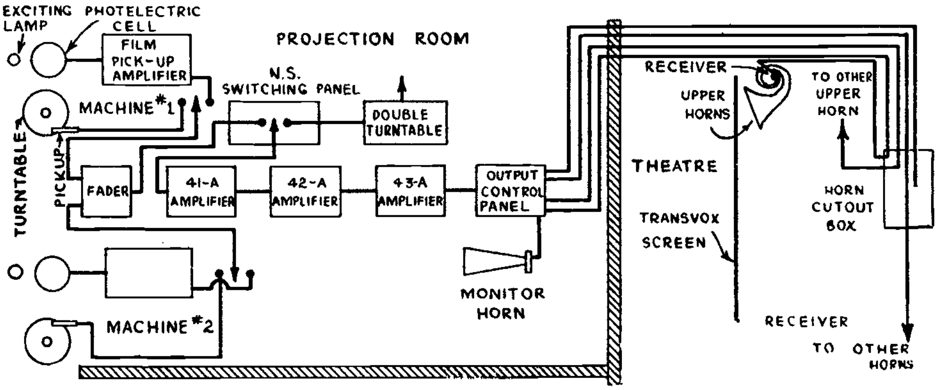
Courtesy Electrical Research Prod. Corp.

Fig. 495—Left: Two flat-type exponential horn speakers mounted directly on the back of the motion picture screen of the Roxy Theatre in New York City. The speakers are lowered and raised with the screen. Each speaker has 4-driving units on it. Right: A typical coiled-type exponential horn speaker 30" deep, employed in sound picture work.

strengthen the speakers at the back, and the use of 4 driving units on each speaker. This type of speaker is also very advantageous in theatres where the screen is located very near the rear wall of the theatre. At the right of Fig. 495 is shown one of the coil-type exponential horns which have been used extensively. Notice that this provides for the use of two driving units (see Art. 471).

There are several reasons for placing all of the horns at the front of the theatre rather than distributing them throughout the theatre.

One of these is what may appear to be a lack of synchronism between the moving picture and the sound; that is to say, the ear may subconsciously detect a fraction of a second difference between the movement of the actor's lips and the reception of his voice. This is not a technical defect but a perfectly natural law that governs the difference between the speed of light and the speed of sound. Now the movement of light is practically instantaneous (186,000 miles per second), so that the man sitting in the farthermost row of a large theatre actually sees the image on the screen at the exact instant that it appears on the screen, while the sound, coming the entire length of the theatre, strikes his ear a fraction of a second later, since it moves at the rate of only 1130 feet per second. The natural reaction to this, is to wonder why loud speakers could not be placed in all the different parts of the theatre. However, a careful analysis of this suggestion will make the drawbacks self-evident. A cure of this kind would be worse than the original ill, due just to this very time-lag. It is true that the spectator in the far row would hear the sound from the speakers in the rear of the theatre at exactly the same time that he would see the image, but a fraction of a second later he would hear this same sound coming up from one of the speakers located in the front of the house. The result would be a fuzzy or blurred sound to every one in the house, as the spectator down front would also hear the response from the speaker located at the back of the house later than from the speaker nearby. For this reason, it has become standard practice to place all loud speakers at the front of the theatre, and facing out toward the audience. Fig. 496 shows a typical installation



Courtesy Bell Telephone Laboratories

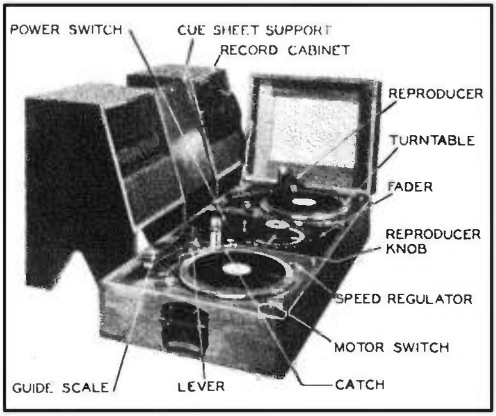
Fig. 496—Block diagram showing the typical sound picture equipment employed in a theatre. The various amplifier and control units are shown. The signal impulses originate in the photoelectric cell at the upper left, are greatly amplified, and then progress through the equipment to the loud speaker horns behind the screen.

of equipment for sound pictures. The directive sound characteristic of the particular horns used is important, since it is responsible for the illusion that the sound comes directly from the lips of the persons appearing on the screen.

If speakers which radiate their sound over a wide angle are used, the sound appears to be coming from a point some distance behind the screen. A special type of screen, reflecting light well, but transparent to sound, is used for the picture, so that the sound from the speakers located behind the screen is not seriously interfered with.

A small monitoring horn is placed in the projection booth for the convenience of the operators to enable them to follow the program continuously, and to instantly detect any trouble which may occur in the reproducing system.

646. Speech amplifier: In addition to their convenience as a part of the sound motion picture equipment, the audio amplifier and loud speakers may also be used as a public address system for speech amplification. Microphones can be concealed in the floor lights and placed in

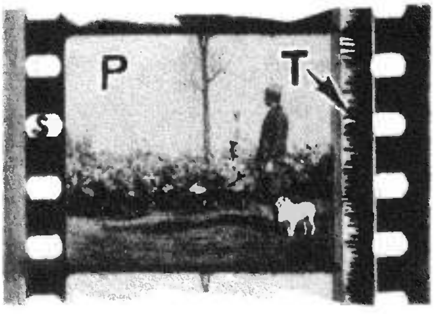


Courtesy Bell Telephone Laboratories

Fig. 497—Equipment for producing non-synchronized music accompaniment for silent pictures. Two turntables and reproducers are provided, together with record cabinets. The usual Fader, amplifier and loud speaker equipment must also be employed.

such positions that they will not be affected by the sound waves issuing from the horns. A microphone is also installed in the manager's office for announcements to the audience in the theatre.

647. Non-synchronized music: By means of the auxiliary equipment shown in Fig. 497, the sound picture system can also be used to pro-

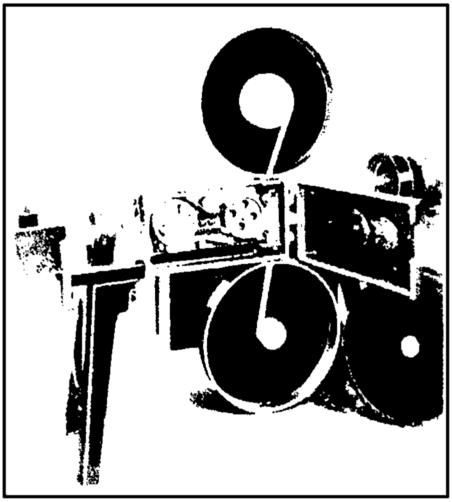


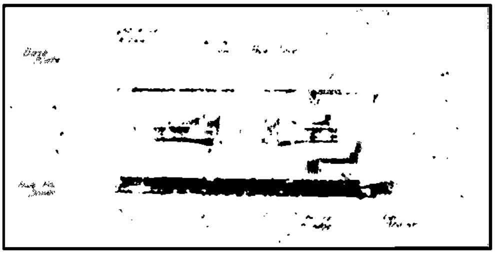
Courtesy E. R. P. Corp. *Courtesy R. C. A. Corp.*

Fig. 498—Left: Enlargement of Movietone sound recordings on a motion picture film. The sound recordings consist of the parallel light and dark lines "T" at the right. Right: Enlargement of sound recordings employed in R. C. A. Photophone system. The recordings at T consist of a uniformly-dark band of varying width and area.

vide non-synchronized music as an accompaniment to silent pictures with which no sound recordings are provided. There is a cabinet containing two motor-driven turntables, each having a pick-up unit and means for locating it accurately on a record. A fader is provided to make continuous playing possible from one record to the next. Two record cabinets are also supplied, as shown. This is sometimes called an "electrical transcription" program, and may also be employed for supplying music during the intermission period on the program. The same amplifiers and loud speakers are used, as are employed for the synchronized speech and music.

648. Sound-on-film system: There are two methods of sound film recording in general use. In the Movietone method, the variations in sound are produced by variations in light through the sound track "T" of variable density and constant width along one edge of the film. The





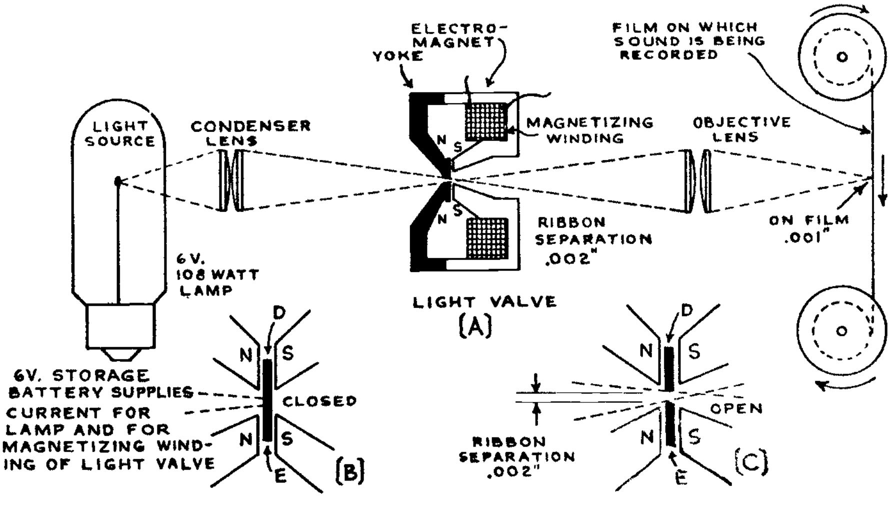
Courtesy Elect. Research Prod. Corp.

Fig. 499—Left: A sound-on-film recording machine employed in the motion picture studio.
Right: The light-valve employed for recording the sound track on the film. This is the heart of the entire recording system.

film also contains the visual pictures "P", as shown at left of Fig. 498. In the R.C.A. Photophone system, the variations in sound are produced by variations in the area of the uniformly dark sound track "T" along one edge of the film, as shown at the right of Fig. 498. The taking of the picture and method of projecting it are quite similar in both systems as we shall see later.

In the Movietone system the sound track on the film is recorded in the machine shown at the left of Fig. 499. This is mounted in a separate room off the "set". The recording machine is driven by a three-phase synchronous electric motor which is supplied with current from the same source as is the camera motor. Both motors are electrically interlocked so they both run at exactly the same speed.

649. The light valve: The heart of the recording machine is the *light valve*. This is shown at the right of Fig. 499. It consists of a loop of duraluminum ribbon, suspended in the narrow slit between two pole-pieces of an electromagnet as shown in the illustration. The duraluminum ribbon is .006 inch wide and .003 inch thick. Its ends are secured to separate insulated windlasses stretched tight by a spring-held pulley. The ribbon is looped around the idler pulley shown at the left. In this way, the two parts of the ribbon form a very narrow slit approximately .0003 inch wide, between them, at the part where they pass between the pole-pieces of the electromagnet. The output terminals of the audio amplifier, which follows the microphones, are connected to both ends of this light-valve ribbon. The audio currents flowing through the continuous loop-circuit formed by the two sides of the ribbon, produce varying magnetic fields. These cause the two sides to repel each other and thereby widen



Courtesy Electrical Research Prod. Corp.

Fig. 500—Light and optical system for sound-film recording. At (A) the beam of light from the light-source is condensed into a narrow beam by the condenser lens. This shines through the slit of varying width between the two sides of the duraluminum ribbon in the light valve. The beam of light which gets through is of varying width, depending upon the recording signal fed to the light valve. This acts on the sensitized negative film which is moved past it at the right, resulting in the sound recordings as shown at T on the film at the left of Fig. 498.
(B) Position of the two sides of the duraluminum ribbon when the slit is closed and no light gets through.
(C) Position of the ribbons when the slit is wide open and maximum light gets through.

the slit between by varying amounts, depending upon the amount of current. The tension on the ribbon is adjusted to tune the valve to about 8,500 cycles to give the best frequency-response.

When the slit between the ribbons in the light valve is placed between the light source and the photographic film, a camera shutter of unconventional design is formed. A diagram of the simple optical system which results, is shown at (A) of Fig. 500. At the left, is the light source which is focused on the very narrow slit between the two sides of the ribbon, onto the light valve, by means of the condenser lens. A very thin band of light passes through the slit in the valve, and is then focused at a two-to-one reduction on the photographic negative film at the right, which is being moved past this slit of light at proper speed. The undisturbed valve opening causes a very thin band of light to appear on the film as a straight line, with its length at right angles to the direction of the film travel. The width of this pencil of light varies in accordance with the opening of the slit, which in turn, depends on the audio current sent through the ribbon. Therefore the negative film receives exposure to light of variable density, depending on the amount of the opening of the slit. The recordings appear as a series of parallel lines of varying darkness, as shown at the left of Fig. 498.

649A. Sound-on-film recording: The recording of the sound program in the studio, is carried out on a film separate from that which receives the picture. This practice permits the use of two machines to make duplicate sound records. The practice of employing separate negatives for sound and picture also permits the picture negative to be developed and printed separately according to well-established technique, and allows the necessary latitude required in developing the film containing the sound record, for best results.

The recording machine is designed to draw the film from the upper feed magazine, past the valve slit, to the take-up magazine below. This is accomplished at a uniform speed of 90 ft. per minute, by means of two sprocket wheels which engage the film

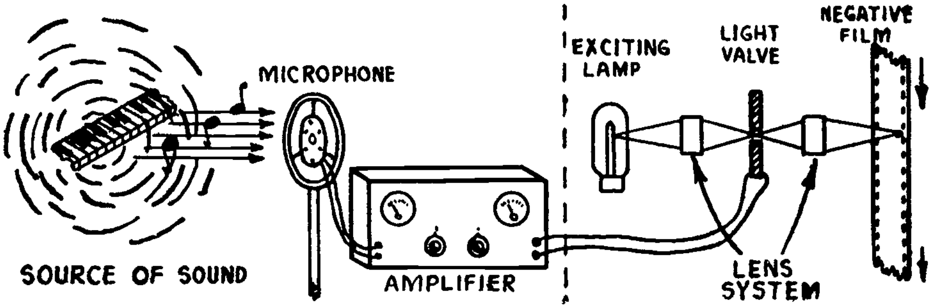


Fig. 501—Simplified diagram of the recording system employed for recording the sound track on the film. (See Figs. 498 and 500.)

perforations. Inside the left hand sprocket, is a photoelectric cell which is affected by the light passing through the "sound track" on the film, so that its amplified curren variations may be heard from a loud speaker used to monitor the recording as it is actually being impressed on the film.

The light source, shown at the left of the machine, is an 18 ampere projection lamp with ribbon filament. Great care is exercised in adjusting, so that the loudest sounds give the maximum allowable exposure. The program is rehearsed until satisfactory arrangements of microphones and amplifier gain is effected, this being judged by the monitoring loud speaker. An outline diagram of the sound-on-film system of sound studio recording is shown in Fig. 501.

Sound picture news reels are usually recorded by a different method in which the heart of the system for changing the electrical currents into light variations, which are in turn applied to the negative film, is a flashing light called the Aeo-Light.

The term "AEO" was derived from the three words, Alkaline Earth Oxide, by taking the first letter in each word. This seemed a fitting term to use, because the coating on the negative electrode of this flashing lamp is an Alkaline Earth Oxide, and it is this coating which gives to the light the inherent properties which make it adaptable to sound pictures.

The Aeo-Light is a tubular-shaped lamp, about six inches long and one inch in diameter, inside of which there is a filament-shaped negative electrode. Adjacent to this electrode there is a plate, which is the positive electrode. The negative electrode, or filament is covered with barium and strontium. The gaseous content of the Aeo-Light is about as follows: 1½ per cent nitrogen; 3 per cent neon; and 95½ per cent helium.

When about 350 volts, direct current, is applied across the "Aeo-Light" in series with 12,000 ohms, a bluish white glow is established within the tube. The d-c voltage varies with different lights, and is usually made of such a value, that there will be a current of about 10 milliamperes flowing through the Aeo-Light circuit, because with a gaseous tube of this type, after the gap between electrodes has become ionized, the impedance of this path is liable to become lower and lower until it is practically a short circuit. The stabilizing resistor obviates this possibility. When the Aeo-Light is energized with the d-c voltage and normal direct current is flowing through its circuit, it is very sensitive to changes in voltage across its terminals. Therefore, if the alternating current output from the audio amplifier is applied across its terminals, it causes the brilliancy of the glow within the tube to vary in accordance with variations in the applied sound energy.

The Aeo-Light is placed in a tube in the back of the motion picture camera. The inner end of this tube, has a minute slit about 100 millimeters long and 1 millimeter wide, and it is through this little slit that light shines from the Aeo-Light through to the film, which is passing the aperture in the end of the Aeo-Light tube at the rate of 90 feet per minute during the course of operation. In the Fox-Case Movietone system of recording sound pictures used in news-reels, the action being recorded by the camera always bears a constant relation to the sound being recorded, because in this system the sound is recorded on the same negative that the picture exposures are made on and they are, therefore, always in synchronism.

In the studios, the sound track is usually recorded on a separate piece of negative film, and the sound and picture are combined into a single print during the printing process, the picture being printed first, with the sound track masked out, and the sound track is printed last, with the exposed picture masked out so as not to fog it. The Aeo-Light has the disadvantage of giving insufficient light to completely expose the film, and hence limits the amount of power which can be obtained in the reproducing system, without excessive surface noise, but has the advantage of being practically independent of frequency within the audio range.

When scenes are to be recorded "on location", away from the motion picture studio, all of the required electrical recording apparatus must be transported to the place where the picture is being filmed. Special complete groups of recording equipment are employed for this purpose. They are installed permanently in automobiles so as to be readily transported and available at all times for "location" work. All of the apparatus is arranged on the automobile, in a way which makes it possible to quickly get it into operation. Flexible cables run from the apparatus in the automobile to the recording cameras, etc.

Courtesy United Artists
Fig. 502—A sound truck with all apparatus necessary for recording the sounds with outdoor scenes.

Fig. 502 shows the interior of a sound truck employed by the United Artists studios in making outdoor scenes for talking pictures. Fleets of these units accompany film companies to distant locations to record voices and sounds that synchronize with the photographic action.

650. Reproducing sound-on-film motion pictures: Most moving picture projectors are equipped both with the sound-on disc turntable and reproducer already described, and also with sound-on-film reproducing equipment, so that either type of picture may be exhibited. The sound-on-film reproducing apparatus is located beneath the ordinary projector mechanism as shown in Fig. 488.

As the film leaves the projector mechanism and enters the sound unit, it passes down from the sound gate, where a beam of light from the exciting lamp is concentrated by an optical lens system and aperture containing a slit which brings the light to focus as a fine line across the sound track, (see Fig. 503). The film moves at the uniform speed of 90 feet per minute through the sound gate, and to the take-up magazine below. The film speed is the same as that used during the recording.

The density of each particular line of the sound track, as it passes the pencil of light at the sound gate, determines the amount of light permitted to pass through the film on to the photoelectric cell beyond. The current flowing in the photoelectric cell is therefore modulated in accordance with the density of the lines on the sound track. This photoelectric cell is located on the side of the sound gate away from the exciting lamp. As the sound gate is 14½ inches below the picture gate, the sound recordings are purposely printed on the film 14½ inches in advance of the corresponding picture, so that the sound track and picture will reach their respective gates at the same time, and the sound will be heard at the same instant that the picture appears.

The photoelectric cells commonly used at the present time are of the gas-filled caesium type. A cell of this kind is shown at the right of Fig. 436. The arrangement of the exciting lamp at the left, the sound gate at the center, and the photo-electric cell at the right are shown in Fig. 504. This is an interior view of the sound-head on the projector. A simplified schematic view is shown at the left of Fig. 505. A form of photo-electric cell which is not supplied with a base but which is simply mounted between two pieces of sponge rubber held by a spring, is shown at the right. This shock-absorbing mounting may be seen by inspecting the photoelectric cell in the compartment at the right of Fig. 504.

The photoelectric cell output is strengthened by a small "head amplifier", (of type shown at the left of Fig. 438 and in Fig. 503), mounted close to the sound unit. The output of this amplifier goes to the "film-disc" switch. The output from either the sound-on-film pickup or the sound-on-disc pickup, (depending upon which is being employed), is carried to the *fader*, which regulates the volume of the sound during the show. From here the current is carried to the main rack-and-panel amplifiers, the output of which passes to the loud speakers located behind the screen, from which the sound issues in synchronism with the action of the picture. The simple schematic drawing of the system employed in reproducing sound-on-film programs is shown in Fig. 506.

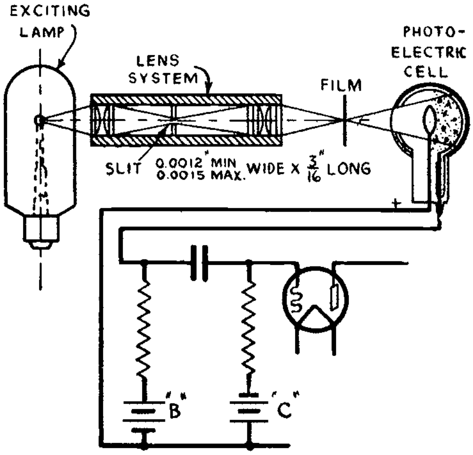


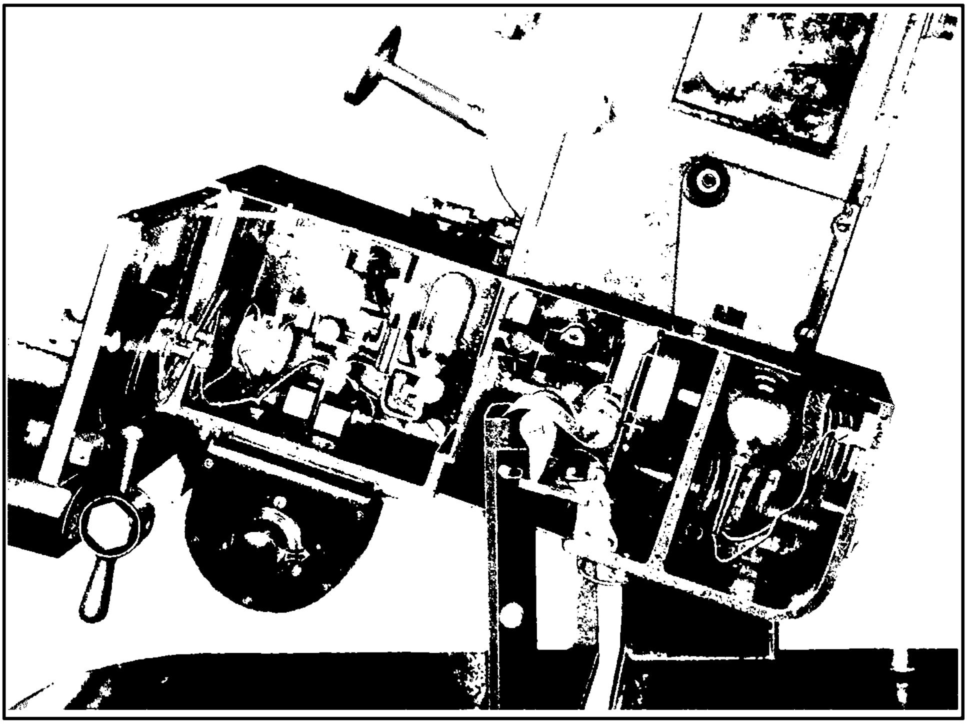
Fig. 503—The exciting lamp, optical system, photoelectric cell, and connection to the first amplifier stage (called the "head amplifier") in the sound-on-film reproducing system.

This shows how the narrow slit of light from the exciting lamp shines through the film to the photo-electric cell. The output of the cell is amplified by the audio amplifier, and is finally fed to the loud speaker which produces the sound. The changes in the frequency of the sound, are determined by the number of changes from dark to light and back again per inch length of the sound track. The changes in the intensity of the sound, are determined by the changes in the density or darkness of the lines on the sound track as the film is moved past the narrow film of light, the light and dark lines on the sound track rapidly interrupting the light film, thereby interrupting the output of the photo-electric cell. These interruptions appear as sound waves from the loud speaker.

651. R. C. A. Photophone system: In the R. C. A. Photophone system, the recording is accomplished by an oscillograph whose mirror is actuated by the variations in the frequency and intensity of the output voltage of the photoelectric cell, so as to throw a strong beam of light on to a moving film. These light variations, corresponding to sound variations, are recorded as a single jagged, heavy line that looks like a succession of mountain peaks viewed from a distance.

Fig. 507 shows the combined picture and sound projector. In this, as in the Movietone, the light beam passes through the sound-track on the film, on to a photoelectric cell. In this cell, the varying light gives rise to feeble variations of electric currents which are greatly magnified by the amplifier, so as to operate a number of loud speakers on the stage. The machine is usually provided with an attachment whereby either the variable density (Movietone) film or the disc records (Vitaphone) may also be reproduced as sound.

652. Splicing film: In case the film which is synchronized with the sound from a separate disc-record becomes broken, it is necessary to

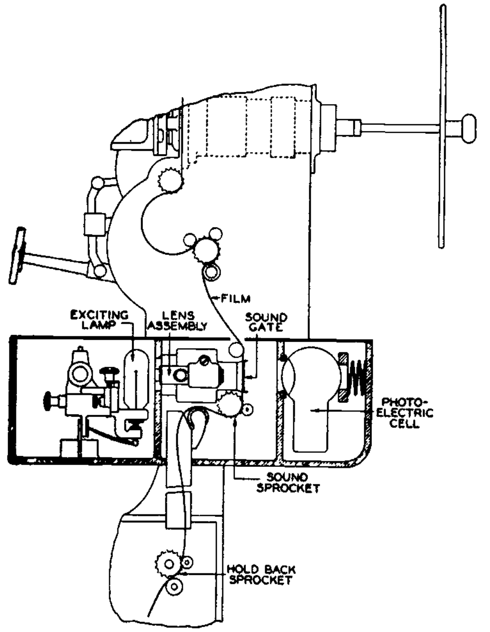


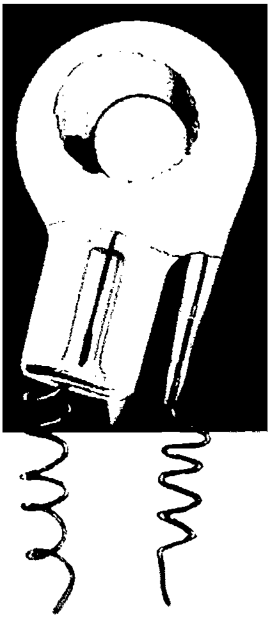
Courtesy Electrical Research Products Corp.

Fig. 504—An interior view of a typical sound head on a motion picture projector. The exciting lamp and control rheostat are in the compartment at the left. The condenser lens system is in the center compartment. The film also comes down through this compartment. The photoelectric cell (see Fig. 505) is in the compartment at the right. It is held between two thick pieces of sponge rubber by the coiled spring shown. See left of Fig. 505.

splice in a length of blank film equal to the length of film removed due to the break, in order to prevent the sound from getting out of synchronism with the picture.

In case a film which has the sound track on it becomes broken, the splice must be made in a special way in order to prevent a loud thump from being heard from the horns when the splice passes through the sound gate. This "thump" would be caused by the electrical impulses sent into the amplifier by any discontinuity which was present in the sound track.





Courtesy Bell Laboratories

Fig. 505—Left: Simplified diagram showing the arrangement of the apparatus in the sound head of a motion picture projector equipped to reproduce from sound-on-film pictures. (See Fig. 504.)
Right: A photoelectric cell employed in sound-on-film reproducing apparatus. Notice the clear "window" in the glass bulb through which the light may shine on to the sensitized surface inside. The circular-hoop plate is also visible inside. (See right of Fig. 504.)

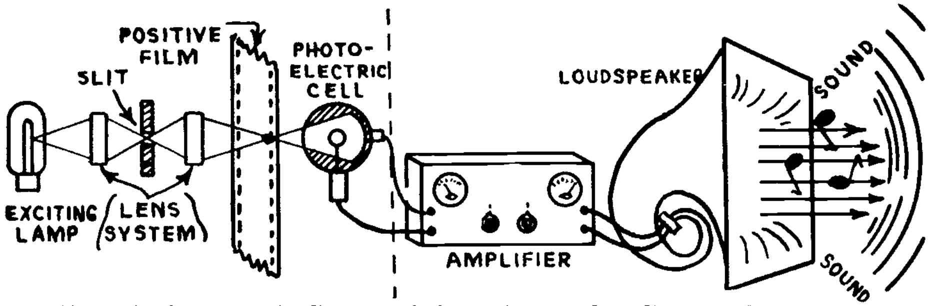


Fig. 506—A simple schematic diagram of the entire sound-on-film reproducing system. The actual apparatus is shown in the accompanying illustrations.

In dealing with a film of this type, the splice is first made in the usual manner. Then it should be painted with black or red lacquer as shown at A of Fig. 508. The painted mark on the sound track should be roughly triangular in shape with a rounded apex, and between ⅜ inches and ½ inches wide at the base. If the splice is painted in this manner, it will be almost inaudible when passing through the reproducing mechanism, as any change in light intensity which it causes, will be at a low frequency below the audible range. If the base of the triangle is made too short, as shown at "B", the change in light will be abrupt, and the thump produced will be very pronounced. If it is made too long, as shown at "C", enough of the sound track may be obliterated to cause noticeable interruption or pause in the sound. Therefore,

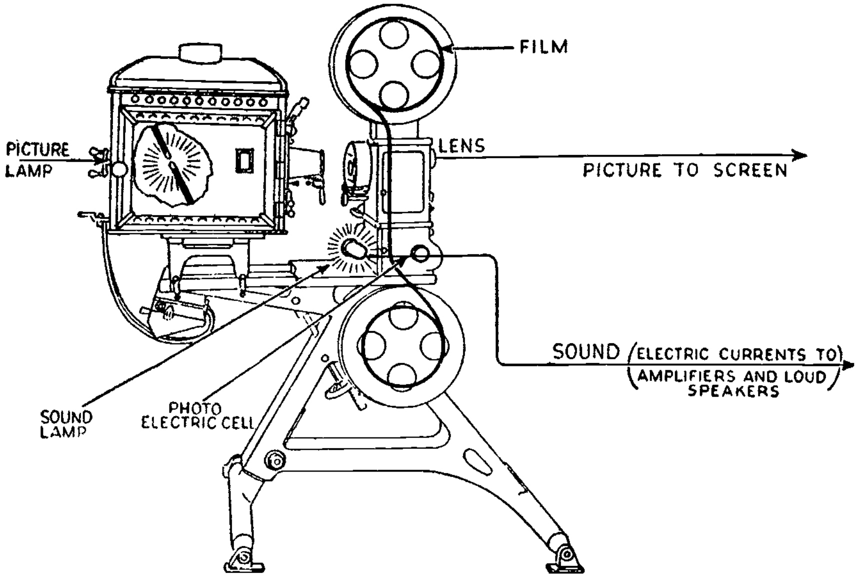


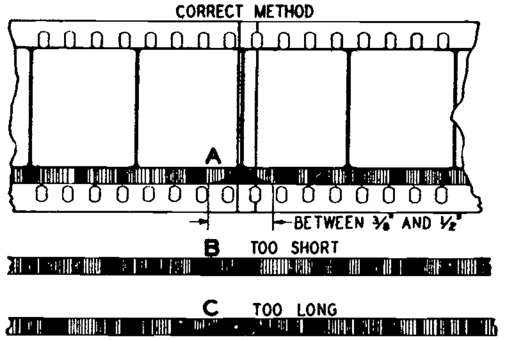
Fig. 507—R. C. A. Photophone picture projector and sound reproducing equipment. The sound recordings are shown at the right of Fig. 498.

the painting of the triangle should be done with care. It is done on the shiny celluloid side of the film.

653. Comparison of sound-on-disc and sound-on-film systems: While both the sound-on-disc, and sound-on-film systems are being used at the present time, it is probable that the sound-on-disc system will be abandoned in the near future, in favor of the sound-on-film method. The present arrangement of using both systems has many disadvantages, possibly the most important of which is the fact that motion picture exhibitors are forced to install projecting machines equipped both with the turntable and pick-up unit for sound-on-disc films, and the exciting lamp, lens system, photo-electric cell and head amplifier for exhibiting sound-on-film pictures. This greatly adds to the expense and maintenance costs of the projectors.

While each of the systems has certain advantages, it seems probable that the economic disadvantages of the sound-on-disc system film will cause it to be dropped.

In the first place, two discs must be shipped with each reel of film—one disc for the actual playing and one to be used as a spare in case of damage to the first one. This means that the cost of shipping the discs from theatre to theatre is very high, also since the discs must be shipped in separate containers from those which hold the films, the problem of handling them is quite troublesome. Since, in the sound-on-film system, both the sound track and the picture are on the same film, the shipping of the films is no more expensive than it is with the old silent-type films. One advantage of the sound-on-disc system is that the film which contains the picture can be used much longer than it can in the sound-on-film



Courtesy Electrical Research Prod. Corp.

Fig. 508—How film with a sound track should be spliced. An opaque triangle is painted in on the sound track as shown at A.

system. In the latter the life of the film is determined by the time when the film becomes sufficiently scratched due to running through the projector, so that the sound track becomes very noisy. The entire film must then be scrapped. In the sound-on-disc system, when the disc becomes too noisy due to wear, new duplicate discs are supplied, the same film still being used for the picture.

REVIEW QUESTIONS

1. Describe the sound-on-disc method of recording sound motion pictures.
2. What is the "wax"; the "play-back"?
3. What is the "fader", and what is it used for in sound picture systems?
4. Describe the sound-on-film method of recording.
5. Why are motion picture cameras covered with sound proof enclosures when recording sound pictures?
6. Describe the process of reproduction in the sound-on-disc system.
7. How is synchronization accomplished and maintained between the motion picture projector mechanism and the sound disc in this system?
8. Describe the process of reproduction in the sound-on-film system. How is synchronization accomplished and maintained between the picture on the film, and the sound track during reproduction?

9. What is the function of the photoelectric cell in the sound-on-film reproducing system? Draw a simple schematic sketch showing the relation to the light source, lens system, slit, sound track on the film, amplifier and loud speakers, in the sound-on-disc reproducing system.
10. Describe the loud speakers used in sound picture reproduction. Where are they located, and how are they arranged? Give the reason for the particular location that is employed.
11. How should splices be made in sound-film to avoid objectionable noises?
12. Draw a sketch showing how the sound track on Movietone film appears. How are the darkness of the lines of the track, and the number of lines per inch, related to the sounds?
13. Draw a sketch showing the sound track on the film used in the Photophone system. Explain what features of this sound track are responsible for the variations in frequency and the variations in loudness of the sound produced.
14. Draw a schematic sketch showing the light source, condensing lens, light valve, objective lens and film used in the recording of the sound track in sound-on-film pictures. Explain the function of each part, and explain how the light valve operates.
15. What is the difference in the recording methods used for recording the sound track in the studio, and those used in recording the sound track for news reels, travel pictures, etc.?

APPENDIX A

RADIO SYMBOLS

The tremendous growth of the radio art has resulted in the invention of many new electrical devices unknown a few years ago. These, together with such well known things as coils, condensers, resistors, etc., make the total number of different parts used in radio receivers very large.

In order to represent these pieces of equipment in their proper relation in drawings and circuit diagrams, conventional graphical symbols have been devised. It is unfortunate that no absolute standardization of radio symbols has been accepted in radio work up to the present time (even though the R.M.A. has adopted a standard set of radio symbols) but the following chart contains most of the symbols which have become well known through more or less popular usage. In those cases where more than one symbol is commonly used for a piece of equipment, the several symbols are given.

These symbols have been used throughout this book, so it would be well for the reader to thoroughly acquaint himself with them, in order that he may quickly and thoroughly understand the diagrams. It must be remembered that radio transmitters and receivers are built up of many component parts or units. So, the circuit diagrams are also built up by properly connecting up many of these symbols together. It is suggested that the reader select some circuit diagrams in this book and see if he can name all of the parts shown. Then he should attempt to re-draw the circuits himself, using the proper symbols. This practice is very necessary in order to remember the symbols, and to become proficient in drawing and tracing out circuits for which no diagrams may be available.

(See Chart on Next Page)

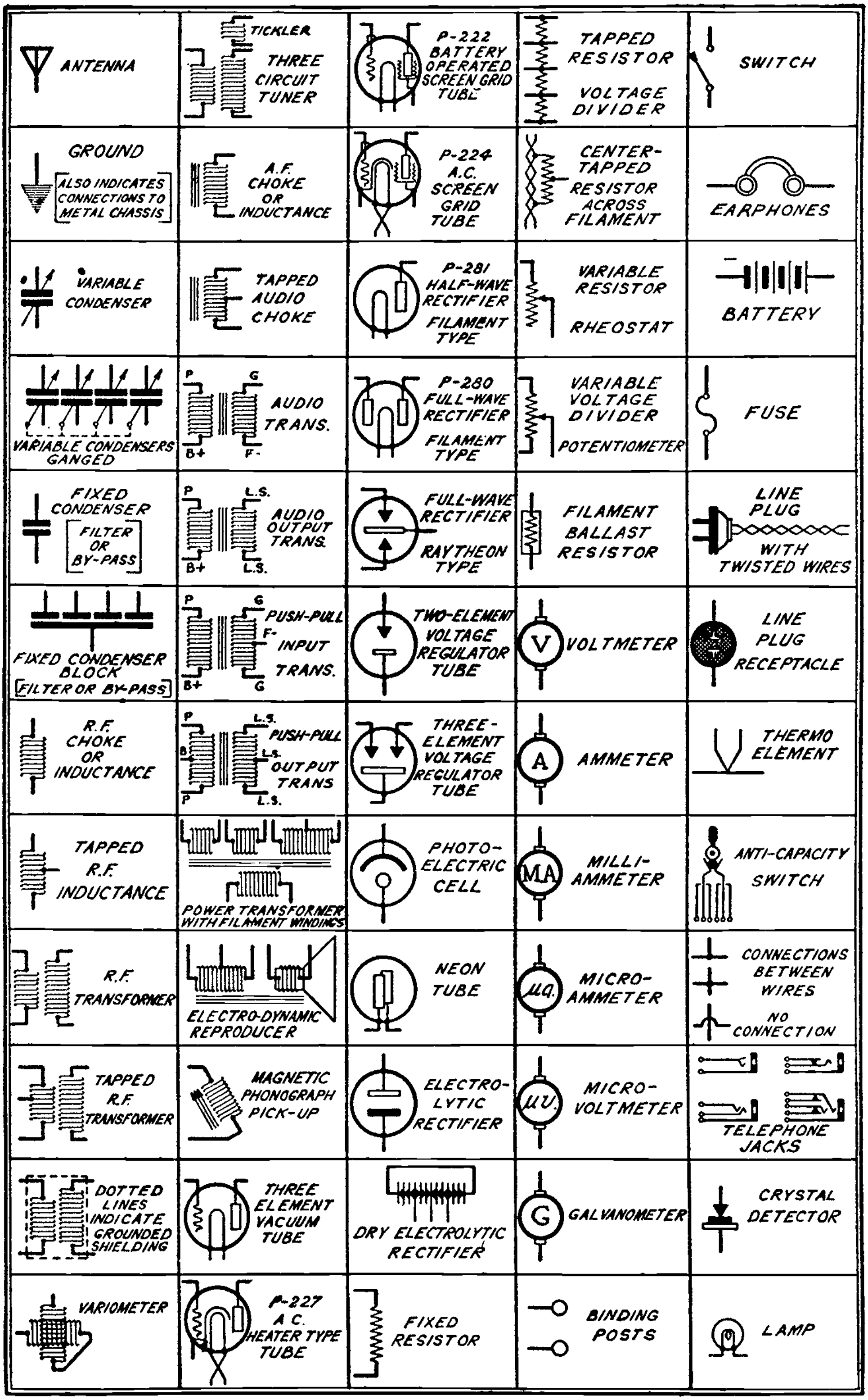


Fig. 509—Symbols commonly used in radio circuit diagrams.

LETTER SYMBOLS AND ABBREVIATIONS

In radio language there are many symbols and abbreviations (shorthand expressions) that make it convenient to express, otherwise long or cumbersome words in a rather short and simple manner. No one can do much in the way of studying radio or electrical diagrams, or reading technical articles without first becoming familiar with the letter symbols and abbreviations in common use. Following is a list of those which have been adopted by the Radio Manufacturers Association (R. M. A.) in the United States. Some of these have international acceptance, some are used only in this country, and some have not been agreed upon generally in practice even in the United States. These abbreviations have been used throughout this book wherever possible, in order to further the cause of a standard simplified practice.

Many of the abbreviations are given in lower-case letters. Where the original word would have been capitalized, the abbreviations should be similarly capitalized. A two-word adjective expression should contain a hyphen. The greek letter μ is sometimes written as "mu".

These abbreviations are published here through the courtesy and co-operation of the Radio Manufacturers Association.

Term	Abbreviation, or letter-symbol.
Alternating-current (adjective)	a-c
Alternating current	spell out.
Ampere	a
Antenna	ant.
Audio-frequency (adjective)	a-f
Continuous waves	CW
Cycles per second	~
Decibel	db
Direct-current (adjective)	d-c
Direct-current	spell out.
Electromotive force	e.m.f.
Frequency	f
Ground	Gnd.
Henry	h
Intermediate-frequency (adjective)	i-f
Interrupted continuous waves	ICW
Kilocycles (per second)	kc
Kilowatt	kw
Megohm	M Ω
Microfarad	μf
Microhenry	μh
Micromicrofarad (pico-farad)	μμf

(Continued on next page)

APPENDIX B—Cont'd.

Term	Abbreviation, or letter-symbol.
Microvolt	μv
Microvolt per meter	$\mu v/m$
Millivolt per meter	mv/m
Milliwatt	mw
Ohm	Ω
Power Factor	p.f.
Radio-Frequency (adjective)	r-f
Volt	v

LETTER SYMBOLS—VACUUM TUBE NOTATION

The accepted R. M. A. System of notation of terms used in connection with vacuum tube nomenclature follows. The small letter "r" is used for resistance. Thus r_p indicates the plate resistance of a vacuum tube. The letter p is called a subscript and states that "r" in this case is a particular resistance, namely, the resistance of the plate circuit of a vacuum tube.

In a similar manner, subscripts are used on the letters E, I, etc. denoting voltages and currents, to form E_p, E_g, E_f for the plate, grid and filament voltages of a vacuum tube, and I_p, I_g and I_f to indicate the plate, grid, and filament currents. When current, voltage, and power vary with time, lower-case italics are used for instantaneous values, and capital italics for constant values.. The root-mean-square value is designated by capitals. The letter g is the symbol for conductance. Thus, the mutual conductance of a vacuum tube is g_m.

Quantity	Symbol
Grid potential	E_g, e_g
Grid current	I_g, i_g
Grid conductance	g_g
Grid resistance	$r_g = \frac{1}{g_g}$
Grid bias voltage	E_c
Plate potential	E_p, e_p
Plate current	I_p, i_p
Plate conductance	g_p
Plate resistance	$r_p = \frac{1}{g_p}$
Plate supply voltage	E_b
Emission current	I_s
Mutual conductance	g_m

Quantity	Symbol
Amplification factor	μ (mu) $= \frac{g_m}{g_p}$
Filament terminal voltage	E_f
Filament current	I_f
Filament supply voltage	E_a
Grid-plate capacity	C_{gp}
Grid-filament capacity	C_{gf}
Plate-filament capacity	C_{pf}
Grid capacity	$C_g = C_{gp} + C_{gf}$
Plate capacity	$C_p = C_{gp} + C_{pf}$
Filament capacity	$C_f = C_{gf} + C_{pf}$

Although at first glance the abbreviation system may look complicated, it is in reality a simple and logical system, and one with which it is important to be familiar. The majority of the symbols used in radio work belong to electrical terminology established years ago. They have been carried over to similar application in radio work.

APPENDIX C

METRIC PREFIXES USED IN RADIO WORK

It so happens that many of the units used extensively in electrical work are either too small or too large for convenient expression or use in radio work. Instead of using large, cumbersome numbers to indicate the fractional or multiple parts of these units, it has become customary to make use of standard metric prefixes ahead of the standard units to simplify expressions and calculations involving these quantities. These metric prefixes are so commonly used in radio work that the service man should familiarize himself with them, so that he may become proficient in understanding and using them. A list of these prefixes is given below:

Prefix	*Abbreviation*	*Meaning*
deci	*d*	one-tenth part of
centi	*c*	one hundredth part of
mil or *milli*	*m*	one-thousandth part of
micro	μ	one-millionth part of
pica or *micro-micro*	μμ or *mm*	one-millionth of a millionth part of
deka	*dk*	10 times
hekto	*h*	100 times
kilo	*k*	1,000 times
mega	*M*	1,000,000 times

Thus, *deci*, means that the new unit is 0.1 of the standard unit. A *decimeter* is 0.1 of a meter. A *milliampere* is 0.001 of an ampere. A *microhenry* is 0.000001 of a henry. A *microfarad* is 0.000001 of a farad. Instead of saying that a condenser has a capacity of 0.00035 microfarads, we can say that it has a capacity of 350 micro-microfarads, etc.

A *centimeter* of inductance is equal to 0.001 of a microhenry. This unit does not follow the general rule.

The prefix *deka* means that the new unit is ten times the standard unit. The prefix *kilo* means that the new unit is 1,000 times the standard unit. Thus, one *kilocycle* equals 1,000 cycles. The prefix *meg* or *mega* means that the new unit is 1,000,000 times the original unit. Thus, one *megohm* equals 1,000,000 ohms, etc.

The word microfarad used in general radio work as a unit of capacitance has several notations for its abbreviation now in common use. According to the above list of prefixes, microfarad should be abbreviated μf but other notations such as mfd. and mf. are also firmly entrenched in the minds of radio men and are used extensively by condenser manufacturers for marking condensers.

(Continued on next page)

CONVERSION OF UNITS EXPRESSED WITH METRIC PREFIXES

As it is often very difficult for persons inexperienced in the handling of mathematical computations to correctly convert from one form into another the various electrical units which are expressed with the common metric prefixes, the following factors for conversion have been arranged alphabetically here to assist the student in this work.

Multiply	*By*	*To Convert To:*
Amperes	× 1,000,000,000,000	micromicroamperes
Amperes	× 1,000,000	microamperes
Amperes	× 1,000	milliamperes
Cycles	× .000,001	megacycles
Cycles	× .001	kilocycles
Farads	× 1,000,000,000,000	micromicrofarads or picofarads
Farads	× 1,000,000	microfarads
Farads	× 1,000	millifarads
Henries	× 1,000,000	microhenries
Henries	× 1,000	millihenries
Horsepower	× .7457	kilowatts
Horsepower	× 745.7	watts
Kilocycles	× 1,000	cycles
Kilovolts	× 1,000	volts
Kilowatts	× 1,000	watts
Kilowatts	× 1.341	horsepower
Megacycles	× 1,000,000	cycles
Mhos	× 1,000,000	micromhos
Mhos	× 1,000	millimhos
Microamperes	× .000,001	amperes
Microfarads	× .000,001	farads
Microhenries	× .000,001	henrys
Micromhos	× .000,001	mhos
Micro-ohms	× .000,001	ohms
Microvolts	× .000,001	volts
Microwatts	× .000,001	watts
Micromicrofarads	× .000,000,000,001	farads
Micromicro-ohms	× .000,000,000,001	ohms
Milliamperes	× .001	amperes
Millihenries	× .001	henrys
Millimhos	× .001	mhos
Milliohms	× .001	ohms
Millivolts	× .001	volts
Milliwatts	× .001	watts
Ohms	× 1,000,000,000,000	micromicro-ohms
Ohms	× 1,000,000	micro-ohms
Ohms	× 1,000	milliohms
Volts	× 1,000,000	microvolts
Volts	× 1,000	millivolts
Watts	× 1,000,000	microwatts
Watts	× 1,000	milliwatts
Watts	× .001	kilowatts

APPENDIX D

THE USE OF EXPONENTS IN CALCULATIONS

It is very convenient to express very large or very small quantities by means of whole numbers with suitable exponents. For instance, the rather cumbersome number 350,000,000 may be written as 3.5×10^8, which really means that 3.5 is multiplied by *ten*, eight times. The small number above, and to the side of the figure 10 is called the *exponent*. In this case the exponent is 8. Numbers less than 1 have *negative* exponents. Thus five ten-thousandths may be expressed in the following ways.

$$.0005 \text{ or } 5\times10^{-4}, \text{ or } \frac{5}{10{,}000} \text{ or } \frac{5}{10^4}.$$

This representation is really a shorthand method of working with inconveniently large or small quantities, and the student should become thoroughly familiar with it, as it is used extensively in technical work. The table below will be found helpful in understanding how the proper exponent is found.

$$1 = 10^0 = \text{Units}$$
$$10 = 10^1 = \text{Tens}$$
$$100 = 10^2 = \text{Hundreds}$$
$$1{,}000 = 10^3 = \text{Thousands } (\textit{Kilo.})$$
$$1{,}000{,}000 = 10^6 = \text{Millions } (\textit{Mega.})$$

$$1 = 10^0 = \text{Units}$$
$$.1 = 10^{-1} = \text{Tenths}$$
$$.01 = 10^{-2} = \text{Hundredths}$$
$$.001 = 10^{-3} = \text{Thousandths } (\textit{Milli.})$$
$$.000001 = 10^{-6} = \text{Millionths } (\textit{Micro.})$$

The rules dealing with these complicated looking figures are simple, and, when mastered, provide an exceptionally easy method of handling large numbers. The rules are as follows:

When multiplying numbers, *add* the exponents.

When dividing numbers, *subtract* the exponents.

When squaring a number, *double* its exponent.

When obtaining a square root, *halve* the exponent.

When transfering an exponent across the dividing line, *change its sign.*

Example: Express the following quantities in simple numbers by the use of exponents. (*a*) 342,000,000,000 (*b*) 9,653,000 (*c*) 0.0000084 (*d*) 0.000432.

Answers: (*a*) 3.42×10^{11} (*b*) 9.653×10^6 (*c*) 8.4×10^{-6} (*d*) 4.32×10^{-4}. *Ans.*

Example: 6.28×10^{18} electrons flowing past a given point in a second constitute a current of 1 ampere. How many electrons flow past a given point in a second when the number of amperes is (*a*) 600? (*b*) 0.002?

Solutions: (*a*) $6.28\times10^{18}\times6\times10^2=37.68\times10^{20}$ or 3.768×10^{21}. *Ans.*

(*b*) $6.28\times10^{18}\times2\times10^{-3}=12.56\times10^{15}$ or 1.256×10^{16}. *Ans.*

SUMMARY OF FORMULAE COMMONLY USED IN RADIO WORK

(Formula numbers refer to numbers used in text)

Voltage, Current, Resistance

$$\text{Amperes} = \frac{\text{Volts}}{\text{Ohms}} \qquad \left(I = \frac{E}{R}\right) \tag{1}$$

$$\text{Volts} = \text{Amperes} \times \text{Ohms} \qquad (E = I \times R) \tag{2}$$

$$\text{Ohms} = \frac{\text{Volts}}{\text{Amperes}} \qquad \left(R = \frac{E}{I}\right) \tag{3}$$

Power: $$\text{Watts} = \text{Volts} \times \text{Amperes} \qquad (W = E \times I) \tag{4}$$

$$\text{Watts} = \text{Volts squared divided by ohms} \left(W = \frac{E^2}{R}\right) \tag{5}$$

$$\text{Watts} = \text{Amperes squared} \times \text{ohms} \qquad (W = I^2 R) \tag{6}$$

Resistance: $$R = \frac{kL}{CM} \tag{7}$$

Resistance: $$R = \frac{kL}{CM}\left[1 \pm (a \times t)\right] \tag{8}$$

Resistances in Series: (all resistances in same units)

R is total resistance; r_1, r_2, r_3, etc., are individual resistances.

$$R = r_1 + r_2 + r_3 + \text{etc.} \tag{9}$$

Resistances in Parallel: (all resistances must be in same units)

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \text{etc.} \tag{10}$$

or $$R = \frac{1}{\frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \text{etc.}}$$

$$F = \frac{m\,m^1}{d^2} \tag{11}$$

$$L = 0.0251\, d^2 n^2 l K \tag{12}$$

Capacity of a Condenser:

$$C = \frac{2235\,(N\text{-}1)\,A\,k}{10^{10}\,t} \tag{13}$$

Capacity of Condensers in Parallel: (all capacities must be in same units)

$$C = c_1 + c_2 + c_3 + \text{etc.} \tag{14}$$

Capacity of Condensers in Series: (all capacities must be in same units)

$$\frac{1}{C} = \frac{1}{c_1} + \frac{1}{c_2} + \frac{1}{c_3} + \text{etc.} \tag{15}$$

APPENDIX E—Cont'd.

or $$C=\frac{1}{\frac{1}{c_1}+\frac{1}{c_2}+\frac{1}{c_3}+\text{etc.}}$$

Inductive reactance: $X_L=2\pi fL$ (16)

Capacity reactance: $X_c=\frac{1}{2\pi fC}$ (17)

Impedance (Z) of A.C. Circuit Containing Inductance (L), Capacity (C) and Resistance (R). (frequency f).

$$Z=\sqrt{R^2+X^2}=\sqrt{R^2+\left(2\times3.1416\times f\times L-\frac{1}{2\times3.1416\times f\times C}\right)^2} \quad (18)$$

$$I=\frac{E}{\sqrt{R^2+\left(2\pi fL-\frac{1}{2\pi fC}\right)^2}} \quad (19)$$

$$f=\frac{1}{2\pi\sqrt{LC}} \quad (20)$$

Frequency and Wavelength Relations for radio (not for sound)

$$\text{Meters (wavelength)}=\frac{300{,}000{,}000}{\text{cycles}} \quad (21)$$

$$\text{Frequency (Cycles)}=\frac{300{,}000{,}000}{\text{meters (wavelength)}} \quad (22)$$

$$\text{Frequency (Kilocycles)}=\frac{300{,}000}{\text{meters (wavelength)}} \quad (23)$$

Wavelength at which resonance in a series tuned circuit takes place with given inductance (L) and capacity (C)

$$\text{Meters (wavelength)}=1885\sqrt{\text{L (microhenries)}\times\text{C (microfarads)}} \quad (24)$$

$$\text{Meters (wavelength)}=1.885\sqrt{\text{L (microhenries)}\times\text{C (micro-microfarads)}} \quad (25)$$

Frequency at which resonance takes place with given constants of inductance and capacity.

$$\text{Frequency (Cycles)}=\frac{159{,}000}{\sqrt{\text{L (microhenries)}\times\text{C (microfarads)}}} \quad (26)$$

$$\text{Frequency (Cycles)}=\frac{159{,}000{,}000}{\sqrt{\text{L (microhenries)}\times\text{C (micro-microfarads)}}} \quad (27)$$

Inductance of a single-layer Inductor: $L=0.0251\ d^2\ n^2\ l\ K$ (28)

$$\text{Loud Speaker Baffle length (in feet)}=\frac{282}{\text{frequency}} \quad (29)$$

WIRE TABLES

In design, construction, or repair work on electrical or radio apparatus, it is very helpful to have at hand complete data on the various types of magnet wire used for winding inductors, transformers, loud speaker coils, etc. It is often very helpful to know just how many turns of wire of a certain size can be wound into a certain available space, what the resistance-per-foot, or the feet-per-ohm, of the wire is, etc. In the case of repair work, it is usually easy to rewind a damaged coil with wire of the same size and type as was on it previously, but when new apparatus is designed it is necessary to refer to tables of wire data for this information.

The reader is urged to familiarize himself with the contents of these tables, for he will find that they will will prove to be real time-savers for him.

TABLE NO. 1

THICKNESS OF COTTON AND SILK INSULATION ON MAGNET WIRE

Wire Size	Thickness of Insulation in Mils (1 Mil = .001 inch)				
B & S	S.C.C.	D.C.C.	T.C.C.	S.S.C.	D.S.C.
0000-5	4.5	9.0	13.5	1.0	2.0
6-7	4.0	8.0	12.0	1.0	2.0
8	3.5	7.0	10.5	1.0	2.0
9	3.0	6.0	9.0	1.0	2.0
10-12	2.5	5.0	7.5	1.0	2.0
13-19	2.25	4.5	7.75	1.0	2.0
13-32	2.5	4.5	7.0	1.0	2.0
14-15	3.0	5.0	7.0	----	----
16-18	2.5	4.0	----	----	----
19-22	2.0	4.0	----	----	----
23-25	2.0	4.0	----	1.5	3.0
20-40	2.0	4.0	6.0	1.0	2.0
26-28	2.0	4.0	----	1.5	3.0
29-34	2.0	4.0	----	1.2	2.5
32-36	----	----	----	0.87	1.75
35-40	2.0	4.0	----	1.0	2.0

(Continued on next page)

APPENDIX F—Cont'd.

BARE COPPER WIRE TABLE

TABLE NO. 2

Giving Measurements at 68° F. (20° C.) with Specific Gravity of 8.89
(Brown & Sharpe)

A. W. G. B. & S. Gauge	Diameter Inches	Area Circular Mils	Weight Pounds per 1000 Feet	Length Feet per Pound	RESISTANCE Ohms per 1000 Feet	Ohms per Pound
0000	0.4600	211,600.	640.5	1.561	0.04901	.00007652
000	0.4096	167,800.	507.9	1.969	.06180	.0001217
00	0.3648	133,100.	402.8	2.483	.07793	.0001935
0	0.3249	105,500.	319.5	3.130	.09827	.0003076
1	0.2893	83,690.	253.3	3.948	.1239	.0004891
2	0.2576	66,370.	200.9	4.978	.1563	.0007778
3	0.2294	52,630.	159.3	6.276	.1970	.001237
4	0.2043	41,740.	126.4	7.911	.2485	.001966
5	0.1819	33,100.	100.2	9.980	.3133	.003127
6	0.1620	26,250.	79.46	12.58	.3951	.004972
7	0.1443	20,820.	63.02	15.87	.4982	.007905
8	0.1285	16,510.	49.98	20.01	.6282	.01257
9	0.1144	13,090.	39.63	25.23	.7921	.01999
10	0.1019	10,380.	31.43	31.82	.9989	.03178
11	0.09074	8,234.	24.92	40.13	1.260	.05053
12	0.08081	6,530.	19.77	50.58	1.588	.08035
13	0.07196	5,178.	15.68	63.77	2.003	.1278
14	0.06408	4,107.	12.43	80.45	2.525	.2032
15	0.05707	3,257.	9.858	101.4	3.184	.3230
16	0.05082	2,583.	7.818	127.9	4.016	.5136
17	0.04526	2,048.	6.200	161.3	5.064	.8167
18	0.04030	1,624.	4.917	203.4	6.385	1.299
19	0.03589	1,288.	3.899	265.5	8.051	2.065
20	0.03196	1,022.	3.092	323.4	10.15	3.283
21	0.02846	810.1	2.452	407.8	12.80	5.221
22	0.02535	642.4	1.945	514.1	16.14	8.301
23	0.02257	509.5	1.542	648.5	20.36	13.20
24	0.02010	404.0	1.223	817.7	25.67	20.99
25	0.01790	320.4	0.9699	1,031.	32.37	33.37
26	0.01594	254.1	0.7692	1,300.	40.81	53.06
27	0.01420	201.5	0.6100	1,639.	51.47	84.37
28	0.01264	159.8	0.4837	2,067.	64.90	134.2
29	0.01126	126.7	0.3836	2,606.	81.83	213.3
30	0.01003	100.5	0.3042	3,287.	103.2	329.2
31	0.008928	79.70	0.2413	4,144.	130.1	539.3
32	0.007950	63.21	0.1913	5,227.	164.1	857.6
33	0.007080	50.13	0.1517	6,591.	206.9	1,364.
34	0.006305	39.75	0.1203	8,312.	260.9	2,168.
35	0.005615	31.52	0.09542	10,480.	329.0	3,448.
36	0.005000	25.00	0.07568	13,213.	414.8	5,482.
37	0.004453	19.83	0.0601	16,664.	523.1	8,717.
38	0.003965	15.72	0.04759	21,012.	659.6	13,860.
39	0.003531	12.47	0.03774	26,497.	831.8	22,040.
40	0.003145	9.888	0.02990	33,411.	1049.	35,040.
41	0.00275	7.5625	0.02289	43,700.	1370.	59,900.
42	0.00250	6.2500	0.01892	52,800.	1660.	87,700.
43	0.00225	5.0625	0.01532	65,300.	2050.	133,700.
44	0.00200	4.0000	0.01211	82,600.	2600.	214,000.
45	0.00175	3.0625	0.00927	107,900.	3390.	365.200.
46	0.00150	2.2500	0.00681	146,800.	4610.	676,800.

Note: A mil is 1/1000 (one-thousandth) of an inch
Dia. in mils equals dia. in inches × 1000

PROPERTIES OF METALS

The following table, which is published here through the courtesy of the United States Bureau of Standards, gives several of the important physical and electrical characteristics of the common metals and alloys used in industry. For instance, a glance at the column of temperature coefficients of resistance shows that the alloys Therlo, Constantin, and Manganin have the lowest values (.00001). It is for this reason that they are used for shunts and resistances in electrical instruments and for precision resistors, in which it is necessary that the resistance value remain absolutely constant even though the temperature change slightly due to weather changes or to the heat developed by the electric current flowing through them.

A glance at the column of melting points reveals that tungsten has the highest melting point (3000° C.). That is why tungsten is used for the filaments of vacuum tubes and incandescent lamps. Many other interesting facts can be found from a study of this table of the properties of metals.

(See table on next page)

PROPERTIES OF METALS

Metal	Temperature coefficient at 20° C	Specific gravity	Tensile strength lbs./in.^{2}	Melting point, °C
Advance. See Constantin				
Aluminum	0.0039	2.70	30,000	659
Antimony	.0036	6.6		630
Bismuth	.004	9.8		271
Brass	.002	8.6	70,000	900
Cadmium	.0038	8.6		321
Calido. See Nichrome.				
Climax	.0007	8.1	150,000	1250
Constantin	.00001	8.9	120,000	1190
Copper, annealed	.00393	8.89	30,000	1083
Copper, hard-drawn	.00382	8.89	60,000	
Eureka. See Constantin				
Excello	.00016	8.9	95,000	1500
German silver, (18% nickel)	.0004	8.4	150,000	1100
German silver, (30% nickel) See Constantin.				
Gold	.00342	19.3	20,000	1063
Ia Ia. See Constantin.				
Ideal. See Constantin.				
Iron, 99.98 per cent pure	.0050	7.8		1530
Iron. See Steel.				
Lead	.0039	11.4	3,000	327
Magnesium	.004	1.74	33,000	651
Manganin	.00001	8.4	150,000	910
Mercury	.00089	13.546	0	—38.9
Molybdenum, drawn	.004	9.0		2500
Monel metal	.0020	8.9	160,000	1300
Nichrome	.0004	8.2	150,000	1500
Nickel	.006	8.9	120,000	1452
Palladium	.0033	12.2	39,000	1550
Phosphor bronze	.0018	8.9	25,000	750
Platinum	.003	21.4	50,000	1755
Silver	.0038	10.5	42,000	960
Steel, E. B. B.	.005	7.7	53,000	1510
Steel, B. B.	.004	7.7	58,000	1510
Steel, Siemens-Martin	.003	7.7	100,000	1510
Steel, manganese	.001	7.5	230,000	1260
Superior. See Climax				
Tantalum	.0031	16.6		2850
Therlo	.00001	8.2		
Tin	.0042	7.3	4,000	232
Tungsten, drawn	.0045	19	500,000	3000
Zinc	.0037	7.1	10,000	419

Note: See also the tables in Arts. 27, 29 and 48.

DRILL & TAP SIZES

In the construction of radio and electrical equipment, it is necessary to drill and tap holes in various kinds of metals and insulating materials for the machine screws which hold the parts together. Various sizes of machine screws are used in radio work, the most common being the 6x32 (number 6 screw with 32 threads per inch), and the 8x32. The following table shows the screw numbers, the number of threads per inch, their diameter, and the drills to be used in making holes either for threading (tapping) or for allowing the screw to slide through the hole freely (clearance). Thus, to tap a hole for a 6x32 screw, first drill the hole with a No. 36 drill. Then tap it with a 6x32 tap. To drill a clearance hole through which a 6x32 screw will slide freely, use the No. 28 clearance size drill

All metal drilling should be done with round twist drills which are obtainable in the sizes designated by numbers as in the table. When drilling brass, aluminum and cast iron, no lubricant is used. When drilling steel, the drill should be lubricated with light machine oil as it enters the hole.

Insulating materials such as Bakelite, Formica, Celoron, hard rubber, fibre, etc. should be drilled with the point of the drill ground to the usual sixty degree angle but with the front edge of the cutting edge ground straight or flat to remove the hook. Speeds up to 1500 R. P. M. may be used and the drill may be left dry, or lubricated with lard oil or light machine oil. Insulating materials of this kind are rather hard on the drills and dull the points quickly. When the drill comes through the hole in the back it is advisable to hold a block of scrap wood solidly against the surface to prevent the material chipping or breaking through around the edges.

Taps are used for cutting threads on the inside of holes. *Dies* are for threading the outside of rods or screws. The first part of each tap or die number indicates the gauge number of the rod stock from which the screws were cut, or the gauge number of the rod to be threaded, respectively. The second part of each number indicates the number of threads per inch.

SIZES OF TAP* AND CLEARANCE DRILLS

Screw No.	*Th'ds Per Inch*	*Tap Size*	*Drill Number*		*Screw No.*	*Th'ds Per Inch*	*Tap Size*	*Drill Number*	
			For Tap	*Clearance*				*For Tap*	*Clearance*
2	48	2x48	No. 50	No. 44	8	24	8x24	30	17
2	56	2x56	50	44	8	32	8x32	29	19
2	64	2x64	50	44	10	24	10x24	25	10
3	40	3x40	47	39	10	30	10x30	22	10
3	48	3x48	47	39	10	32	10x32	21	10
3	56	3x56	45	39	12	20	12x20	19	2
4	32	4x32	45	31	12	24	12x24	16	2
4	36	4x36	44	31	12	28	12x28	14	2
4	40	4x40	43	31	14	20	14x20	10	¼
6	32	6x32	36	28	14	24	14x24	7	¼
6	36	6x36	34	28					

*Note: These are the drill sizes for average use. The size drill to use really varies somewhat with the material being drilled.

APPENDIX I

INDUCTANCE × CAPACITANCE (LC) VALVES

The formula for determining the frequency to which any circuit containing inductance and capacity will tune is:

$$f = \frac{159{,}000}{\sqrt{L \times C}} \quad \text{or, } Wavelength = 1885\sqrt{L \times C}$$

where, f=the frequency in cycles per second
L=the inductance of the coil in microhenries
C=the capacity of the entire circuit in microfarads.

The product of the inductance L and the capacity C of the circuit determines the frequency at which the circuit is resonant or in "tune". For each frequency there is a definite value of this product (called the inductance-capacity product, or the "$L \times C$" value) for which resonance occurs. If this value is known, it is possible to determine the correct amount of inductance required for use with any value of capacity, or the correct amount of capacity for use with any value of inductance, to produce resonance at that frequency. The $L \times C$ value is divided by the known capacity, or the known inductance, the quotient of the division being the required inductance or capacitance. Thus:

$$\text{Inductance} = \frac{L \times C \text{ value}}{\text{capacity}} \qquad \text{Capacity} = \frac{L \times C \text{ value}}{\text{inductance}}$$

The following table gives the inductance-capacity values necessary to produce resonance at frequencies from 1 to 39,000 meters. The inductance is in microhenries, the capacity is in microfarads, and n is the frequency in cycles per second.

As examples of the use of this table, let it be desired to find the required inductance of a coil to tune to a frequency of 600 kilocycles (500 meters) with a tuning condenser of 0.00035 microfarads maximum capacity. From the table, the $L \times C$ value for this frequency is found to be 0.0704. Dividing this value by the capacity (0.00035) gives the result, 201 microhenries of inductance.

Let is be desired to find the required capacity of this tuning condenser to tune to the frequency of 1500 kilocycles (200 meters) with the above coil of 201 microhenries inductance. The $L \times C$ value for this frequency is found from the table to be 0.01126. Dividing this by the inductance (201) gives as a result 0.000055 microfarads for the minimum capacity. The tuning condenser must then have a range of capacitance from 0.000055 to 0.00035 microfarads to cover this frequency range with this inductor. Any other coil and condenser combination may be calculated in this same way.

Looking at the table we note that, as the frequency decreases, the $L \times C$ constant increases. If we divide the frequency by 10, the $L \times C$ constant must be multiplied by 100. This must be kept in mind if values beyond the ranges of the table are to be determined. For instance, if we wish to determine the $L \times C$ constant for 2 kc (2,000 cycles), we look up the value for (2,000,000 *cycles* on the table) and move the decimal point six places to the right; 6330 is the correct constant. If it is desired to check the results, remember that resonance occurs when the inductive reactance is equal to the capacitive reactance. The frequency at which this occurs is the *resonance* frequency.

RELATION BETWEEN WAVELENGTH IN METERS, FREQUENCY IN KILOCYCLES, AND THE PRODUCT OF INDUCTANCE IN MICROHENRIES, AND CAPACITY IN MICROFARADS, REQUIRED TO PRODUCE RESONANCE AT THESE CORRESPONDING FREQUENCIES OR WAVELENGTHS.
(L x C CONSTANT)

W.L. in Meters	*f* in Kc.	*L* x *C*	W.L. in Meters	*f* in Kc.	*L* x *C*	W.L. in Meters	*f* in Kc.	*L* x *C*
1	300,000	0.0000003	450	667	0.0570	740	405	0.1541
2	150,000	0.0000111	460	652	0.0596	745	403	0.1562
3	100,000	0.0000018	470	639	0.0622	750	400	0.1583
4	75,000	0.0000045	480	625	0.0649	755	397	0.1604
5	60,000	0.0000057	490	612	0.0676	760	395	0.1626
6	50,000	0.0000101	500	600	0.0704	765	392	0.1647
7	42,900	0.0000138	505	594	0.0718	770	390	0.1669
8	37,500	0.0000180	510	588	0.0732	775	387	0.1690
9	33,333	0.0000228	515	583	0.0747	780	385	0.1712
10	30,000	0.0000282	520	577	0.0761	785	382	0.1734
20	15,000	0.0001129	525	572	0.0776	790	380	0.1756
30	10,000	0.0002530	530	566	0.0791	795	377	0.1779
40	7,500	0.0004500	535	561	0.0806	800	375	0.1801
50	6,000	0.0007040	540	556	0.0821	805	373	0.1824
60	5,000	0.0010140	545	551	0.0836	810	370	0.1847
70	4,290	0.0013780	550	546	0.0852	815	368	0.1870
80	3,750	0.0018010	555	541	0.0867	820	366	0.1893
90	3,333	0.0022800	560	536	0.0883	825	364	0.1916
100	3,000	0.00282	565	531	0.0899	830	361	0.1939
110	2,727	0.00341	570	527	0.0915	835	359	0.1962
120	2,500	0.00405	575	522	0.0931	840	357	0.1986
130	2,308	0.00476	580	517	0.0947	845	355	0.201
140	2,143	0.00552	585	513	0.0963	850	353	0.203
150	2,000	0.00633	590	509	0.0980	855	351	0.206
160	1,875	0.00721	595	504	0.0996	860	349	0.208
170	1,764	0.00813	600	500	0.1013	865	347	0.211
180	1,667	0.00912	605	496	0.1030	870	345	0.213
190	1,579	0.01015	610	492	0.1047	875	343	0.216
200	1,500	0.01126	615	488	0.1065	880	341	0.218
210	1,429	0.01241	620	484	0.1082	885	339	0.220
220	1,364	0.01362	625	480	0.1100	890	337	0.223
230	1,304	0.01489	630	476	0.1117	895	335	0.225
240	1,250	0.01621	635	472	0.1135	900	333	0.228
250	1,200	0.01759	640	469	0.1153	905	331	0.231
260	1,154	0.01903	645	465	0.1171	910	330	0.233
270	1,111	0.0205	650	462	0.1189	915	328	0.236
280	1,071	0.0221	655	458	0.1208	920	326	0.238
290	1,034	0.0237	660	455	0.1226	925	324	0.241
300	1,000	0.0253	665	451	0.1245	930	323	0.243
310	968	0.0270	670	448	0.1264	935	321	0.246
320	938	0.0288	675	444	0.1283	940	319	0.249
330	909	0.0306	680	441	0.1302	945	317	0.251
340	883	0.0325	685	438	0.1321	950	316	0.254
350	857	0.0345	690	435	0.1340	955	314	0.257
360	834	0.0365	695	432	0.1360	960	313	0.259
370	811	0.0385	700	429	0.1379	965	311	0.262
380	790	0.0406	705	426	0.1399	970	309	0.265
390	769	0.0428	710	423	0.1419	975	308	0.268
400	750	0.0450	715	420	0.1439	980	306	0.270
410	732	0.0473	720	417	0.1459	985	305	0.273
420	715	0.0496	725	414	0.1479	990	303	0.276
430	698	0.0520	730	411	0.1500	995	302	0.279
440	682	0.0545	735	408	0.1521	1000	300	0.282

APPENDIX J

WAVELENGTH — FREQUENCY CHANNEL CHART

Radio engineers started so long ago to think and calculate in terms of wavelength (meters) that no one remembers just why they started that way. Today, however, with the governments of all countries allocating transmitting stations by definite frequency separations (in kilocycles), it is much more convenient and accurate to work in terms of frequency.

Unfortunately, this new habit is not easy to acquire, because the kilocycle difference per wavelength is very great at short wavelengths (that is, below about 50 meters), and very small at the usual broadcast wavelengths, between 200 and 550 meters.

The relation between frequency and wavelength is this: radio wave disturbances are propagated at the same speed as light, approximately 300,000,000 meters per second. This corresponds to about 186,000 miles per second. If the *wavelength* of a particular transmitting station, for instance, is 100 meters, each wave travels 100 meters before the next one starts. Therefore, during one second there is time for 300,000,000 ÷ 100 = 3,000,000 such waves. Consequently the frequency is 3,000,000 cycles.

$$\text{Frequency (cycles per sec.)} = \frac{300{,}000{,}000}{\text{Wavelength (in meters)}}$$

In general, the frequency as expressed in cycles is a large and unwieldy number, so radio engineers use the term "kilocycle," which stands for one thousand cycles. Thus, instead of saying 1,000,000 cycles (equivalent to 300 meters), we say 1,000 kilocycles. The term is usually abbreviated into the letters "kc." On the very short wavelengths, the frequency runs up into several million cycles, so the term "megacycles," meaning one million cycles, is frequently found to be more convenient than "kilocycles".

Nowadays, we work in terms of frequency rather than wavelength, because it has been found that a uniform 10-kilocycle separation between stations is enough to prevent the transmitters from causing interference with each other in selective receiving sets. There is no way of expressing this separation as a uniform quantity in terms of wavelength. For example, the difference between 590 to 600 meters is approximately 10 kilocycles, while the difference between 10 meters and 20 meters is 15,000 kilocycles.

The chart on a following page discloses one very interesting fact that many people do not appreciate. If we take the range from 200 to 500 meters, for broadcasting, we find it equal to a band 900 kilocycles wide. This means it is big enough to accommodate ninety transmitting bands or "channels" each 10 kilocycles wide. In the space between 10 meters and 200 meters (a band only 190 meters wide compared to 300 meters for the 200-500 range) there is a frequency difference of 28,500 kilocycles, which will give us 2,850 ten-kilocycle channels. In other words, between 10 and 200 meters there is room for 32 times as many broadcasting stations as between 200 and 500 meters. There is room for even a greater number of code stations, since they do not require as much frequency separation as broadcasting stations. When we consider this, we realize why short waves have assumed such a tremendous commercial importance, with many different communication companies asking for more channels than there are available.

Even though you are not in the habit of thinking in terms of frequency, when you read that the band between 6,000 and 6,150 kilocycles is reserved for shortwave broadcasting you can look at the chart, find 6,000 kc., and, following the line from left to right, see that this refers to a space between 50 meters and about 51 meters. Then you will realize that, although the wavelength separation is only one meter, the band has fifteen 10-kilocycle bands, or room for one-sixth as many stations as can operate between 200 and 500 meters.

Again, the band between 28,000 and 30,000 kc. has been assigned to amateurs and experimenters. Here is a separation of only .7 meters, yet there are two hundred 10kc. bands in what appears to be a very small wavelength range.

(See following page for Chart)

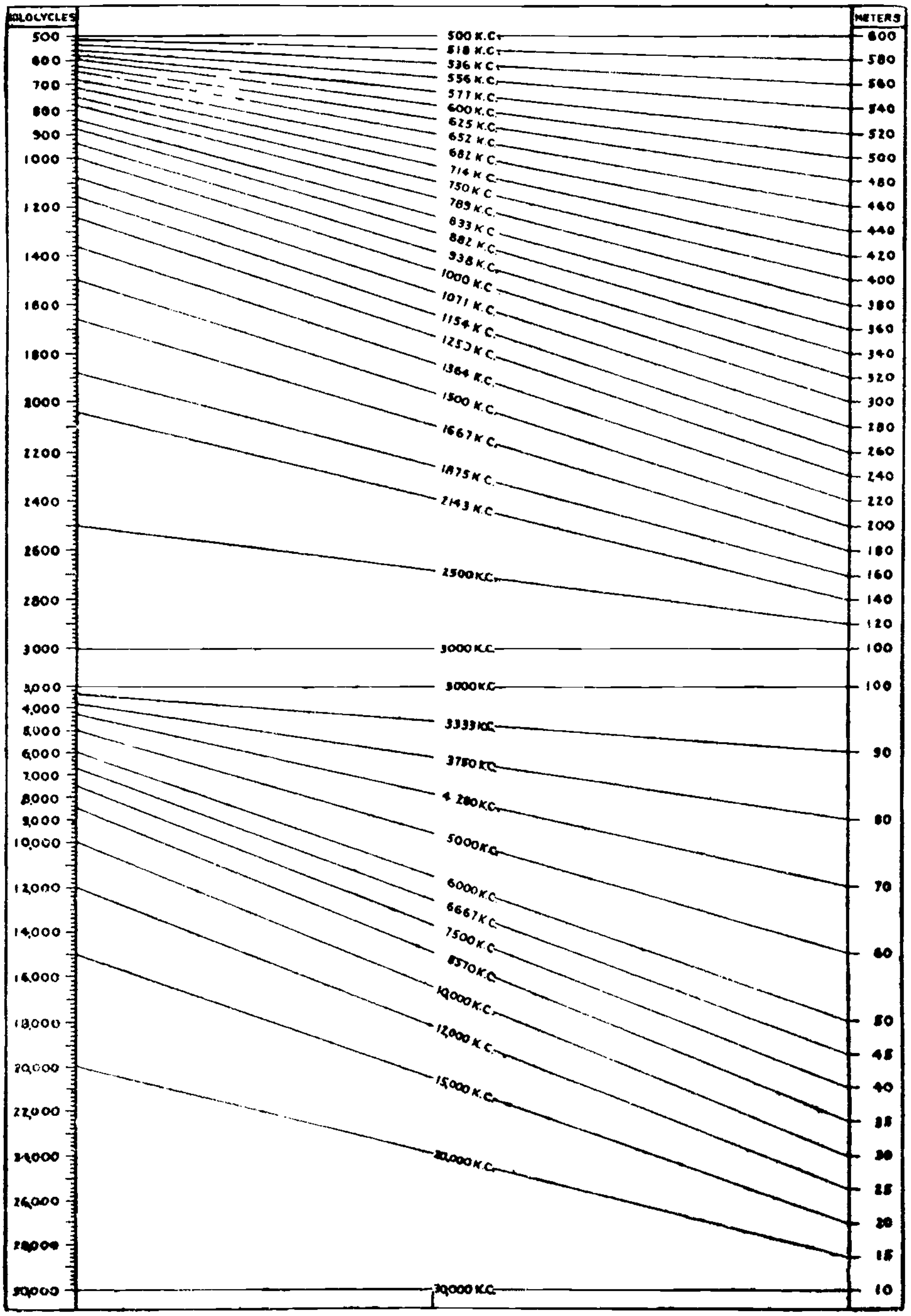


Fig. 510—Wavelength—frequency channel chart.

KILOCYCLE — METER CONVERSION TABLE

There is an increasing tendency in radio practice to think and deal with radio waves in terms of frequencies in kilocycles rather than wavelengths in meters. "Kilo" means a thousand, and "cycle" means one complete alternation. The number of kilocycles (abbreviated kc.) indicates the number of thousands of times that the rapidly alternating current in the antenna repeats its flow in either direction in one second. The smaller is the wave length in meters, the larger is the frequency in kilocycles. The numerical relation between the two is given by the following rule. For approximate calculation, to obtain kilocycles divide 300,000 by the number of meters, and to obtain meters divide 300,000 by the number of kilocycles. For example, 100 meters equals approximately 3,000 kilocycles, 300 m equals 1,000 kc, 1,000 m equals 300 kc, 3,000 m equals 100 kc. For very accurate conversion, the factor 299,820 is used instead of 300,000. This rule is based on the fact that wave length is equal to velocity divided by frequency, and the velocity of radio waves in space according to the best data available is 299,820,000 meters per second.

This table gives accurate values of kilocycles corresponding to any number of meters, and vice versa. It is based on the factor 299,820, and gives values for every 10 kilocycles or meters. It should be particularly noticed that the table is entirely reversible. For example, 50 kilocycles is 5,996 meters, and also, 50 meters is 5,996 kilocycles. The range of the table is easily extended by shifting the decimal point; the shift is in opposite directions for each pair of values; for example, one cannot find 223 in the first column, but its equivalent is obtained by finding later in the table that 2,230 kilocycles or meters is equivalent to 1,344 meters or kilocycles.

It is suggested that the student make frequent use of this table, to accustom himself as quickly as possible to use of the term "kilocycles" in referring to frequencies of stations, although wavelengths or corresponding frequencies can be calculated by the formulas given elsewhere in this book. The use of this table makes the rather laborious calculations unnecessary and insures accuracy of results. The table is reproduced here by the courtesy of the Bureau of Standards.

(See next page for Table)

KILOCYCLES (kc) TO METERS (m), OR METERS TO KILOCYCLES
[Columns Are Interchangeable]

kc or m	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*
10	29,982	510	587.9	1,010	296.9	1,510	198.6	2,010	149.2
20	14,991	520	576.6	1,020	293.9	1,520	197.2	2,020	148.4
30	9,994	530	565.7	1,030	291.1	1,530	196.0	2,030	147.7
40	7,496	540	555.2	1,040	288.3	1,540	194.7	2,040	147.0
50	5,996	550	545.1	1,050	285.5	1,550	193.4	2,050	146.3
60	4,997	560	535.4	1,060	282.8	1,560	192.2	2,060	145.5
70	4,283	570	526.0	1,070	280.2	1,570	191.0	2,070	144.8
80	3,748	580	516.9	1,080	277.6	1,580	189.8	2,080	144.1
90	3,331	590	508.2	1,090	275.1	1,590	188.6	2,090	143.5
100	2,998	600	499.7	1,100	272.6	1,600	187.4	2,100	142.8
110	2,726	610	491.5	1,110	270.1	1,610	186.2	2,110	142.1
120	3,499	620	483.6	1,120	267.7	1,620	185.1	2,120	141.4
130	2,306	630	475.9	1,130	265.3	1,630	183.9	2,130	140.8
140	2,142	640	468.5	1,140	263.0	1,640	182.8	2,140	140.1
150	1,999	650	461.3	1,150	260.7	1,650	181.7	2,150	139.5
160	1,874	660	454.3	1,160	258.5	1,660	180.6	2,160	138.8
170	1,764	670	447.5	1,170	256.3	1,670	179.5	2,170	138.1
180	1,666	680	440.9	1,180	254.1	1,680	178.5	2,180	137.5
190	1,578	690	434.5	1,190	252.0	1,690	177.4	2,190	136.9
200	1,499	700	428.3	1,200	249.9	1,700	176.4	2,200	136.3
210	1,428	710	422.3	1,210	247.8	1,710	175.3	2,210	135.7
220	1,363	720	416.4	1,220	245.8	1,720	174.3	2,220	135.1
230	1,304	730	410.7	1,230	243.8	1,730	173.3	2,230	134.4
240	1,249	740	405.2	1,240	241.8	1,740	172.3	2,240	133.8
250	1,199	750	399.8	1,250	239.9	1,750	171.3	2,250	133.3
260	1,153	760	394.5	1,260	238.0	1,760	170.4	2,260	132.7
270	1,110	770	389.4	1,270	236.1	1,770	169.4	2,270	132.1
280	1,071	780	384.4	1,280	234.2	1,780	168.4	2,280	131.5
290	1,034	790	379.5	1,290	232.4	1,790	167.5	2,290	130.9
300	999.4	800	374.8	1,300	230.6	1,800	166.6	2,300	130.4
310	967.2	810	370.2	1,310	228.9	1,810	165.6	2,310	129.8
320	967.9	820	365.6	1,320	227.1	1,820	164.7	2,320	129.2
330	908.6	830	361.2	1,330	225.4	1,830	163.8	2,330	128.7
340	881.8	840	356.9	1,340	223.7	1,840	162.9	2,340	128.1
350	856.6	850	352.7	1,350	222.1	1,850	162.1	2,350	127.6
360	832.8	860	348.6	1,360	220.4	1,860	161.2	2,360	127.0
370	810.3	870	344.6	1,370	218.8	1,870	160.3	2,370	126.5
380	789.0	880	340.7	1,380	217.3	1,880	159.5	2,380	126.0
390	768.8	890	336.9	1,390	215.7	1,890	158.6	2,390	125.4
400	749.6	900	333.1	1,400	214.2	1,900	157.8	2,400	124.9
410	731.3	910	329.5	1,410	212.6	1,910	157.0	2,410	124.4
420	713.9	920	325.9	1,420	211.1	1,920	156.2	2,420	123.9
430	697.3	930	322.4	1,430	209.7	1,930	155.3	2,430	123.4
440	681.4	940	319.0	1,440	208.2	1,940	154.5	2,440	122.9
450	666.3	950	315.6	1,450	206.8	1,950	153.8	2,450	122.4
460	651.8	960	312.3	1,460	205.4	1,960	153.0	2,460	121.9
470	637.9	970	309.1	1,470	204.0	1,970	152.2	2,470	121.4
480	624.6	980	303.9	1,480	202.6	1,980	151.4	2,480	120.9
490	611.9	990	302.8	1,490	201.2	1,990	150.7	2,490	120.4
500	599.6	1,000	299.8	1,500	199.9	2,000	149.9	2,500	119.9

Kilocycles (kc) to Meters (m), or Meters to Kilocycles
(Cont'd) [Columns Are Interchangeable]

kc or m	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*
2,510	119.5	3,010	99.61	3,510	85.42	4,010	74.77	4,510	66.48
2,520	119.0	3,020	99.28	3,520	85.18	4,020	74.58	4,520	66.33
2,530	118.5	3,030	98.95	3,530	84.94	4,030	74.40	4,530	66.19
2,540	118.0	3,040	98.62	3,540	84.70	4,040	74.21	4,540	66.04
2,550	117.6	3,050	98.30	3,550	84.46	4,050	74.03	4,550	65.89
2,560	117.1	3,060	97.98	3,560	84.22	4,060	73.85	4,560	65.75
2,570	116.7	3,070	97.66	3,570	83.98	4,070	73.67	4,570	65.61
2,580	116.2	3,080	97.34	3,580	83.75	4,080	73.49	4,580	65.46
2,590	115.8	3,090	97.03	3,590	83.52	4,090	73.31	4,590	65.32
2,600	115.3	3,100	96.72	3,600	83.28	4,100	73.13	4,600	65.18
2,610	114.9	3,110	96.41	3,610	83.05	4,110	72.95	4,610	65.04
2,620	114.4	3,120	96.10	3,620	82.82	4,120	72.77	4,620	64.90
2,630	114.0	3,130	95.79	3,630	82.60	4,130	72.60	4,630	64.76
2,640	113.6	3,140	95.48	3,640	82.37	4,140	72.42	4,640	64.62
2.650	113.1	3,150	95.18	3,650	82.14	4,150	72.25	4,650	64.48
2,660	112.7	3,160	94.88	3,660	81.92	4,160	72.07	4,660	64.34
2,670	112.3	3,170	94.58	3,670	81.70	4,170	71,90	4,670	64.20
2.680	111.9	3,180	94.28	3,680	81.47	4,180	71.73	4,680	64.06
2,690	111.5	3,190	93.99	3,690	81.25	4,190	71.56	4,690	63.93
2,700	111.0	3,200	93.69	3,700	81.03	4,200	71.30	4,700	63.79
2,710	110.6	3,210	93.40	3,710	80.81	4,210	71.22	4,710	63.66
2,720	110.2	3,220	93.11	3,720	80.60	4,220	71.05	4,720	63.52
2,730	109.8	3,230	92.82	3,730	80.38	4,230	70.88	4,730	63.39
2,740	109.4	3,240	92.54	3,740	80.17	4,240	70.71	4,740	63.25
2,750	109.0	3,250	92.25	3,750	79.95	4,250	70.55	4,750	63.12
2,760	108.6	3,260	91.97	3,760	79.74	4,260	70.38	4,760	62.99
2,770	108.2	3,270	91.69	3,770	79.53	4,270	70.22	4,770	62.86
2,780	107.8	3,280	91.41	3,780	79.32	4,280	70.05	4,780	62.72
2,790	107.5	3,290	91.13	3,790	79.11	4,290	69.89	4,790	62.59
2,800	107.1	3,300	90.86	3,800	78.90	4,300	69.73	4,800	62.46
2,810	106.7	3,310	90.58	3,810	78.69	4,310	69.56	4,810	62.33
2,820	106.3	3,320	90.31	3,820	78.49	4,320	69.40	4,820	62.20
2,830	105.9	3,330	90.04	3,830	78.28	4,330	69.24	4,830	62.07
2,840	105.6	3,340	89.77	3,840	78.08	4,340	69.08	4,840	61.95
2,850	105.2	3,350	89.50	3,850	77.88	4,350	68.92	4,850	61.82
2,860	104.8	3,360	89.23	3,860	77.67	4,360	68.77	4,860	61.69
2,870	104.5	3,370	88.97	3,870	77.47	4,370	68.61	4,870	61.56
2,880	104.1	3,380	88.70	3,880	77.27	4,380	68.45	4,880	61.44
2,890	103.7	3,390	88.44	3,890	77.07	4,390	68.30	4,890	61.31
2,900	103.4	3,400	88.18	3,900	76.88	4,400	68.14	4,900	61.19
2,910	103.0	3,410	87.92	3,910	76.68	4,410	67.99	4,910	61.06
2,920	102.7	3,420	87.67	3,920	76.48	4,420	67.83	4,920	60.94
2,930	102.3	3,430	87.41	3,930	76.29	4,430	67.68	4,930	60.82
2,940	102.0	3,440	87.16	3,940	76.10	4,440	67.53	4,940	60.69
2,950	101.6	3,450	86.90	3,950	75.90	4,450	67.38	4,950	60.57
2,960	101.3	3,460	96.65	3,960	75.51	4,460	67.22	4,960	60.45
2,970	100.9	3,470	86.40	3,970	75.52	4,470	67.07	4,970	60.33
2,980	100.6	3.480	86.16	3,980	75.33	4,480	66.92	4,980	60.20
2,990	100.3	3,490	85.91	3,990	75.14	4,490	66.78	4,990	60.08
3,000	99.94	3,500	85.66	4,000	74.96	4,500	66.63	5,000	59.96

KILOCYCLES (kc) TO METERS (m), OR METERS TO KILOCYCLES
(Cont'd) [Columns Are Interchangeable]

kc or m	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*
5,010	59.84	5,510	54.41	6,010	49.89	6,510	46.06	7,010	42.77
5,020	59.73	5,520	54.32	6,020	49.80	6,520	45.98	7,020	42.71
5,030	59.61	5,530	54.22	6,030	49.72	6,530	45.91	7,030	42.65
5,040	59.49	5,540	54.12	6,040	49.64	6,540	45.84	7,040	42.59
5,050	59.37	5,550	54.02	6,050	49.56	6,550	45.77	7,050	42.53
5,060	59.25	5,560	53.92	6,060	49.48	6,560	45.70	7,060	42.47
5,070	59.13	5,570	53.83	6,070	49.39	6,570	45.63	7,070	42.41
5,080	59.02	5,580	53.73	6,080	49.31	6,580	45.57	7,080	42.35
5,090	58.90	5,590	53.64	6,090	49.23	6,590	45.50	7,090	42.29
5,100	58.79	5,600	53.54	6,100	49.15	6,600	45.43	7,100	42.23
5,110	58.67	5,610	53.44	6,110	49.07	6,610	45.36	7,110	42.17
5,120	58.56	5,620	53.35	6,120	48.99	6,620	45.29	7,120	42.11
5,130	58.44	5,630	53.25	6,130	48.91	6,630	45.22	7,130	42.05
5,140	58.33	5,640	53.16	6,140	48.83	6,640	45.15	7,140	41.99
5,150	58.22	5,650	53.07	6,150	48.75	6,650	45.09	7,150	41.93
5,160	58.10	5,660	52.97	6,160	48.67	6,660	45.02	7,160	41.87
5,170	57.99	5,670	52.88	6,170	48.59	6,670	44.95	7,170	41.82
5,180	57.88	5,680	52.79	6,180	48.51	6,680	44.88	7,180	41.76
5,190	57.77	5,690	52.69	6,190	48.44	6,690	44.82	7,190	41.70
5,200	57.66	5,700	52.60	6,200	48.36	6,700	44.75	7,200	41.64
5,210	57.55	5,710	52.51	6,210	48.28	6,710	44.68	7,210	41.58
5,220	57.44	5,720	52.42	6,220	48.20	6,720	44.62	7,220	41.53
5,230	57.33	5,730	52.32	6,230	48.13	6,730	44.55	7,230	41.47
5,240	57.22	5,740	52.23	6.240	48.05	6,740	44.48	7,240	41.41
5,250	57.11	5,750	52.14	6,250	47.97	6,750	44.42	7,250	41.35
5,260	57.00	5,760	52.05	6,260	47.89	6,760	44.35	7,260	41.30
5,270	56.89	5,770	51.96	6,270	47.82	6,770	44.29	7,270	41.24
5,280	56.78	5.780	51.87	6,280	47.74	6,780	44.22	7,280	41.18
5,290	56.68	5,790	51.78	6,290	47.67	6,790	44.16	7,290	41.13
5,300	56.57	5,800	51.69	6.300	47.59	6,800	44.09	7,300	41.07
5,310	56.46	5,810	51.60	6,310	47.52	6,810	44.03	7,310	41.02
5,320	56.36	5,820	51.52	6.320	47.44	6.820	43.96	7,320	40.96
5,330	56.25	5,830	51.43	6,330	47.36	6,830	43.90	7,330	40.90
5,340	56.15	5,840	51.34	6,340	47.29	6.840	43.83	7,340	40.85
5,350	56.04	5,850	51.25	6,350	47.22	6,850	43.77	7,350	40.79
5,360	55.94	5,860	51.16	6.360	47.14	6.860	43.71	7.360	40.74
5,370	55.83	5,870	51.08	6,370	47.07	6,870	43.64	7,370	40.68
5,380	55.73	5,880	50.99	6,380	46.99	6,880	43.58	7,380	40.63
5,390	55.63	5,890	50.90	6,390	46.92	6.890	43.52	7,390	40.57
5,400	55.52	5,900	50.82	6,400	46.85	6,900	43.45	7,400	40.52
5,410	55.42	5,910	50.73	6,410	46.77	6.910	43.39	7,410	40.46
5,420	55.32	5,920	50.65	6,420	46.70	6,920	43.33	7,420	40.41
5,430	55.22	5,930	50.56	6,430	46.63	6.930	43.26	7,430	40.35
5,440	55.11	5,940	50.47	6,440	46.56	6.940	43.20	7,440	40.30
5,450	55.01	5,950	50.39	6,450	46.48	6,950	43.14	7,450	40.24
5,460	54.91	5,960	50.31	6,460	46.41	6,960	43.08	7,460	40.19
5,470	54.81	5,970	50.22	6,470	46.34	6,970	43.02	7,470	40.14
5,480	54.71	5,980	50.14	6,480	46.27	6.980	42.95	7,480	40.08
5,490	54.61	5,990	50.05	6.490	46.20	6,990	42.89	7,490	40.03
5.500	54.51	6,000	49.97	6.500	46.13	7,000	42.83	7,500	39.98

KILOCYCLES (kc) TO METERS (m), OR METERS TO KILOCYCLES
(Cont'd) [Columns Are Interchangeable]

kc or m	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*
7,510	39.92	8,010	37.43	8,510	35.23	9,010	33.28	9,510	31.53
7,520	39.87	8,020	37.38	8,520	35.19	9,020	33.24	9,520	31.49
7,530	39.82	8,030	37.34	8,530	35.15	9,030	33.20	9,530	31.46
7,540	39.76	8,040	37.29	8,540	35.11	9,040	33.17	9,540	31.43
7,550	39.71	8,050	37.24	8,550	35.07	9,050	33.13	9,550	31.39
7,560	39.66	8,060	37.20	8,560	35.03	9,060	33.09	9,560	31.36
7,570	39.61	8,070	37.15	8,570	34.98	9,070	33.06	9,570	31.33
7,580	39.55	8,080	37.11	8,580	34.94	9,080	33.02	9,580	31.30
7,590	39.50	8,090	37.06	8,590	34.90	9,090	32.98	9,590	31.26
7,600	39.45	8,100	37.01	8,600	34.86	9,100	32.95	9,600	31.23
7,610	39.40	8,110	36.97	8,610	34.82	9,110	32.91	9,610	31.20
7,620	39.35	8,120	36.92	8,620	34.78	9,120	32.88	9,620	31.17
7,630	39.29	8,130	36.88	8,630	34.74	9,130	32.84	9,630	31.13
7,640	39.24	8,140	36.83	8,640	34.70	9,140	32.80	9,640	31.10
7,650	39.19	8,150	36.79	8,650	34.66	9,150	32.77	9,650	31.07
7,660	39.14	8,160	36.74	8,660	34.62	9,160	32.73	9,660	31.04
7,670	39.09	8,170	36.70	8,670	34.58	9,170	32.70	9,670	31.01
7,680	39.04	8,180	36.65	8,680	34.54	9,180	32.66	9,680	30.97
7,690	38.99	8,190	36.61	8,690	34.50	9,190	32.62	9,690	30.94
7,700	38.04	8,200	36.56	8,700	34.46	9,200	32.59	9,700	30.91
7,710	38.89	8,210	36.52	8,710	34.42	9,210	32.55	9,710	30.88
7,720	38.84	8,220	36.47	8,720	34.38	9,220	32.52	9,720	30.85
7,730	38.79	8,230	36.43	8,730	34.34	9,230	32.48	9,730	30.81
7,740	38.74	8,240	36.39	8,740	34.30	9,240	32.45	9,740	30.78
7,750	38.69	8,250	36.34	8,750	34.27	9,250	32.41	9,750	30.75
7,760	38.64	8,260	36.30	8,760	34.23	9,260	32.38	9,760	30.72
7,770	38.59	8,270	36.25	8,770	34.19	9,270	32.34	9,770	30.69
7,780	38.54	8,280	36.21	8,780	34.15	9,280	32.31	9,780	30.66
7,790	38.49	8,290	36.17	8,790	34.11	9,290	32.27	9,790	30.63
7,800	38.44	8,300	36.12	8,800	34.07	9,300	32.24	9,800	30.59
7,810	38.39	8,310	36.08	8,810	34.03	9,310	32.20	9,810	30.56
7,820	38.34	8,320	36.04	8,820	33.99	9,320	32.17	9,820	30.53
7,830	38.29	8,330	35.99	8,830	33.95	9,330	32.14	9,830	30.50
7,840	38.24	8,340	35.95	8,840	33.92	9,340	32.10	9,840	30.47
7,850	38.19	8,350	35.91	8,850	33.88	9,350	32.07	9,850	30.44
7,860	38.14	8,360	35.86	8,860	33.84	9,360	32.03	9,860	30.41
7,870	38.10	8,370	35.82	8,870	33.80	9,370	32.00	9,870	30.38
7,880	38.05	8,380	35.78	8,880	33.76	9,380	31.96	9,880	30.35
7,890	38.00	8,390	35.74	8,890	33.73	9,390	31.93	9,890	30.32
7,900	37.95	8,400	35.69	8,900	33.69	9,400	31.90	9,900	30.28
7,910	37.90	8,410	35.65	8,910	33.65	9,410	31.86	9,910	30.25
7,920	37.86	8,420	35.61	8,920	33.61	9,420	31.83	9,920	30.22
7,930	37.81	8,430	35.57	8,930	33.57	9,430	31.79	9,930	30.19
7,940	37.76	8,440	35.52	8,940	33.54	9,440	31.76	9,940	30.16
7,950	37.71	8,450	35.48	8,950	33.50	9,450	31.73	9,950	30.13
7,960	37.67	8,460	35.44	8,960	33.46	9,460	31.69	9,960	30.10
7,970	37.62	8,470	35.40	8,970	33.42	9,470	31.66	9,970	30.07
7,980	37.57	8,480	35.36	8,980	33.39	9,480	31.63	9,980	30.04
7,990	37.52	8,490	35.31	8,990	33.35	9,490	31.59	9,990	30.01
8,000	37.48	8,500	35.27	9,000	33.31	9,500	31.56	10,000	29.98

INDEX

(The figures refer to page numbers)

tube, 391, 438, 440.

—L—

—M—