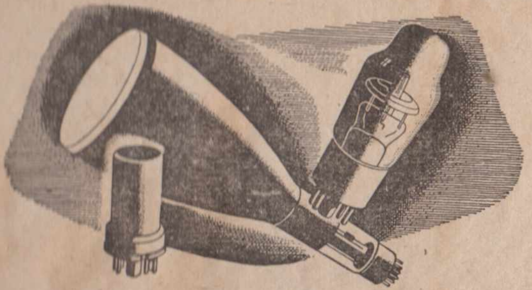
RADIO VALVE APPLICATION MANUAL

Compiled by

BERNARD B. BABANI

BERNARDS (PUBLISHERS) LTD.



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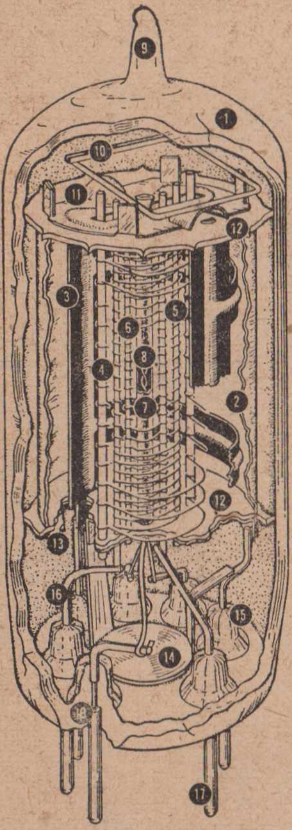


2½ times actual size

1 – Glass Envelope
2 – Internal Shield
3 – Plate
4 – Grid No. 3 (Suppressor)
5 – Grid No. 2 (Screen)
6 – Grid No. 1 (Control Grid)
7 – Cathode
8 – Heater
9 – Exhaust Tip
10 – Getter
11 – Spacer Shield Header
12 – Insulating Spacer
13 – Spacer Shield
14 – Inter-Pin Shield
15 – Glass Button-Stem Seal
16 – Lead Wire
17 – Base Pin
18 – Glass-to-Metal Seal

Structure of a Miniature Tube

RECEIVING TUBES

Electrons, Electrodes, and Electron Tubes

The electron tube is a marvelous device. It makes possible the performing of operations, amazing in conception, with a precision and a certainty that are astounding. It is an exceedingly sensitive and accurate instrument—the product of coordinated efforts of engineers and craftsmen. Its construction requires materials from every corner of the earth. Its use is world-wide. Its future possibilities, even in the light of present-day accomplishments, are but dimly foreseen; for each development opens new fields of design and application.

The importance of the electron tube lies in its ability to control almost instantly the flight of the millions of electrons supplied by the cathode. It accomplishes this with a minimum of control energy. Because it is almost instantaneous in its action, the electron tube can operate efficiently and accurately at electrical frequencies much higher than those attainable with rotating machines.

ELECTRONS

All matter exists in the solid, liquid, or gaseous state. These three forms consist entirely of minute divisions known as molecules. Molecules are assumed to be composed of atoms. According to a present accepted theory, atoms have a nucleus which is a positive charge of electricity. Around this nucleus revolve tiny charges of negative electricity known as **electrons.** Scientists have estimated that these invisible bits of electricity weigh only 1/30-billion, billion, billion, billionths of an ounce, and that they may travel at speeds of thousands of miles per second.

Electron movement may be accelerated by the addition of energy. Heat is one form of energy which can be conveniently used to speed up the electron. For example, if the temperature of a metal is gradually raised, the electrons in the metal gain velocity. When the metal becomes hot enough to glow, some electrons may acquire sufficient speed to break away from the surface of the metal. This action, which is accelerated when the metal is heated in a vacuum, is utilized in most electron tubes to produce the necessary electron supply.

An electron tube consists of a cathode, which supplies electrons, and one or more additional electrodes, which control and collect these electrons, mounted in an evacuated envelope. The envelope may be a glass bulb or a metal shell.

CATHODES

A cathode is an essential part of an electron tube because it supplies the electrons necessary for tube operation. When energy in some form is applied to the cathode, electrons are released. Heat is the form of energy generally used. The method of heating the cathode may be used to distinguish between the different forms of cathodes. For example, a directly heated cathode, or filament-cathode, is a wire heated by the passage of an electric current. An indirectly heated cathode, or heater-cathode, consists of a filament, or heater, enclosed in a metal sleeve. The sleeve carries the electron-emitting material on its outside surface and is heated by radiation and conduction from the heater.

A filament, or directly heated cathode, may be further classified by identifying the filament or electron-emitting material. The materials in regular use are tungsten, thoriated tungsten, and metals which have been coated with alkaline-earth oxides. Tungsten filaments are made from the pure metal. Since they must operate at high temperatures (a dazzling white) to emit sufficient electrons, a relatively large amount of filament power is required. Thoriated-tungsten filaments are made from tungsten impregnated with thoria. Due to the presence of thorium, these filaments liberate electrons at a more moderate temperature of about 1700°C (a bright yellow) and are, therefore, much more economical of filament power than are pure tungsten filaments. Alkaline earths are usually applied as a coating on a nickel alloy wire or ribbon. This coating, which is dried in a relatively thick layer on the filament, requires only a very low temperature of about 700-750°C (a dull red) to produce a copious supply of electrons. Coated filaments operate very efficiently and require relatively little filament power. However, each of these cathode materials has special advantages which determine the choice for a particular application.

Directly heated filament-cathodes require comparatively little heating power. They are used in almost all of the tube types designed for battery operation because it is, of course, desirable to impose as small a drain as possible on the batteries. Examples of battery-operated filament types are the 1A7-GT, 1R5, 1U4, 3V4, and 31. AC-operated types having directly heated filament-cathodes include the 2A3 and 5Y3-GT.

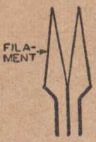


Fig. 1

An indirectly heated cathode, or heater-cathode, consists of a thin metal sleeve coated with electron-emitting material. Within the sleeve is a heater which is insulated from the sleeve. The heater is made of tungsten or tungsten-alloy wire and is used only for the purpose of heating the cathode sleeve and sleeve coating to an electron-emitting temperature. Useful emission does not take place from the heater wire.

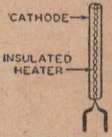


Fig. 2

The heater-cathode construction is well adapted for use in electron tubes intended for operation from ac power lines and from storage batteries. The use of separate parts for emitter and heater functions, the electrical insulation of the heater from the emitter, and the shielding effect of the sleeve may all be utilized in the design of the tube to minimize the introduction of hum from the ac heater supply and to minimize electrical interference which might enter the tube circuit through the heater-supply line. From the viewpoint of circuit design, the heater-cathode construction offers advantages in connection flexibility due to the electrical separation of the heater from the cathode. Another advantage of the heater-cathode construction is that it makes practical the design of a rectifier tube with close spacing between its cathode and plate, and of an amplifier tube with close spacing between its cathode and grid. In a close-spaced rectifier tube the voltage drop in the tube is low and the regulation is, therefore, improved. In an amplifier tube, the close spacing increases the gain obtainable from the tube. Because of the advantages of the heater-cathode construction, almost all present-day receiving tubes designed for ac operation have heater-cathodes.

GENERIC TUBE TYPES

Electrons are of no value in an electron tube unless they can be put to work. A tube is, therefore, designed with the parts necessary to utilize electrons as well as to produce them. These parts consist of a cathode and one or more supplementary electrodes. The electrodes are enclosed in an evacuated envelope with the necessary connections brought out through air-tight seals. The air is removed from the envelope to allow free movement of the electrons and to prevent injury to the emitting surface of the cathode. When the cathode is heated, electrons leave the cathode surface and form an invisible cloud in the space around it. Any positive electric potential within the evacuated envelope will offer a strong attraction to the electrons (unlike electric charges attract; like charges repel).

DIODES

The simplest form of electron tube contains two electrodes, a cathode and an anode (plate) and is often called a diode, the family name for a two-electrode tube. In a diode, the positive potential is supplied by a suitable electrical source connected between the plate terminal and a cathode terminal. Under the influence of the positive plate potential, electrons flow from the cathode to the plate and return through the external plate-battery circuit to the cathode, thus completing the circuit. This flow of electrons is known as the plate current, and may be measured by a sensitive current meter.

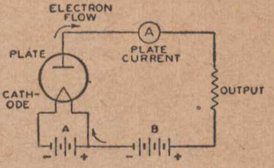


Fig. 3

If a negative potential is applied to the plate, the free electrons in the space surrounding the cathode will be forced back to the cathode and no plate current will flow. Thus, electrons can flow from the cathode to the plate but not from the plate to the cathode. If an alternating voltage is applied to the plate, the plate is alternately made positive and negative. Plate current flows only during the time when the plate is positive. Hence the current through the tube flows in one direction and is said to be rectified. See Fig. 4. Diode rectifiers are used in ac receivers to convert ac to dc voltage for the electrodes of the other tubes in the receiver. Rectifier tubes may have one plate and one cathode. The 1-v and 35W4 are of this form and are called **half-wave rectifiers**, since current can flow only during one-half of the alternating-current cycle. When two plates and one or more cathodes are used in the same tube, current may be obtained on both halves of the ac cycle. The 6X4, 5Y3-GT, and 5U4-G are examples of this type and are called **full-wave rectifiers.**

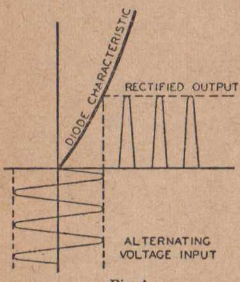


Fig. 4

Not all of the electrons emitted by the cathode reach the plate. Some return to the cathode while others remain in the space between the cathode and plate for a brief period to produce an effect known as **space-charge.** This charge has a repelling action on other electrons which leave the cathode surface and impedes their passage to the plate. The extent of this action and the amount of space-charge depend on the cathode temperature and the plate potential. The higher the plate potential, the less is the tendency for electrons to remain in the space-charge region and repel others. This effect may be noted by applying increasingly higher plate voltages to a tube operating at a fixed heater or filament voltage. Under these conditions, the maximum number of available electrons is fixed, but increasingly higher plate voltages will succeed in attracting a greater proportion of the free electrons.

Beyond a certain plate voltage, however, additional plate voltage has little effect in increasing the plate current. The reason is that all of the electrons emitted by the cathode are already being drawn to the plate. This maximum current is called **saturation current** (see Fig. 5) and because it is an indication of the total number of electrons emitted, it is also known as the **emission current**, or, simply,

emission. Tubes are sometimes tested by the measurement of their emission current but it is generally not advisable to measure the full value of emission because this value would be sufficiently large to cause change in the tube's characteristics or even to damage the tube. Consequently, while the test value of emission current is somewhat larger than the maximum current which will be required from the cathode in the use of the tube, it is ordinarily less than the full emission current. The emission test, therefore, is used to indicate whether the cathode can supply a sufficient number of electrons for satisfactory operation of the tube.

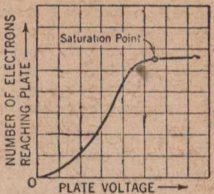


Fig. 5

If space charge were not present to repel electrons coming from the cathode, it follows that the same plate current could be produced at a lower plate voltage. One way to make the effect of space charge small is to make the distance between plate and cathode small. This method is used in rectifier types, such as the 5V4-G and the 25Z6-GT, having heater-cathodes. In these types the radial distance between cathode and plate is only about two hundredths of an inch. Another method of reducing space-charge effect is utilized in the **mercury-vapor rectifier tubes**, such as the 83. This tube contains a small amount of mercury, which is partially vaporized when the tube is operated. The mercury vapor consists of mercury atoms permeating the space inside the bulb. These atoms are bombarded by the electrons on their way to the plate. If the electrons are moving at a sufficiently high speed, the collisions will tear off electrons from the mercury atoms. When this happens, the mercury atom is said to be "**ionized,**" that is, it has lost one or more electrons and, therefore, is charged positive. Ionization, in the case of mercury vapor, is made evident by a bluish-green glow between the cathode and plate. When ionization due to bombardment of mercury atoms by electrons leaving the cathode occurs, the space-charge is neutralized by the positive mercury ions so that increased numbers of electrons are made available. A mercury-vapor rectifier has a small voltage drop between cathode and plate (about 15 volts). This drop is practically independent of current requirements up to the limit of emission of electrons from the cathode, but is dependent to some degree on bulb temperature.

An **ionic-heated-cathode rectifier tube** is another type which depends for its operation on gas ionization. The 0Z4 and 0Z4-G are tubes in this classification. They are of the full-wave design and contain two anodes and a coated cathode sealed in a bulb under a reduced pressure of inert gas. The cathode in each of these types becomes hot during tube operation but the heating effect is caused by bombardment of the cathode by the ions from within the tube rather than by heater or filament current from an external source. The internal structure of the tube is designed so that when sufficient voltage is applied to the tube, ionization of the gas occurs between the anode which is instantaneously positive and the cathode. Under normal operating voltages, ionization does not take place between the anode that is negative and the cathode. This, of course, satisfies the requirements for rectification. The initial small flow of current through the tube is sufficient to raise the cathode temperature quickly to incandescence whereupon the cathode emits electrons. The voltage drop in such tubes is slightly higher than that of the usual hot-cathode gas rectifiers because energy is taken from the ionization discharge to keep the cathode at operating temperature. Proper operation of these rectifiers requires a minimum flow of load current at all times in order to maintain the cathode at the temperature required to supply sufficient emission.

TRIODES

When a third electrode, called the **grid**, is placed between the cathode and plate, the tube is known as a triode, the family name for a three-electrode tube.

The grid usually is a winding of wire extending the length of the cathode. The spaces between turns are comparatively large so that the passage of electrons from cathode to plate is practically unobstructed by the turns of the grid. The purpose of the grid is to control the flow of plate current. When a tube is used as an amplifier, a negative dc voltage is usually applied to the grid. Under this condition the grid does not draw appreciable current.

The number of electrons attracted to the plate depends on the combined effect of the grid and plate polarities. When the plate is positive, as is normal, and the dc grid voltage is made more and more negative, the plate is less able to attract electrons to it and plate current decreases. When the grid is made less and less negative (more and more positive), the plate more readily attracts electrons to it and plate current increases. Hence, when the voltage on the grid is varied in accordance with a signal, the plate current varies with the signal. Because a small voltage applied to the grid can control a comparatively large amount of plate current, the signal is amplified by the tube. Typical three-electrode tube types are the 6C4, 6J5, and 2A3.

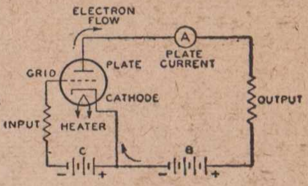


Fig. 6

The grid, plate, and cathode of a triode form an electrostatic system, each electrode acting as one plate of a small capacitor. The capacitances are those existing between grid and plate, plate and cathode, and grid and cathode. These capacitances are known as **interelectrode capacitances**. Generally, the capacitance between grid and plate is of the most importance. In high-gain radio-frequency amplifier circuits, this capacitance may act to produce undesired coupling between the **input circuit**, the circuit between grid and cathode, and the **output circuit**, the circuit between plate and cathode. This coupling is undesirable in an amplifier because it may cause instability and unsatisfactory performance.

TETRODES

The capacitance between grid and plate can be made small by mounting an additional electrode, called the screen (grid No. 2), in the tube. With the addition of the screen, the tube has four electrodes and is, accordingly, called a tetrode. The screen is mounted between the grid and the plate and acts as an electrostatic shield between them, thus reducing the grid-to-plate capacitance. The effectiveness of this shielding action is increased by connecting a bypass capacitor between screen and cathode. By means of the screen and this bypass capacitor, the grid-plate capacitance of a tetrode is made very small. In practice, the grid-plate capacitance is reduced from several micromicrofarads ($\mu\mu$f) for a triode to 0.01 $\mu\mu$f or less for a screen-grid tube.

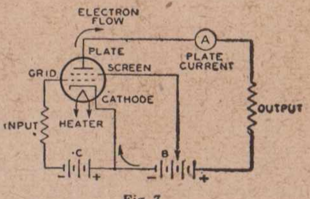


Fig. 7

The screen has another desirable effect in that it makes plate current practically independent of plate voltage over a certain range. The screen is operated at a positive voltage and, therefore, attracts electrons from the cathode. But because of the comparatively large space between wires of the screen, most of the electrons drawn to the screen pass through it to the plate. Hence the screen supplies an electrostatic force pulling electrons from the cathode to the plate. At the same time the screen shields the electrons between cathode and screen from the plate so that the plate exerts very little electrostatic force on electrons near the cathode. So long as the plate voltage is higher than the screen voltage, plate current in a screen-grid tube depends to a great degree on the screen voltage and very little on the plate voltage. The fact that plate current in a screen-grid tube is largely independent of plate voltage makes it possible to obtain much higher amplification with a tetrode than with a triode. The low grid-plate capacitance makes it possible to obtain this high amplification without plate-to-grid feedback and resultant instability. Representative screen-grid types are the 32 and 24-A.

PENTODES

In all electron tubes, electrons striking the plate may, if moving at sufficient speed, dislodge other electrons. In two- and three-electrode types, these dislodged electrons usually do not cause trouble because no positive electrode other than the plate itself is present to attract them. These electrons, therefore, are drawn back to the plate. Emission caused by bombardment of an electrode by electrons from the cathode is called **secondary emission** because the effect is secondary to the original cathode emission. In the case of screen-grid tubes, the proximity of the positive screen to the plate offers a strong attraction to these secondary electrons and particularly so if the plate voltage swings lower than the screen voltage. This effect lowers the plate current and limits the permissible plate-voltage swing for tetrodes.

The plate-current limitation is removed when a fifth electrode is placed within the tube between the screen and plate. This fifth electrode is known as the **suppressor** (grid No. 3) and is usually connected to the cathode. Because of its negative potential with respect to the plate, the suppressor retards the flight of secondary electrons and diverts them back to the plate where they cannot cause trouble. The family name for a five-electrode tube is "pentode". In power-output pentodes, the suppressor makes possible higher power output with lower grid-driving voltage; in radio-frequency amplifier pentodes the suppressor makes possible high voltage amplification at moderate values of plate voltage. These desirable features are due to the fact that the plate-voltage swing can be made very large. In fact, the plate voltage may be as low as, or lower than, the screen voltage without serious loss in signal-gain capability. Representative pentodes used for power amplification are the 3V4 and 6K6-GT; representative pentodes used for voltage amplification are the 1U4, 6SJ7, 12SK7, and 6BA6.

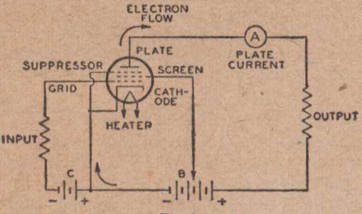


Fig. 8

BEAM POWER TUBES

A **beam power tube** is a tetrode or pentode in which directed electron beams are used to increase substantially the power-handling capability of the tube. Such a tube contains a cathode, a control-grid, a screen, a plate, and, optionally, a suppressor grid. When a beam power tube is designed without an actual suppressor, the electrodes are so spaced that secondary emission from the plate is suppressed by space-charge effects between screen and plate. The space charge is produced by the slowing up of electrons traveling from a high-potential screen to a lower potential plate. In this low-velocity region, the space charge produced is sufficient to repel secondary electrons emitted from the plate and to cause them to return to the plate. Beam power tubes of this design employ beam-confining electrodes at cathode potential to assist in producing the desired beam effects and to prevent stray electrons from the plate from returning to the screen outside of the beam. A feature of a beam power tube is its low screen current. The screen and the grid are spiral wires wound so that each turn of the screen is shaded from the cathode by a grid turn. This alignment of the screen and grid causes the electrons to travel in sheets between the turns of the screen so that very few of them strike the screen. Because of the effective suppressor action provided by space charge and because of the low current drawn by the screen, the beam power tube has the advantages of high power output, high power sensitivity, and high efficiency.

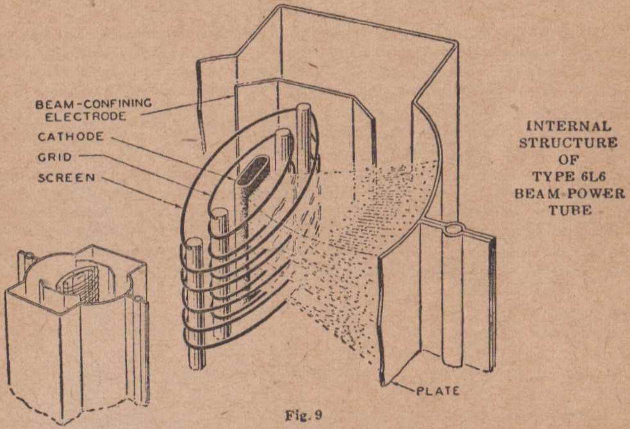


Fig. 9

Fig. 9 shows the structure of a beam power tube employing space-charge suppression and illustrates how the electrons are confined to beams. The beam condition illustrated is that for a plate potential less than the screen potential. The high-density space-charge region is indicated by the heavily dashed lines in the beam. Note that the edges of the beam-confining electrodes coincide with the dashed portion of the beam. In this way the space-charge potential region is extended beyond the beam boundaries and stray secondary electrons are prevented from returning to the screen outside of the beam. The space-charge effect may also be obtained by use of an actual suppressor grid. Examples of beam power tubes are 6L6, 6V6-GT, and 50B5.

MULTI-ELECTRODE and MULTI-UNIT TUBES

Early in the history of tube development and application, tubes were designed for general service; that is, a single tube type—a triode—was used as a radio-frequency amplifier, an intermediate-frequency amplifier, an audio-frequency amplifier, an oscillator, or a detector. Obviously, with this diversity of application, one tube did not meet all requirements to the best advantage.

Later and present trends of tube design are the development of "specialty" types. These types are intended either to give optimum performance in a particular application or to combine in one bulb functions which formerly required two or more tubes. The first class of tubes includes such examples of specialty types as the 6F6, 12SK7, 6L7, and 6K8. Types of this class generally require more than three electrodes to obtain the desired special characteristics and may be broadly classed as multi-electrode types. The 6L7 is an especially interesting type in this class. This tube has an unusually large number of electrodes, namely seven, exclusive of the heater. Plate current in the tube is varied at two different frequencies at the same time. The tube is designed primarily for use as a mixer in superheterodyne receivers. In this use, the tube mixes the signal frequency with the oscillator frequency to give an intermediate-frequency output.

Tubes of the multi-electrode class often present interesting possibilities of application besides the one for which they are primarily designed. The 6L7, for instance, can also be used as a variable-gain audio amplifier in volume-expander and compressor application. The 6F6, besides its use as a power-output pentode, can also be connected as a triode and used as a driver for a pair of 6L6's.

The second class includes multi-unit tubes such as the twin-diode triodes 6BF6 and 6SQ7, as well as the twin-diode pentodes 1F7-G and 12C8 and the twin class A and class B types 12AU7 and 6N7, respectively. In this class also is included the multi-unit type 117N7-GT. This tube combines in one bulb a diode for use as a power rectifier and a power-output pentode. Related to multi-unit tubes are the electron-ray types 6U5/6G5 and 6AB5/6N5. These combine a triode amplifier with a fluorescent target. Full-wave rectifiers are also multi-unit types.

A third class of tubes combines features of each of the other two classes. Typical of this third class are the pentagrid-converter types 1R5, 6BE6, and 6SA7 These tubes are similar to the multi-electrode types in that they have seven electrodes, all of which affect the electron stream; and they are similar to the multi-unit tubes in that they perform simultaneously the double function of oscillator and mixer in superheterodyne receivers.

Electron Tube Characteristics

The term "characteristics" is used to identify the distinguishing electrical features and values of an electron tube. These values may be shown in curve form or they may be tabulated. When given in curve form, they are called characteristic curves and may be used for the determination of tube performance and the calculation of additional tube factors.

Tube characteristics are obtained from electrical measurements of a tube in various circuits under certain definite conditions of voltages. Characteristics may be further described by denoting the conditions of measurements. For example, Static Characteristics are the values obtained with different dc potentials applied to the tube electrodes, while Dynamic Characteristics are the values obtained with an ac voltage on the control grid under various conditions of dc potentials on the electrodes. The dynamic characteristics, therefore, are indicative of the performance capabilities of a tube under actual working conditions.

Static characteristics may be shown by plate characteristics curves and transfer (mutual) characteristics curves. These curves present the same information, but in two different forms to increase its usefulness. The plate characteristic curve is obtained by varying plate voltage and measuring plate current for different control-grid bias voltages, while the transfer-characteristic curve is obtained by varying control-grid bias voltage and measuring plate current for different plate voltages. A plate-characteristic family of curves is illustrated by Fig. 10. Fig. 11 gives the transfer characteristic family of curves for the same tube.

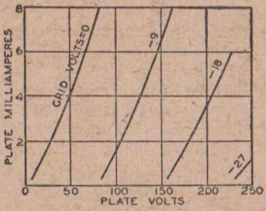


Fig. 10

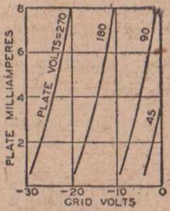


Fig. 11

Dynamic characteristics include amplification factor, plate resistance, control-grid—plate transconductance and certain detector characteristics, and may be shown in curve form for variations in tube operating conditions.

The **amplification factor,** or μ, is the ratio of the change in plate voltage to a change in control-electrode voltage in the opposite direction, under the condition that the plate current remains unchanged, and that all other electrode voltages are maintained constant. For example, if, when the plate voltage is made 1 volt more positive, the grid voltage must be made 0.1 volt more negative to hold plate current unchanged, the amplification factor is 1 divided by 0.1, or 10. In other words, a small voltage variation in the grid circuit of a tube has the same effect on the plate current as a large plate voltage change—the latter equal to the product of the grid voltage change and amplification factor. The μ of a tube is useful for calculating stage gain. This use is discussed in the ELECTRON TUBE APPLICATIONS SECTION.

Plate resistance (r_p) of a radio tube is the resistance of the path between cathode and plate to the flow of alternating current. It is the quotient of a small change in plate voltage divided by the corresponding change in plate current and is expressed in ohms, the unit of resistance. Thus, if a change of 0.1 milliampere (0.0001 ampere) is produced by a plate voltage variation of 1 volt, the plate resistance is 1 divided by 0.0001, or 10000 ohms.

Control-grid—plate transconductance, or simply **transconductance** (g_m), is a factor which combines in one term the amplification factor and the plate resistance, and is the quotient of the first divided by the second. This term is also known as mutual conductance. Transconductance may be more strictly defined as the quotient of a small change in plate current (amperes) divided by the small change in the control-grid voltage producing it, under the condition that all other voltages remain unchanged. Thus, if a grid-voltage change of 0.5 volt causes a plate-current change of 1 milliampere (0.001 ampere), with all other voltages constant, the transconductance is 0.001 divided by 0.5, or 0.002 mho. A "mho" is the unit of conductance and was named by spelling ohm backwards. For convenience, a millionth of a mho, or a micromho (μmho), is used to express transconductance. Thus, in the example, 0.002 mho is 2000 micromhos.

Conversion transconductance (g_c) is a characteristic associated with the mixer (first detector) function of tubes and may be defined as the quotient of the intermediate-frequency (if) current in the primary of the if transformer divided by the applied radio-frequency (rf) voltage producing it; or more precisely, it is the limiting value of this quotient as the rf voltage and if current approach zero. When the performance of a frequency converter is determined, conversion transconductance is used in the same way as control-grid—plate transconductance is used in single-frequency amplifier computations.

The **plate efficiency** of a power amplifier tube is the ratio of the ac power output to the product of the average dc plate voltage and dc plate current at full signal, or

$$\text{Plate efficiency } (\%) = \frac{\text{power output watts}}{\text{average dc plate volts} \times \text{average dc plate amperes}} \times 100$$

The **power sensitivity** of a tube is the ratio of the power output to the square of the input signal voltage (RMS) and is expressed in mhos as follows:

$$\text{Power sensitivity (mhos)} = \frac{\text{power output watts}}{(\text{input signal volts, RMS})^2}$$

Electron Tube Applications

The diversified applications of an electron receiving tube have, within the scope of this section, been treated under eight headings. These are: Amplification, Rectification, Detection, Automatic Volume Control, Tuning Indication with Electron-Ray Tubes, Oscillation, Frequency Conversion, and Automatic Frequency Control. Although these operations may take place at either radio or audio frequencies and may involve the use of different circuits and different supplemental parts, the general considerations of each kind of operation are basic.

AMPLIFICATION

The amplifying action of an electron tube was mentioned under **Triodes** in the section on ELECTRONS, ELECTRODES, and ELECTRON TUBES.

This action can be utilized in electronic circuits in a number of ways, depending upon the results desired. Four classes of amplifier service recognized by engineers are covered by definitions standardized by the Institute of Radio Engineers. This classification depends primarily on the fraction of input cycle during which plate current is expected to flow under rated full-load conditions. The classes are class A, class AB, class B, and class C. The term, cutoff bias, used in these definitions is the value of grid bias at which plate current is some very small value.

Class A Amplifier. A class A amplifier is an amplifier in which the grid bias and alternating grid voltages are such that plate current in a specific tube flows at all times.

Class AB Amplifier. A class AB amplifier is an amplifier in which the grid bias and alternating grid voltages are such that plate current in a specific tube flows for appreciably more than half but less than the entire electrical cycle.

Class B Amplifier. A class B amplifier is an amplifier in which the grid bias is approximately equal to the cutoff value so that the plate current is approximately zero when no exciting grid voltage is applied, and so that plate current in a specific tube flows for approximately one-half of each cycle when an alternating grid voltage is applied.

Class C Amplifier. A class C amplifier is an amplifier in which the grid bias is appreciably greater than the cutoff value so that the plate current in each tube is zero when no alternating grid voltage is applied, and so that plate current flows in a specific tube for appreciably less than one-half of each cycle when an alternating grid voltage is applied.

NOTE:—To denote that grid current does not flow during any part of the input cycle, the suffix 1 may be added to the letter or letters of the class identification. The suffix 2 may be used to denote that grid current flows during some part of the cycle.

For radio-frequency amplifiers which operate into a selective tuned circuit, as in radio transmitter applications, or under requirements where distortion is not an important factor, any of the above classes of amplifiers may be used, either with a single tube or a push-pull stage. For audio-frequency amplifiers in which distortion is an important factor, only class A amplifiers permit single-tube operation. In this case, operating conditions are usually chosen so that distortion is kept below the conventional 5% for triodes and the conventional 7 to 10% for tetrodes or pentodes. Distortion can be reduced below these figures by means of special circuit arrangements such as that discussed under **inverse feedback.** With class A amplifiers, reduced distortion with improved power performance can be obtained by using a push-pull stage for audio service. With class AB and class B amplifiers, a balanced amplifier stage using two tubes is required for audio service.

As a **class A voltage amplifier,** an electron tube is used to reproduce grid voltage variations across an impedance or a resistance in the plate circuit. These variations are essentially of the same form as the input signal voltage impressed on the grid, but of increased amplitude. This is accomplished by operating the tube at a suitable grid bias so that the applied grid-input voltage produces plate-current variations proportional to the signal swings. Since the voltage variation obtained in the plate circuit is much larger than that required to swing the grid, amplification of the signal is obtained. Fig. 12 gives a graphical illustration of this method of amplification and shows, by means of the grid-voltage vs. plate-current characteristics curve, the effect of an input signal (S) applied to the grid of a tube. O is the resulting amplified plate-current variation.

The plate current flowing through the load resistance (R) of Fig. 13 causes a voltage drop which varies directly with the plate current. The ratio of this voltage variation produced in the load resistance to the input signal voltage is the voltage amplification, or **gain,** provided by the tube. The voltage amplification due to the tube is expressed by the following convenient formulas:

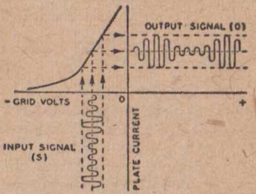


Fig. 12

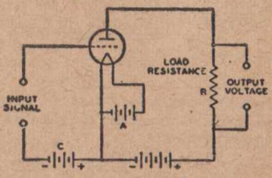


Fig. 13

$$\text{Voltage amplification} = \frac{\text{amplification factor} \times \text{load resistance}}{\text{load resistance} + \text{plate resistance}}, \text{ or}$$

$$\frac{\text{transconductance in micromhos} \times \text{plate resistance} \times \text{load resistance}}{1000000 \times (\text{plate resistance} + \text{load resistance})}$$

From the first formula, it can be seen that the gain actually obtainable from the tube is less than the tube's amplification factor but that the gain approaches the amplification factor when the load resistance is large compared to the tube's plate resistance. Fig. 14 shows graphically how the gain approaches the mu of the tube as load resistance is increased. From the curve it can be seen that to obtain high gain in a voltage amplifier, a high value of load resistance should be used.

In a resistance-coupled amplifier, the load resistance of the tube is approximately equal to the resistance of the plate resistor in parallel with the grid resistor of the following stage. Hence, to obtain a large value of load resistance, it is necessary to use a plate resistor and a grid resistor of large resistance. However, the plate resistor should not be too large because the flow of plate current through the plate resistor produces a voltage drop which reduces the plate voltage applied to the tube. If the plate resistor is too large, this drop will be too large, the plate voltage on the tube will be too small, and the voltage output of the tube will be too small. Also, the grid resistor of the following stage should not be too large, the actual maximum value being dependent on the particular tube type. This precaution is necessary because all tubes contain minute amounts of residual gas which cause a minute flow of current through the grid resistor. If the grid resistor is too large, the positive bias developed by the flow of this current through the resistor decreases the normal negative bias and produces an increase in the plate current. This increased current may over-heat the tube and cause liberation of more gas which, in turn, will cause further decrease in bias. The action is cumulative and results in a runaway condition which can destroy the tube. A higher value of grid resistance is permissible when cathode bias is used than when fixed bias is used. When cathode bias is used, a loss in bias due to grid-emission effects is nearly completely offset by an increase in bias due to the voltage drop across the cathode resistor.

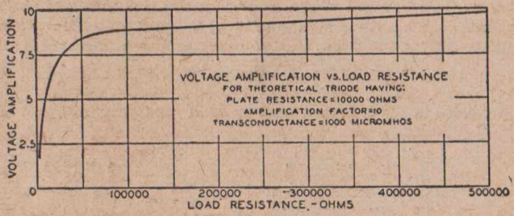


Fig. 14

The **input impedance** of an electron tube, that is, the impedance between grid and cathode is made up of (1) a reactive component due to the capacitance between grid and cathode, (2) a resistive component resulting from the time of transit of electrons between cathode and grid, and (3) a resistive component developed by the part of the cathode lead inductance which is common to both the input and output circuits. Components (2) and (3) are dependent on the frequency of the incoming signal. The input impedance is very high at audio frequencies when a tube is operated with its grid biased negative. Hence, in a class A_1 or class AB_1 transformer-coupled audio amplifier, the loading imposed by the grid on the input transformer is negligible. The secondary impedance of a class A_1 or class AB_1 input transformer can, therefore, be made very high since the choice is not limited by the input impedance of the tube; however, transformer design considerations may limit the choice. At the higher radio frequencies, the input impedance may become very low even when the grid is negative, due to the finite time of passage of electrons between cathode and grid and to the appreciable lead reactance. This impedance drops very rapidly as the frequency is raised and increases input-circuit loading. In fact, the input impedance may become low enough at very high radio frequencies to affect appreciably the gain and selectivity of a preceding stage. Tubes such as the "acorn" types and the high-frequency miniatures have been developed to have low input capacitances, low electron transit time, and low lead inductance so that their input impedance is high even at the ultra-high radio frequencies. **Input admittance** is the reciprocal of input impedance.

A remote-cutoff amplifier tube is a modified construction of a pentode or a tetrode type and is designed to reduce modulation-distortion and cross-modulation in radio-frequency stages. **Cross-modulation** is the effect produced in a radio receiver by an interfering station "riding through" on the carrier of the station to which the receiver is tuned. **Modulation-distortion** is a distortion of the modulated carrier and appears as audio-frequency distortion in the output. This effect is produced by a radio-frequency amplifier stage operating on an excessively curved characteristic when the grid bias has been increased to reduce volume. The offending stage for cross-modulation is usually the first radio-frequency amplifier, while for modulation-distortion, the cause is usually the last intermediate-frequency stage. The characteristics of remote-cutoff types are such as to enable them to handle both large and small input signals with minimum distortion over a wide range.

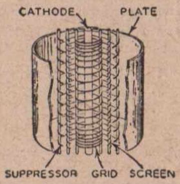


Fig. 15

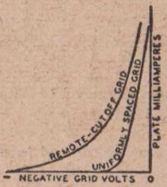


Fig. 16

Fig. 15 illustrates the construction of the control grid in such a tube. The remote-cutoff action is due to the structure of the grid which provides a variation in amplification factor with change in grid bias. The grid is wound with open spacing at the middle and with close spacing at the ends. When weak signals and low grid bias are applied to the tube, the effect of the non-uniform turn spacing of the grid on cathode emission and tube characteristics is essentially the same as for uniform spacing. As the grid bias is made more negative to handle larger input signals, the electron flow from the sections of the cathode enclosed by the ends of the grid is cut off. The plate current and other tube characteristics are then dependent on the electron flow through the open section of the grid. This action changes the gain of the tube so that large signals may be handled with minimum distortion due to cross-modulation and modulation-distortion. Fig. 16 shows a typical plate-current vs. grid-voltage curve for a remote-cutoff type compared with the curve for a type having a uniformly spaced grid. It will be noted that while the curves are similar at small grid-bias voltages, the plate current of the remote-cutoff tube drops quite slowly with large values of bias voltage. This slow change makes it possible for the tube to handle large signals satisfactorily. Since remote-cutoff types can accommodate large and small signals, they are particularly suitable for use in sets having automatic volume control. Remote-cutoff tubes also are known as variable-mu types. The 6SK7 is a representative remote-cutoff type.

As a **class A power amplifier,** an electron tube is used in the output stage of a radio receiver to supply a relatively large amount of power to the loudspeaker. For this application, large power output is of more importance than high voltage amplification; therefore, gain possibilities are sacrificed in the design of power tubes to obtain power-handling capability. Triodes, pentodes, and beam power tubes designed for power amplifier service have certain inherent features for each structure. Power tubes of the triode type for class A service are characterized by low power sensitivity, low plate-power efficiency, and low distortion. Power tubes of the pentode type are characterized by high power sensitivity, high plate-power efficiency and, usually, somewhat higher distortion than class A triodes. Beam power tubes such as the 6L6 have still higher power sensitivity and efficiency and have higher power-output capability than triode or conventional pentode types.

A class A power amplifier is used also as a driver to supply power to a class AB_2 or a class B stage. It is usually advisable to use a triode, rather than a pentode, in a driver stage because of the lower plate impedance of the triode.

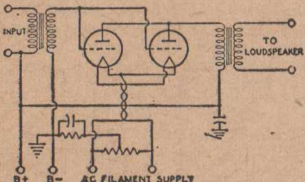


Fig. 17

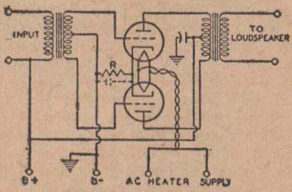


Fig. 18

Power tubes connected in either **parallel** or **push-pull** may be employed as class A amplifiers to obtain increased output. The parallel connection (Fig. 17) provides twice the output of a single tube with the same value of grid-signal voltage. With this connection, the effective transconductance of the stage is doubled, and the effective plate resistance and the load resistance required are halved as compared with single-tube values. The push-pull connection (Fig. 18), although it requires twice the grid-signal voltage, has, in addition to providing increased power, other important advantages over single-tube operation. Distortion caused by even-order harmonics and hum caused by plate-voltage-supply fluctuations are either eliminated or decidedly reduced through cancellation. Since distortion for push-pull operation is less than for single-tube operation, appreciably more than twice single-tube output can be obtained by decreasing the load resistance for the stage to a value approaching the load resistance for a single tube. For either parallel or push-pull class A operation of two tubes, all electrode currents are doubled while all dc electrode voltages remain the same as for single-tube operation. If a cathode resistor is used, its value should be about one-half that for a single tube. Should oscillations occur with either type of connection, they can often be eliminated by connecting a non-inductive resistor of approximately 100 ohms in series with each grid at the socket terminal.

Operation of power tubes so that the grids run positive is inadvisable except under conditions such as those discussed in this section for class AB and class B amplifiers.

Calculation of the **power output of a triode** used as a class A amplifier with either an output transformer or a choke having low dc resistance can be made without serious error from the plate family of curves by assuming a resistance load. The proper plate current, grid bias, optimum load resistance, and the per cent second-harmonic distortion can also be determined. The calculations are made graphically and are illustrated in Fig. 19 for given conditions. The procedure is as follows: (1) Locate the zero-signal bias point P by determining the zero-signal bias Ec_o from the formula:

$$\text{Zero-signal bias } (Ec_o) = -(0.68 \times E_b)/\mu$$

where E_b is the chosen value in volts of dc plate voltage at which the tube is to be operated, and μ is the amplification factor of the tube. This quantity is shown as negative to indicate that a negative bias is used. (2) Locate on the plate family the value of zero-signal plate current, I_o, corresponding to point P. (3) Locate $2I_o$, which is twice the value of I_o and corresponds to the value of the maximum-signal plate current I_{max}. (4) Locate the point X on the dc bias curve at zero volts, $E_c = 0$, corresponding to the value of I_{max}. (5) Draw a straight line XY through X and P.

Line XY is known as the load resistance line. Its slope corresponds to the value of the load resistance. The load resistance in ohms is equal to ($E_{max} - E_{min}$) divided by ($I_{max} - I_{min}$), where E is in volts and I is in amperes.

It should be noted that in the case of filament types of tubes, the calculations are given on the basis of a dc-operated filament. When, however, the filament is ac-operated, the calculated value of dc bias should be increased by approximately one-half the filament voltage rating of the tube.

The value of zero-signal plate current I_o should be used to determine the plate dissipation, an important factor influencing tube life. In a class A amplifier under no-signal conditions, the plate dissipation is equal to the power input, i.e., the product of the dc plate voltage E_o and the zero-signal dc plate current I_o. If it is found that the plate-dissipation rating of the tube is exceeded with the zero-signal bias Ec_o calculated above, it will be necessary to increase the bias by a sufficient amount so that the actual plate dissipation does not exceed the rating before proceeding further with the remaining calculations.

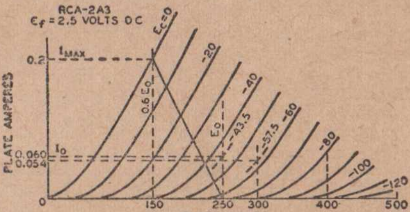


Fig. 19

For power output calculations, it is assumed that the peak alternating grid voltage is sufficient (1) to swing the grid from the zero-signal bias value Ec_o to zero bias ($E_c = 0$) on the positive swing and (2) to swing the grid to a value twice the zero-signal bias value on the negative swing. During the negative swing, the plate voltage and plate current reach values of E_{max} and I_{min}; during the positive swing, they reach values of E_{max} and I_{min}. Since power is the product of voltage and current, the power output as shown by a wattmeter is given by

$$\text{Power output} = \frac{(I_{max} - I_{min})\ \ (E_{max} - E_{min})}{8}$$

where E is in volts, I is in amperes, and power output is in watts.

In the output of power amplifier triodes, some distortion is present. This distortion is due predominantly to second harmonics in single-tube amplifiers. The percentage of second-harmonic distortion may be calculated by the following formula:

$$\%\ \text{2nd-harmonic distortion} = \frac{\dfrac{I_{max} + I_{min}}{2} - I_o}{I_{max} - I_{min}} \times 100$$

where I_o is the zero-signal plate current in amperes. In case the distortion is excessive, the load resistance should be increased or decreased slightly and the calculations repeated.

Example: Determine the load resistance, power output, and distortion of a triode having an amplification factor of 4.2, a plate-dissipation rating of 15 watts, and plate characteristics curves as shown in Fig. 19. The tube is to be operated at 250 volts on the plate.

Procedure: For a first approximation, determine the operating point P from the zero-signal bias formula, $Ec_o = -(0.68 \times 250) / 4.2 = -40.5$ volts. From the curve for this voltage, it is found that the zero-signal plate current I_o at a plate voltage of 250 volts is 0.08 ampere and, therefore, the plate-dissipation rating is exceeded ($0.08 \times 250 = 20$ watts). Consequently, it is necessary to reduce the zero-signal plate current to 0.06 ampere at 250 volts. The grid bias is now seen to be –43.5 volts. Note that the curve was taken with a dc filament supply; if the filament is to be operated on an ac supply, the bias must be increased by about one-half the filament voltage, or to –45 volts, and the circuit returns made to the mid-point of the filament circuit.

Point X can now be determined. Point X is at the intersection of the dc bias curve at zero volts with I_{max}, where $I_{max} = 2I_o = 2 \times 0.06 = 0.12$ ampere. Line XY is drawn through points P and X. E_{max}, E_{min}, and I_{min} are then found from the curves. Substituting these values in the power output formula, we obtain

$$\text{Power output} = \frac{(0.12 - 0.012) \quad (365 - 105)}{8} = 3.52 \text{ watts}$$

The resistance represented by load line XY is

$$\frac{(365 - 105)}{(0.12 - 0.012)} = 2410 \text{ ohms}$$

If now the values from the curves are substituted in the distortion formula, we obtain

$$\%\ \text{2nd-harmonic distortion} = \frac{\dfrac{0.12 + 0.012}{2} - 0.06}{0.12 - 0.012} \times 100 = 5.5\%$$

It is customary to select the load resistance so that the distortion does not exceed five per cent. When the method shown is used to determine the slope of the load resistance line, the second-harmonic distortion generally does not exceed five per cent. In the example, however, the distortion is excessive and it is desirable, therefore, to use a slightly higher load resistance. A load resistance of 2500 ohms will give a distortion of about 4.9 per cent. The power output is reduced only slightly to 3.5 watts.

Operating conditions for **triodes in push-pull** depend on the type of operation desired. Under class A conditions, distortion, power output, and efficiency are all relatively low. The operating bias can be anywhere between that specified for single-tube operation and that equal to one-half the grid-bias voltage required to produce plate-current cutoff at a plate voltage of $1.4E_o$ where E_o is the operating plate voltage. Higher bias than this value requires higher grid-signal voltage and results in class AB_1 operation which is discussed later.

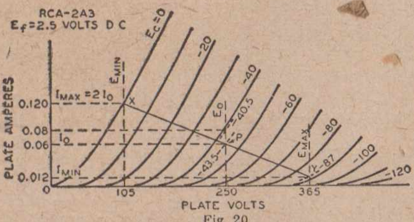


Fig. 20

The method for calculating power output for **triodes in push-pull class A operation** is as follows: Erect a vertical line at $0.6E_o$ (see Fig. 20), intersecting the $E_c = 0$ curve at the point I_{max}. Then, I_{max} is determined from the curve for use in the formula

$$\text{Power output} = (I_{max} \times E_o) / 5.$$

If I_{max} is expressed in amperes and E_o in volts, power output is in watts.

The method for determining the proper load resistance for triodes in push-pull is as follows: Draw a load line through I_{max} on the zero-bias curve and through the E_o point on the zero-current axis. Four times the resistance represented by this load line is the plate-to-plate load for two triodes in a class A push-pull amplifier. Expressed as a formula,

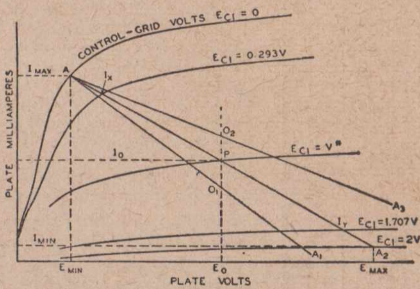
$$\text{Plate-to-plate load } (R_{pp}) = (E_o - 0.6E_o)/I_{max}$$

E_o is expressed in volts, I_{max} in amperes, and R_{pp} in ohms.

Example: Assume that the plate voltage (E_o) is to be 300 volts, and the plate dissipation rating of the tube is 15 watts. Then, for class A operation, the operating bias can be equal to, but not more than, one-half the grid bias for cutoff with a plate voltage of 1.4 × 300 = 420 volts. (Since cutoff bias is approximately −115 volts at a plate voltage of 420 volts, one-half of this value is −57.5 volts bias.) At this bias, the plate current is found from the plate family to be 0.054 ampere and, therefore, the plate dissipation is 0.054 × 300 or 16.2 watts. Since −57.5 volts is the limit of bias for class A operation of these tubes at a plate voltage of 300 volts, the dissipation cannot be reduced by increasing the bias and it, therefore, becomes necessary to reduce the plate voltage.

If the plate voltage is reduced to 250 volts, the bias will be found to be −43.5 volts. For this value, the plate current is 0.06 ampere, and the plate dissipation is 15 watts. Then, following the method for calculating power output, erect a vertical line at $0.6E_o = 150$ volts. The intersection of the line with the curve $E_c = 0$ is I_{max} or 0.2 ampere. When this value is substituted in the power formula, the power output is $(0.2 \times 250)/5 = 10$ watts. The load resistance is determined from the load formula: Plate-to-plate load $(R_{pp}) = 4(250 - 150)/0.2 = 2000$ ohms.

Power output for a pentode or a beam power tube as a class A amplifier can be calculated in much the same way as for triodes. The calculations can be made graphically from a special plate family of curves, as illustrated in Fig. 21.



*V is the Negative Control-Grid Bias Voltage at the Operating Point

Fig. 21

From a point A just above the knee of the zero-bias curve, draw arbitrarily selected load lines to intersect the zero-plate-current axis. These lines should be on both sides of the operating point P whose position is determined by the desired operating plate voltage E_o, and one-half the maximum-signal plate current. Along any load line, say AA_1, measure the distance AO_1. On the same line, lay off an equal distance O_1A_1. For optimum operation, the change in bias from A to O_1 should be nearly equal to the change in bias from O_1 to A_1. If this condition can not be met with one line, as is the case for the line first chosen, then, another should be chosen. When the most satisfactory line has been selected, its resistance may be determined by the following formula:

$$\text{Load resistance } (R_p) = \frac{E_{max} - E_{min}}{I_{max} - I_{min}}$$

The value of R_p may then be substituted in the following formula for calculating power output.

$$\text{Power output} = \frac{[I_{max} - I_{min} + 1.41\,(I_x - I_y)]^2 R_p}{32}$$

In both of these formulas, I is in amperes, E is in volts, R_p is in ohms, and power output is in watts. I_x and I_y are the current values on the load line at bias voltages of $Ec_1 = V - 0.707V = 0.293V$ and $Ec_1 = V + 0.707V = 1.707V$, respectively.

Calculations for distortion may be made by means of the following formulas. The terms used have already been defined.

$$\%\ \text{2nd-harmonic distortion} = \frac{I_{max} + I_{min} - 2\,I_o}{I_{max} - I_{min} + 1.41\,(I_x - I_y)} \times 100$$

$$\%\ \text{3rd-harmonic distortion} = \frac{I_{max} - I_{min} - 1.41\,(I_x - I_y)}{I_{max} - I_{min} + 1.41\,(I_x - I_y)} \times 100$$

$$\%\ \text{total (2nd and 3rd) harmonic distortion} = \sqrt{(\%2nd)^2 + (\%3rd)^2}$$

The conversion curves given in Fig. 22 apply to electron tubes in general but are particularly useful for power tubes. These curves can be used for calculating approximate operating conditions for a plate voltage which is not included in the published data on operating conditions. For instance, suppose it is desired to operate two 6L6's in class A_1 push-pull, fixed bias, with a plate voltage of 200 volts. The nearest published operating conditions for this class of service are for a plate voltage of 250 volts. The operating conditions for the new plate voltage can be determined as follows: First compute the ratio of the new plate voltage to the plate voltage of the published data. In the example, this ratio is 200/250 = 0.8. This figure is the Voltage Conversion Factor, F_e. Multiply by this factor the published values for 250-volt operation in order to obtain the new values of grid bias and screen voltage. This gives a grid bias of $-16 \times 0.8 = -12.8$ volts, and a screen voltage of $250 \times 0.8 = 200$ volts for the new conditions.

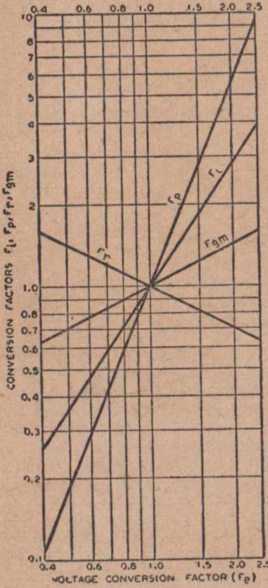


Fig. 22

To obtain the rest of the new conditions, multiply the published values by factors shown on the chart as corresponding to the voltage conversion factor of 0.8. In this chart,

F_i applies to plate current and to screen current,

F_p applies to power output

F_r applies to load resistance and plate resistance,

F_{gm} applies to transconductance.

Thus, to find the power output for the new conditions, determine the value of F_p for a voltage conversion factor of 0.8. The chart shows that this value of F_p is 0.6. Multiplying the published value of power output by 0.6, the power output for the new conditions is $14.5 \times 0.6 = 8.7$ watts.

A class AB power amplifier employs two tubes connected in push-pull with a higher negative grid bias than is used in a class A stage. With this higher negative bias, the plate and screen voltages can usually be made higher than for class A because the increased negative bias holds plate current within the limit of the tube's plate-dissipation rating. As a result of these higher voltages, more power output can be obtained from class AB operation.

Class AB amplifiers are subdivided into class AB_1 and class AB_2. In class AB_1 there is no flow of grid current. That is, the peak signal voltage applied to each grid is not greater than the negative grid-bias voltage. The grids therefore are not driven to a positive potential and do not draw grid current. In class AB_2, the peak signal voltage is greater than the bias so that the grids are driven positive and draw grid current.

Because of the flow of grid current in a class AB_2 stage there is a loss of power in the grid circuit. The sum of this loss and the loss in the input transformer is the total driving power required by the grid circuit. The driver stage should be capable of a power output considerably larger than this required power in order that distortion introduced in the grid circuit be kept low. The input transformer used in a class AB_2 amplifier usually has a step-down turns ratio.

Because of the large fluctuations of plate current in a class AB_2 stage, it is important that the plate power supply should have good regulation. Otherwise the fluctuations in plate current cause fluctuations in the voltage output of the power supply, with the result that power output is decreased and distortion is increased. To obtain satisfactory regulation it is usually advisable to use a low-drop rectifier, such as the 5V4-G, with a choke-input filter. In all cases, the resistance of the filter choke and power transformers should be as low as possible.

In class AB_1 push-pull amplifier service using triodes, the operating conditions may be determined graphically by means of the plate family if E_0, the desired operating plate voltage, is given. In this service, the dynamic load line does not pass through the operating point P as in the case of the single-tube amplifier, but through the point D in Fig. 23. Its position is not affected by the operating grid bias provided the plate-to-plate load resistance remains constant. Under these conditions, grid bias has only a small effect on the power output. Grid bias cannot be neglected, however, since it is used to find the zero-signal plate current and, from it, the zero-signal plate dissipation. Since the grid bias is higher in class AB_1 than in class A service for the same plate voltage, this "overbiased" condition permits the use of a higher signal voltage without grid current being drawn and, therefore, higher power output is obtained than in class A service.

In general, for any load line through point D, Fig. 23, the plate-to-plate load resistance in ohms of a push-pull amplifier is $R_{pp} = 4E_0/I'$, where I' is the plate current value in amperes at which the load line as projected intersects the plate current axis and E_0 is in volts. This is another form of the formula, given under push-pull class A amplifiers, $R_{pp} = 4(E_0 - 0.6E_0)/I_{max}$, but is more general. Power output $= (I_{max}/\sqrt{2})^2 \times R_{pp}/4$, where I_{max} is the peak plate current at zero grid volts for the load chosen. This formula simplified is $(I_{max})^2 \times R_{pp}/8$. The maximum-signal average plate current is $2I_{max}/\pi$ or $0.636\ I_{max}$: the maximum-signal average power input is $0.636\ I_{max}\ E_0$.

It is desirable to simplify these formulas for a first approximation. This simplification can be made if it is assumed that the peak plate current, I_{max}, occurs at the point of the zero-bias curve corresponding approximately to $0.6E_0$. The simplified formulas are

$$\text{Power output (for two tubes)} = (I_{max} \times E_o)/5$$
$$\text{Plate-to-plate load resistance } (R_{pp}) = 1.6E_o/I_{max}$$

where E_o is in volts, I_{max} is in amperes, R_{pp} is in ohms, and power output is in watts.

It may be found during subsequent calculations that the distortion or the plate dissipation is excessive for this approximation; in that case, a different load resistance must be selected using the first approximation as a guide and the process repeated to obtain satisfactory operating conditions.

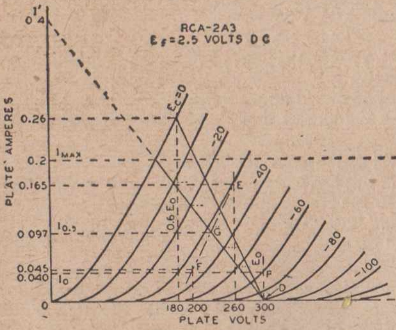


Fig. 23

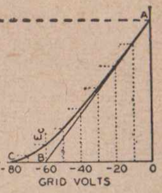


Fig. 24

Example: Fig. 23 illustrates the application of the method to a pair of 2A3's operated at $E_o = 300$ volts. The tubes have a plate-dissipation rating each of 15 watts. The method is to erect a vertical line at $0.6E_o$, or at 180 volts, which intersects the $E_c = 0$ curve at the point $I_{max} = 0.26$ ampere. Using the simplified formulas, we obtain

$$\text{Plate-to-plate load resistance } (R_{pp}) = (1.6 \times 300)/0.26 = 1845 \text{ ohms}$$
$$\text{Power output} = (0.26 \times 300)/5 = 15.6 \text{ watts}$$

At this point, it is well to determine the plate dissipation and to compare it with the maximum rated value. From the average plate current formula ($0.636\ I_{max}$) mentioned previously, the maximum-signal average plate current is 0.166 ampere. The product of this current and the operating plate voltage is 49.8 watts, the average input to the two tubes. From this value, subtract the power output of 15.6 watts to obtain the total dissipation for both tubes which is 34.2 watts. Half of this value, 17 watts, is in excess of the 15-watt rating of the tube and it is necessary, therefore, to assume another and higher load resistance so that the plate-dissipation rating will not be exceeded.

It will be found that at an operating plate voltage of 300 volts, the 2A3's require a plate-to-plate load resistance of 3000 ohms. From the formula for R_{pp}, the value of I' is found to be 0.4 ampere. The load line for the 3000-ohm load resistance is then represented by a straight line from the point $I' = 0.4$ ampere on the plate-current ordinate to the point $E_o = 300$ volts on the plate-voltage abscissa. At the intersection of the load line with the zero-bias curve, the peak plate current, I_{max}, can be read at 0.2 ampere. Then

$$\text{Power output} = (I_{max}/\sqrt{2})^2\ R_{pp}/4 = (0.2/1.41)^2\ \ 3000/4 = 15 \text{ watts}$$

Proceeding as in the first approximation, we find that the maximum-signal average plate current, $0.636I_{max}$, is 0.127 ampere, and the maximum-signal average power input is 38.1 watts. This input minus the power output is $38.1 - 15 = 23.1$ watts.

This is the dissipation for two tubes; the value per tube is 11.6 watts, a value well within the rating of this tube type.

The operating bias and the zero-signal plate current may now be found by use of a curve which is derived from the plate family and the load line. Fig. 24 is a curve of instantaneous values of plate current and dc grid-bias voltages taken from Fig. 23. Values of grid bias are read from each of the grid-bias curves of Fig. 23 along the load line and are transferred to Fig. 24 to produce the curved line from A to C. A tangent to this curve, starting at A, is drawn to intersect the grid-voltage abscissa. The point of intersection, B, is the operating grid bias for fixed-bias operation. In the example, the bias is –60 volts. Refer back to the plate family at the operating conditions of plate volts = 300 and grid bias = –60 volts; the zero-signal plate current per tube is seen to be 0.04 ampere. This procedure locates the operating point for each tube at P. The plate current must be doubled, of course, to obtain the zero-signal plate current for both tubes. Under maximum-signal conditions, the signal voltage swings from zero-signal bias voltage to zero bias for each tube on alternate half cycles. Hence, in the example, the peak af signal voltage per tube is 60 volts, or the grid-to-grid value is 120 volts.

As in the case of the push-pull class A amplifier, the second-harmonic distortion in a class AB_1 amplifier using triodes is very small and is largely cancelled by virtue of the push-pull connection. Third-harmonic distortion, however, which may be larger than permissible, can be found by means of composite characteristic curves. A complete family of curves can be plotted, but for the present purpose only the one corresponding to a grid bias of one-half the peak grid-voltage swing is needed. In the example, the peak grid voltage per tube is 60 volts, and the half value is 30 volts. The composite curve, since it is nearly a straight line, can be constructed with only two points (see Fig. 23). These two points are obtained from deviations above and below the operating grid and plate voltages. In order to find the curve for a bias of –30 volts, we have assumed a deviation of 30 volts from the operating grid voltage of –60 volts. Next assume a deviation from the operating plate voltage of, say, 40 volts. Then at 300 – 40 = 260 volts, erect a vertical line to intersect the (–60) – (–30) = –30-volt bias curve and read the plate current at this intersection which is 0.167 ampere; likewise, at the intersection of a vertical line at 300 + 40 = 340 volts and the (–60) + (–30) = –90-volt bias curve, read the plate current. In this example, the plate current is estimated to be 0.002 ampere. The difference of 0.165 ampere between these two currents determines the point E on the 300 – 40 = 260-volt vertical. Similarly, another point F on the same composite curve is found by assuming the same grid-bias deviation but a larger plate-voltage deviation, say, 100 volts. We now have points at 260 volts and 0.165 ampere (E), and at 200 volts and 0.45 ampere (F). A straight line through these points is the composite curve for a bias of –30 volts, shown as a long-short dash line in Fig. 23. At the intersection of the composite curve and the load line, G, the instantaneous composite plate current at the point of one-half the peak signal swing is determined. This current value, designated $I_{0.5}$ and the peak plate current, I_{max}, are used in the following formula to find peak value of the third-harmonic component of the plate current.

$$I_{h3} = (2I_{0.5} - I_{max})/3$$

In the example, where $I_{0.5}$ is 0.097 ampere and I_{max} is 0.2 ampere, $I_{h3} = (2 \times 0.097 - 0.2)/3 = (0.194 - 0.2)/3 = -0.006/3 = -0.002$ ampere. (The fact that I_{h3} is negative indicates that the phase relation of the fundamental (first-harmonic) and third-harmonic components of the plate current is such as to result in a slightly peaked wave form. I_{h3} is positive in some cases, indicating a flattening of the wave form.)

The peak value of the fundamental or first-harmonic component of the plate current

$$I_{b1} = 2/3\ (I_{max} + I_{0.5})$$

In the example: $I_{b1} = 2/3\ (0.2 + 0.097) = 0.198$ ampere. Then, the percentage of third-harmonic distortion is $(I_{b3}/I_{b1})\ 100 = (0.002/0.198)100 = 1\%$ approx.

A **class AB$_2$ amplifier** employs two tubes connected in push-pull as in the case of class AB$_1$ amplifiers. It differs in that it is biased so that plate current flows somewhat more than half the electrical cycle but less than the full cycle, the peak signal voltage is greater than the dc bias voltage, grid current is drawn, and consequently, power is consumed in the grid circuit. These conditions permit obtaining high power output without excessive plate dissipation.

The sum of the power used in the grid circuit and the losses in the input transformer is the total driving power required by the grid circuit. The driver stage should be capable of a power output considerably larger than this required power in order that distortion introduced in the grid circuit be kept low. In addition, the internal impedance of the driver stage as reflected into or as effective in the grid circuit of the power stage should always be as low as possible in order that distortion may be kept low. The input transformer used in a class AB$_2$ stage usually has a step-down ratio adjusted for this condition.

Load resistance, plate dissipation, power output, and distortion determinations are similar to those for class AB$_1$. These quantities are interdependent with peak grid-voltage swing and driving power; a satisfactory set of operating conditions involves a series of approximations. The load resistance and signal swing are limited by the permissible grid current and power, and the distortion. With either a high load resistance or excessive signal swing, the plate-dissipation rating will be exceeded, distortion will be high, and the driving power will be unnecessarily high.

A **class B amplifier** employs two tubes connected in push-pull, so biased that plate current is almost zero when no signal voltage is applied to the grids. Because of this low value of no-signal plate current, class B amplification has the same advantage as class AB$_2$, i.e., large power output can be obtained without excessive plate dissipation. The difference between class B and class AB$_2$ is that, in class B, plate current is cut off for a larger portion of the negative grid swing, and the signal swing is even larger than in class AB$_2$ operation.

Because a class B amplifier is usually operated at zero or low bias, each grid is at a positive potential during all or most of the positive half-cycle of its signal swing and consequently draws considerable grid current. There is, therefore, a loss of power in the grid circuit. This condition imposes the same requirement in the driver stage as in a class AB$_2$ stage, that is, the driver should be capable of delivering considerably more power output than the power required for the class B grid circuit in order that distortion be low. Likewise, the interstage transformer between the driver and class B stage usually has a step-down turns ratio.

Determination of load resistance, plate dissipation, power output, and distortion is similar to that for a class AB$_2$ stage.

Power amplifier tubes designed for class A operation can be used in class AB$_2$ and class B service under suitable operating conditions. There are several tube types designed especially for class B service. The characteristic common to all of these types is a high amplification factor. With a high amplification factor, plate current is small even when the grid bias is zero. These tubes, therefore, can be operated in class B service at a bias of zero volts so that no bias supply is required. A number of class B amplifier tubes consist of two triode units mounted in one tube. The two units can be connected in push-pull so that only one tube is required for a class B stage. Examples of twin triodes used in class B service are the 6N7, 6A6, and 1G6-GT.

An **inverse-feedback** circuit, sometimes called a **degenerative** circuit, is one in which a portion of the output voltage of a tube is applied to the input of the same or a preceding tube in opposite phase to the signal applied to the tube. Two important advantages of feedback are: (1) reduced distortion from each stage included in the feedback circuit and (2) reduction in the variations in gain due to changes in line voltage, possible differences between tubes of the same type, or variations in the values of circuit constants included in the feedback circuit.

Inverse feedback is used in audio amplifiers to reduce distortion in the output stage where the load impedance on the tube is a loudspeaker. Because the impedance of a loudspeaker is not constant for all audio frequencies, the load impedance on the output tube varies with frequency. When the output tube is a pentode or beam power tube having high plate resistance, this variation in plate load impedance can, if not corrected, produce considerable frequency distortion. Such frequency distortion can be reduced by means of inverse feedback. Inverse feedback circuits are of the **constant-voltage** type and the **constant-current** type.

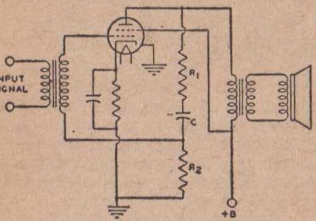


Fig. 25

The application of the **constant-voltage** type of inverse feedback to a power output stage using a single beam power tube is illustrated by Fig. 25. In this circuit, R_1, R_2, and C are connected across the output of the 6L6 as a voltage divider. The secondary of the grid-input transformer is returned to a point on this voltage divider. Capacitor C blocks the dc plate voltage from the grid. However, a portion of the tube's af output voltage, approximately equal to the output voltage multiplied by the fraction $R_2/(R_1 + R_2)$, is applied to the grid. A decrease in distortion results which is explained in the curves of Fig. 26.

Consider first the amplifier without the use of inverse feedback. Suppose that when a signal voltage e_s is applied to the grid the af plate current i'_p has an irregularity in its positive half-cycle. This irregularity represents a departure from the waveform of the input signal and is, therefore, distortion. For this plate-current waveform, the af plate voltage has a waveform shown by e'_p. The plate-voltage waveform is inverted compared to the plate-current waveform because a plate-current increase produces an increase in the drop across the plate load. The voltage at the plate is the difference between the drop across the load and the supply voltage; thus, when plate current goes up, plate voltage goes down; when plate current goes down, plate voltage goes up.

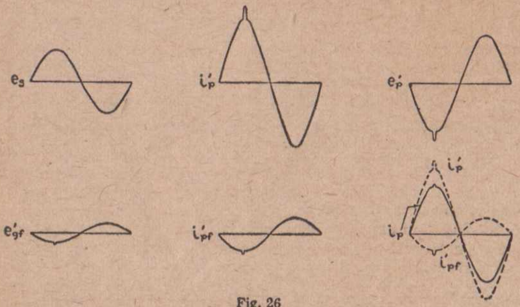


Fig. 26

Now suppose that inverse feedback is applied to the amplifier. The voltage fed back to the grid has the same waveform and phase as the plate voltage, but is smaller in magnitude. Hence, with a plate voltage of waveform shown by e'_p, the feedback voltage appearing on the grid is as shown by e'_{gf}. This voltage applied to the grid produces a component of plate current i'_{pf}. It is evident that the irregularity in the waveform of this component of plate current would act to cancel the original irregularity and thus reduce distortion.

After the correction of distortion has been applied by inverse feedback, the relations are as shown in the curve for i_p. The dotted curve shown by i'_{pf} is the component of plate current due to the feedback voltage on the grid. The dotted curve shown by i'_p is the component of plate current due to the signal voltage on the grid. The algebraic sum of these two components gives the resultant plate current shown by the solid curve of i_p. Since i'_p is the plate current that would flow without inverse feedback, it can be seen that the application of inverse feedback has reduced the irregularity in the output current. In this manner inverse feedback acts to correct any component of plate current that does not correspond to the input signal voltage, and thus reduces distortion.

From the curve for i_p, it can be seen that, besides reducing distortion, inverse feedback also reduces the amplitude of the output current. Consequently, when inverse feedback is applied to an amplifier there is a decrease in power output as well as a decrease in distortion. However, by increasing the signal voltage, it is practical to bring the power output back to its full value. Hence, the application of inverse feedback to an amplifier requires that more driving voltage be applied to obtain full power output but this output is obtained with less distortion.

Inverse feedback may also be applied to resistance-coupled stages as shown in Fig. 27. The circuit is conventional except that a feedback resistor, R_3, is connected between the plate of tubes T_1 and T_2. The output signal voltage of T_1 and a portion of the output signal voltage of T_2 appears across R_2. Because the distortion generated in the plate circuit of T_2 is applied to its grid out of phase with the input signal, the distortion in the output of T_2 is comparatively low. With sufficient inverse feedback of the constant-voltage type in a power-output stage, it is not necessary to employ a network of resistance and capacitance in the output circuit to reduce response at high audio frequencies. Inverse-feedback circuits can also be applied to push-pull class A and class AB_1 amplifiers. When the circuit in Fig. 25 is used in push-pull, the input transformer must have a separate secondary for each grid. Inverse feedback is not recommended for use in amplifiers drawing grid power because of the resistance introduced in the grid circuit.

Constant-current inverse feedback is usually obtained by omitting the bypass capacitor across a cathode resistor. This method decreases the gain and the distortion but increases the plate resistance of the tube. When the plate resistance of an output tube is increased, the output voltage rises at the resonant frequency of the loudspeaker and accentuates hang-over effects.

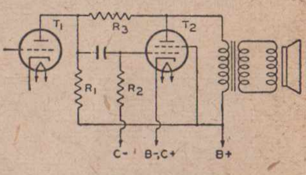


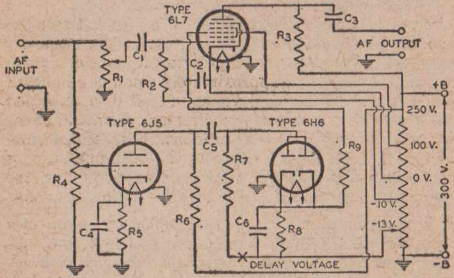
Fig. 27.

Inverse feedback is not generally applied to a triode power amplifier, such as the 2A3, because the variation in speaker impedance with frequency does not produce much distortion in a triode stage having low plate resistance. It is sometimes applied in a pentode stage but is not always convenient. As has been shown, when inverse feedback is used in an amplifier, the driving voltage must be increased in order to give full power output.

When inverse feedback is used with a pentode, the total driving voltage required for full power output may be inconveniently large. Because a beam power tube gives full power output on a comparatively small driving voltage, inverse feedback is especially applicable to beam power tubes. By means of inverse feedback, the high efficiency and high power output of beam power tubes can be combined with freedom from the effects of varying speaker impedance.

A corrective filter can be used to improve the frequency characteristic of an output stage using a beam power tube or a pentode when inverse feedback is not applicable. The filter consists of a resistor and a capacitor connected in series across the primary of the output transformer. Connected in this way, the filter is in parallel with the plate load impedance reflected from the voice-coil by the output transformer. The magnitude of this reflected impedance increases with increasing frequency in the middle and upper audio range. The impedance of the filter, however, decreases with increasing frequency. It follows that by use of the proper values for the resistance and the capacitance in the filter, the effective load impedance on the output tubes can be made practically constant for all frequencies in the middle and upper audio range. The result is an improvement in the frequency characteristic of the output stage.

The resistance to be used in the filter for a push-pull stage is 1.3 times the recommended plate-to-plate load resistance; or, for a single-tube stage, is 1.3 times the recommended plate load resistance. The capacitance in the filter should have a value such that the voltage gain of the output stage at a frequency of 1000 cycles or higher is equal to the voltage gain at 400 cycles. A method of determining the proper value of capacitance for the filter is to make two measurements on the output voltage across the primary of the output transformer: first, when a 400-cycle signal is applied to the input, and second, when a 100-cycle signal of the same voltage as the 400-cycle signal is applied to the input. The correct value of capacitance is the one which gives equal output voltages for the two signal inputs. In practice, this value is usually found to be in the order of 0.05 µf.



C_1, C_3, C_5 = 0.1 µf
C_2, C_4, C_6 = 0.5 µf
R_1 = 1-Megohm Potentiometer (Volume Control)
R_2 = 1 Megohm
R_3, R_6 = 100,000 ohms, 1 watt
R_4 = 1-Megohm Potentiometer (Expansion Control)
R_5 = 10,000 ohms, 0.1 watt
R_7 = 100,000 ohms, 0.1 watt
R_8 = 250,000 ohms, 0.1 watt
R_9 = 500,000 ohms, 0.1 watt

Fig. 28

A volume expander can be used in a phonograph amplifier to make more natural the reproduction of music which has a very large volume range. For instance, in the music of a symphony orchestra, the sound intensity of the loud passages is very much higher than that of the soft passages. When this music is recorded, it is not feasible to make the ratio of maximum amplitude to minimum amplitude as large on the record as it is in the original music. The recording process is therefore monitored so that the volume range of the original is compressed on the record. To compensate for this compression, a volume-expander amplifier has a variable gain which is greater for a high-amplitude signal than for a low-amplitude signal. The volume expander, therefore, amplifies loud passages more than soft passages and thus can restore to the music reproduced from the record the volume range of the original.

A volume expander circuit is shown in Fig. 28. In this circuit, the gain of the 6L7 as an audio amplifier can be varied by changing the bias on grid No. 3. When the bias on grid No. 3 is made less negative, the gain of the 6L7 increases. The signal to be amplified is applied to grid No. 1 of the 6L7 and is amplified by the 6L7 The signal is also applied to the grid of the 6J5, is amplified by the 6J5, and is rectified by the 6H6. The rectified voltage developed across R_8, the load resistor of the 6H6, is applied as a positive bias voltage to grid No. 3 of the 6L7. Then, when the amplitude of the signal input increases, the voltage across R_8 increases, and the bias on grid No. 3 of the 6L7 is made less negative. Because this reduction in bias increases the gain of the 6L7, the gain of the amplifier increases with increase in signal amplitude and thus produces volume expansion of the signal. The voltage gain of the expander varies from 5 to 20.

Grid No. 1 of the 6L7 is a variable-mu grid and, therefore, will produce distortion if the input signal voltage is too large. For that reason, the signal input to the 6L7 should not exceed a peak value of 1 volt. This value is of the same order as the voltage obtainable from a magnetic phonograph pick-up. The no-signal bias voltage on grid No. 3 is controlled by adjustment of contact P. This contact should be adjusted initially to give a no-signal plate current of 0.15 milliampere in the 6L7. No further adjustment of contact P is required if the same 6L7 is always used. If it is desired to delay volume expansion until the signal input reaches a certain amplitude, the delay voltage can be inserted as a negative bias on the 6H6 plates at the point marked X in the diagram. All terminal points on the power-supply voltage divider should be adequately bypassed.

A phase inverter is a circuit used to provide resistance coupling between the output of a single-tube stage and the input of a push-pull stage. The necessity for a phase inverter arises because the signal-voltage inputs to the grids of a push-pull stage must be 180 degrees out of phase and approximately equal in amplitude with respect to each other. Thus, when the signal voltage input to a push-pull stage swings the control grid of one tube in a positive direction, it should swing the other grid in a negative direction by a similar amount. With transformer coupling between stages, the out-of-phase input voltage to the push-pull stage is supplied by means of the center-tapped secondary. With resistance coupling, the out-of-phase input voltage is obtained by means of the inverter action of a tube.

Fig. 29 shows a push-pull power amplifier, resistance-coupled by means of a phase-inverter circuit to a single-stage triode T_1. Phase inversion in this circuit is provided by triode T_2. The output voltage of T_1 is applied to the grid of T_3. A portion of the output voltage of T_1 is also applied through the resistors R_3 and R_5 to the grid of T_2. The output voltage of T_2 is applied to the grid of T_4. When the output voltage of T_1 swings in the positive direction, the plate current of T_2 increases. This action increases the voltage drop across the plate resistor R_2 and swings the plate of T_2 in the negative direction. Thus, when the output voltage of T_1 swings positive, the output voltage of T_2 swings negative and is, therefore, 180° out of phase with the output voltage of T_1. In order to obtain equal voltages at E_a and E_b, R_3/R_5 should equal the voltage gain of T_2. Under the conditions where a twin-type tube or two tubes hav-

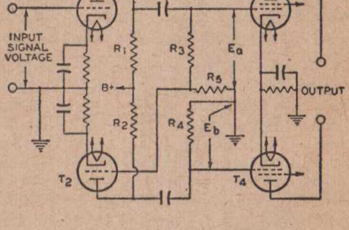


Fig. 29

ing the same characteristics are used at T_1 and T_2, R_4 should be equal to the sum of R_3 and R_5. The ratio of R_5 to R_3 plus R_5 should be the same as the voltage gain ratio of T_2 in order to apply the correct value of signal voltage to T_2. The value of R_5 is, therefore, equal to R_4 divided by the voltage gain of T_2; R_3 is equal to R_4 minus R_5.

In the practical application of this circuit, it is convenient to use a twin-triode tube combining T_1 and T_2.

An amplifier may also be used as a **limiter.** One use of a limiter is in receivers designed for the reception of frequency-modulated signals. The limiter in FM receivers has the function of eliminating amplitude variations from the input to the detector. Because in an FM system, amplitude variations are primarily the result of noise disturbances, the use of a limiter prevents such disturbances from being reproduced in the audio output. The limiter usually follows the last if stage where it can minimize the effects of disturbances coming in on the rf carrier and those produced locally.

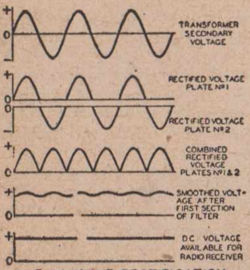
The limiter is essentially an if voltage amplifier designed for saturated operation. Saturated operation means that an increase in signal voltage above a certain value produces very little increase in plate current. A signal voltage which is never less than sufficient to cause saturation of the limiter, even on weak signals, is supplied to the limiter input by the preceding stages. Any change in amplitude, therefore, such as might be produced by noise voltage fluctuation, is not reproduced in the limiter output. The limiting action, of course, does not interfere with the reproduction of frequency variations. Plate-current saturation of the limiter may be obtained by the use of grid-resistor-and-capacitor bias with plate and screen voltages which are low compared with customary if-amplifier operating conditions. As a result of these design features, the limiter is able to maintain its output voltage at a constant amplitude over a wide range of input-signal voltage variations. The output of the limiter is frequency-modulated if voltage, the mean frequency of which is that of the if amplifier. This voltage is impressed on the input of the detector.

The reception of FM signals without serious distortion requires that the response of the receiver be such that satisfactory amplification of the signal is provided over the entire range of frequency deviation from the mean frequency. Since the frequency at any instant depends on the modulation at that instant, it follows that excessive attenuation toward the edges of the band, in the rf or if stages, will cause distortion. This means that, in a high-fidelity receiver, the amplifiers must be capable of amplifying, for the maximum permissible frequency deviation of 75 kilocycles, a band 150 kilocycles wide. Suitable tubes for this purpose are the 6BA6 and 6BJ6.

RECTIFICATION

The rectifying action of a diode finds an important application in supplying a receiver with dc power from an ac line. A typical arrangement for this application includes a rectifier tube, a filter, and a voltage divider. The rectifying action of the tube is explained briefly under **Diodes,** in the ELECTRONS, ELECTRODES, AND ELECTRON TUBE SECTION. The function of a filter is to smooth out the ripple of the tube output, as indicated in Fig. 30. The action of the filter is explained in ELECTRON TUBE INSTALLATION SECTION under **Filters.** The voltage divider is used to cut down the output voltage to the values required by the plates, screens, and grids of the tubes in the receiver.

A **half-wave rectifier** and a **full-wave rectifier** circuit are shown in Fig. 31. In the half-wave circuit, current flows through the rectifier tube to the filter on every other half-cycle of the ac input voltage when the plate is positive with respect to the cathode. In the full-wave circuit, current flows to the filter on every half-cycle,



FULL-WAVE RECTIFICATION

Fig. 30

through plate No. 1 on one half-cycle when plate No. 1 is positive with respect to the cathode, and through plate No. 2 on the next half-cycle when plate No. 2 is positive with respect to the cathode. Because the current flow to the filter is more uniform in the full-wave circuit than in the half-wave circuit, the output of the full-wave circuit requires less filtering.

Parallel operation of rectifier tubes furnishes an output current greater than that obtainable with the use of one tube. For example, when two full-wave rectifier tubes are connected in parallel, the plates of each tube are connected together and each tube acts as a half-wave rectifier. The allowable voltage and load conditions per tube are the same as for full-wave service but the total load-handling capability of the complete rectifier is approximately doubled. When mercury-vapor rectifier tubes are connected in parallel, a stabilizing resistor of 50 to 100 ohms should be connected in series with each plate lead in order that each tube will carry an equal share of the load. The value of the resistor to be used will depend on the amount of plate current that passes through the rectifier. Low plate current requires a high value; high plate current, a low value. When the plates of mercury-vapor rectifier tubes are connected in parallel, the corresponding filament leads should be similarly connected. Otherwise, the tube drops will be considerably unbalanced and larger stabilizing resistors will be required. Two or more vacuum rectifier tubes can also be connected in parallel to give correspondingly higher output current and, as a result of paralleling their internal resistances, give somewhat increased voltage output. With vacuum types, stabilizing resistors may or may not be necessary depending on the tube type and the circuit.

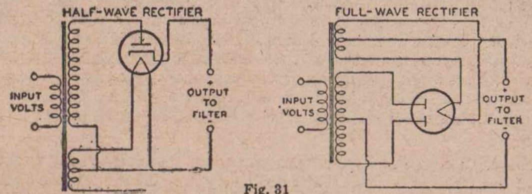
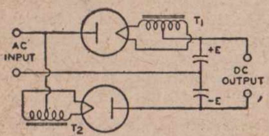


Fig. 31

A **voltage-doubler** circuit of simple form is shown in Fig. 32. The circuit derives its name from the fact that its dc voltage output can be as high as twice the peak value of ac input. Basically, a voltage doubler is a rectifier circuit arranged so that the output voltages of two half-wave rectifiers are in series. The action of a voltage doubler is briefly as follows. On the positive half-cycle of the ac input, that is, when the upper side of the ac input line is positive with respect to the lower side, the upper diode passes current and feeds a positive charge into the upper capacitor. As positive charge accumulates on the upper plate of the capacitor, a positive voltage builds up across the capacitor. On the next half-cycle of

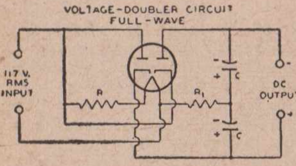


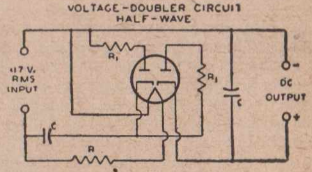
T_1, T_2 = SEPARATE FILAMENT TRANSFORMER WINDINGS

Fig. 32

the ac input, when the upper side of the line is negative with respect to the lower side, the lower diode passes current so that a negative voltage builds up across the lower capacitor. As long as no current is drawn at the output terminals from the capacitor, each capacitor can charge up to a voltage of magnitude E, the peak value of the ac input. It can be seen from the diagram that with a voltage of +E on one capacitor and –E on the other, the total voltage across the capacitors is 2E. Thus the voltage doubler supplies a no-load dc output voltage twice as large as the peak ac input voltage. When current is drawn at the output terminals by the load, the output voltage drops below 2E by an amount that depends on the magnitude of the load current and the capacitance of the capacitors. The arrangement shown in Fig. 32 is called a full-wave voltage doubler because each rectifier passes current to the load on each half of the ac input cycle.

Two rectifier types especially designed for use as voltage doublers are the 25Z6-GT and 117Z6-GT. These tubes combine two separate diodes in one tube. As voltage doublers, the tubes are used in "transformerless" receivers. In these receivers, the heaters of all tubes in the set are connected in series with a voltage-dropping resistor across the line. The connections for the heater supply and the voltage-doubling circuit are shown in Figs. 33 and 34.





R = HEATERS OF OTHER TUBES IN SERIES WITH VOLTAGE-DROPPING RESISTOP
R₁ = PROTECTIVE RESISTOR

Fig. 33

Fig. 34

With the full-wave voltage-doubler circuit in Fig. 33, it will be noted that the dc load circuit can not be connected to ground or to one side of the ac supply line. This presents certain disadvantages when the heaters of all the tubes in the set are connected in series with a resistance across the ac line. Such a circuit arrangement may cause hum because of the high ac potential between the heaters and cathodes of the tubes. The circuit in Fig. 34 overcomes this difficulty by making one side of the ac line common with the negative side of the dc load circuit. In this circuit, one half of the tube is used to charge a capacitor which, on the following half cycle, discharges in series with the line voltage through the other half of the tube. This circuit is called a half-wave voltage doubler because rectified current flows to the load only on alternate halves of the ac input cycle. The voltage regulation of this arrangement is somewhat poorer than that of the full-wave voltage doubler.

DETECTION

When speech or music is transmitted from a radio station, the station radiates a radio-frequency (rf) wave which is of either of two general types. In one type, the wave is said to be amplitude modulated when its frequency remains constant and the amplitude is varied. In the other type, the wave is said to be frequency modulated when its amplitude remains essentially constant but its frequency is varied. In either case, the varying component is modulated in accordance with the audio frequencies (af) of the speech or music being transmitted.

The function of the receiver is to reproduce the original af modulating wave from the modulated rf wave. The receiver stage in which this function is performed is called the demodulator or detector stage.

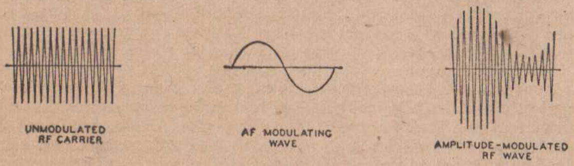


Fig. 35

The effect of **amplitude modulation** on the waveform of the rf wave is shown in Fig. 35. There are three different basic circuits used for the detection of amplitude-modulated waves: the diode detector, the grid-bias detector, and the grid-resistor detector. These circuits are alike in that they eliminate, either partially or completely, alternate half-cycles of the rf wave. With alternate half-cycles removed, the audio variations of the other half-cycles can be amplified to drive headphones or a loudspeaker.

A **diode-detector** circuit is shown in Fig. 36. The action of this circuit when a modulated rf wave is applied is illustrated by Fig. 37. The rf voltage applied to the circuit is shown in light line; the output voltage across capacitor C is shown in heavy line. Between points (a) and (b) on the first positive half-cycle of the applied rf voltage, capacitor C charges up to the peak value of the rf voltage. Then as the applied rf voltage falls away from its peak value, the capacitor holds the cathode at a potential more positive than the voltage applied to the anode. The capacitor thus temporarily cuts off current through the diode. While the diode current is cut off, the capacitor discharges from (b) to (c) through the diode load resistor R. When the rf voltage on the anode rises high enough to exceed the potential at which the capacitor holds the cathode, current flows again and the capacitor charges up to the peak value of the second positive half-cycle at (d). In this way, the voltage across the capacitor follows the peak value of the applied rf voltage and reproduces the af modulation. The curve for voltage across the capacitor, as drawn in Fig. 37, is somewhat jagged. However, this jaggedness, which represents an rf component in the voltage across the capacitor, is exaggerated in the drawing. In an actual circuit the rf component of the voltage across the capacitor is negligible. Hence, when the voltage across the capacitor is amplified, the output of the amplifier reproduces the speech or music originating at the transmitting station.

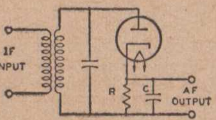


Fig. 36

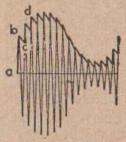


Fig. 37

Another way to describe the action of a diode detector is to consider the circuit as a half-wave rectifier. When the rf signal on the plate swings positive, the tube conducts and the rectified current flows through the load resistance R. Because the dc output voltage of a rectifier depends on the voltage of the ac input, the dc voltage across C varies in accordance with the amplitude of the rf carrier and thus reproduces the af signal. Capacitor C should be large enough to smooth out rf or if variations but should not be so large as to affect the audio variations. Two diodes can be connected in a circuit similar to a full-wave rectifier to give full-wave detection. However, in practice, the advantages of this connection generally do not justify the extra circuit complication.

The diode method of detection has the advantage over other methods in that it produces less distortion. The reason is that the dynamic characteristics of a diode can be made more linear than that of other detectors. A diode has the disadvantages that it does not amplify the signal, and that it draws current from the input circuit and therefore reduces the selectivity of the input circuit. However, because the diode method of detection produces less distortion and because it permits the use of simple avc circuits without the necessity for an additional voltage supply. the diode method of detection is most widely used in broadcast receivers.

A typical diode-detector circuit using a twin-diode triode tube is shown in Fig. 38. Both diodes are connected together R_1 is the diode load resistor. A portion of the af voltage developed across this resistor is applied to the triode grid through the volume control R_3. In a typical circuit, resistor R_1 may be tapped so that five-sixths of the total af voltage across R_1 is applied to the volume control. This tapped connection reduces the af voltage output of the detector circuit slightly but it reduces audio distortion and improves the rf filtering. DC bias for the triode section is provided by the cathode-bias resistor R_2 and the audio bypass capacitor C_3. The function of capacitor C_2 is to block the dc bias of the cathode from the grid. The function of capacitor C_4 is to bypass any rf voltage on the grid to cathode. A twin-diode pentode may also be used in this circuit. With a pentode, the af output should be resistance-coupled rather than transformer-coupled.

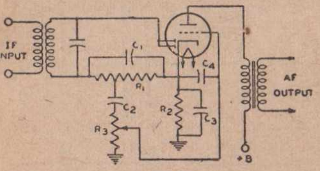


Fig. 38

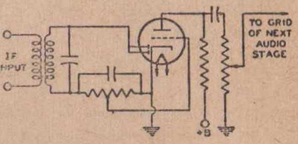


Fig 39

Another diode-detector circuit, called a diode-biased circuit, is shown in Fig. 39. In this circuit, the triode grid is connected directly to a tap on the diode load resistor. When an rf signal voltage is applied to the diode, the dc voltage at the tap supplies bias to the triode grid. When the rf signal is modulated, the af voltage at the tap is applied to the grid and is amplified by the triode. The advantage of this circuit over the self-biased arrangement shown in Fig. 38 is that the diode-biased circuit does not employ a capacitor between the grid and the diode load resistor, and consequently does not produce as much distortion of a signal having a high percentage of modulation.

However, there are restrictions on the use of the diode-biased circuit. Because the bias voltage on the triode depends on the average amplitude of the rf voltage applied to the diode, the average amplitude of the voltage applied to the diode should be constant for all values of signal strength at the antenna. Otherwise there will be different values of bias on the triode grid for different signal strengths and the triode will produce distortion. Since there is no bias applied to the diode-biased triode when no rf voltage is applied to the diode, sufficient resistance should be included in the plate circuit of the triode to limit its zero-bias plate current to a safe value. These restrictions mean, in practice, that the receiver should have a separate-channel avc system. With such an avc system, the average amplitude of the signal voltage applied to the diode can be held within very close limits for all values of signal strength at the antenna. The tube used in a diode-biased circuit should be one which operates at a fairly large value of bias voltage. The variations in bias voltage are then a small percentage of the total bias and hence produce small distortion. Tubes taking a fairly large bias voltage are types such as the 6BF6 or 6ST7 having a medium-mu triode. Tube types having a high-mu triode or a pentode should not be used in a diode-biased circuit.

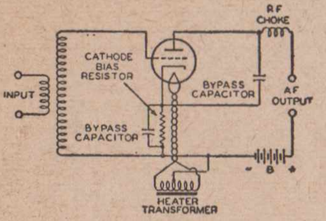


Fig. 40

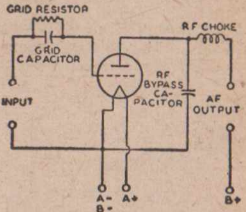


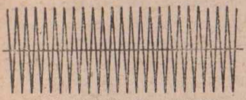
Fig. 41

A **grid-bias detector** circuit is shown in Fig. 40. In this circuit, the grid is biased almost to cutoff, i.e., operated so that the plate current with zero signal is practically zero. The bias voltage can be obtained from a cathode-bias resistor, a C-battery, or a bleeder tap. Because of the high negative bias, only the positive half-cycles of the rf signal are amplified by the tube. The signal is, therefore, detected in the plate circuit. The advantages of this method of detection are that it amplifies the signal, besides detecting it, and that it does not draw current from the input circuit and therefore does not lower the selectivity of the input circuit.

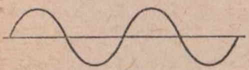
The **grid-resistor-and-capacitor method,** illustrated by Fig. 41, is somewhat more sensitive than the grid-bias method and gives its best results on weak signals. In this circuit, there is no negative dc bias voltage applied to the grid. Hence, on the positive half-cycles of the rf signal, current flows from grid to cathode. The grid and cathode thus act as a diode detector, with the grid resistor as the diode load resistor and the grid capacitor as the rf bypass capacitor. The voltage across the capacitor then reproduces the af modulation in the same manner as has been explained for the diode detector. This voltage appears between the grid and cathode and is therefore amplified in the plate circuit. The output voltage thus reproduces the original af signal.

In this detector circuit, the use of a high-resistance grid resistor increases selectivity and sensitivity. However, improved af response and stability are obtained with lower values of grid-resistor resistance. This detector circuit has the advantage that it amplifies the signal but has the disadvantage that it draws current from the input circuit and therefore lowers the selectivity of the input circuit.

The effect of **frequency modulation** on the waveform of the rf wave is shown in Fig. 42. In this type of transmission, the frequency of the rf wave deviates from



UNMODULATED RF CARRIER



AF MODULATING WAVE

FREQUENCY-MODULATED RF WAVE

Fig. 42

a mean value, at an af rate depending on the modulation, by an amount that is determined in the transmitter and is proportional to the amplitude of the af modulation signal. For this type of modulation, a detector is required to discriminate between deviations above and below the mean frequency and to translate those deviations into a voltage whose amplitude varies at audio frequencies. Since the deviations occur at an audio frequency, the process is one of demodulation, and the degree of frequency deviation determines the amplitude of the demodulated (af) voltage.

A simple circuit for converting frequency variations to amplitude variations is a circuit which is tuned so that the mean radio frequency is on one slope of its resonance characteristic, as at A of Fig. 43. With modulation, the frequency swings between B and C, and the voltage developed across the circuit varies at the modulating rate. In order that no distortion will be introduced in this circuit, the frequency swing must be restricted to the portion of the slope which is effectively straight. Since this portion is very short, the voltage developed is low. Because of these limitations, this circuit is not commonly used but it serves to illustrate the principle.

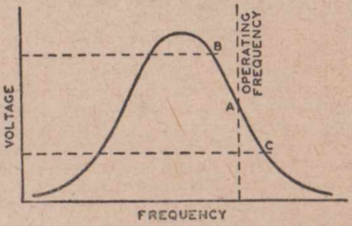


Fig. 43

The faults of the simple circuit are overcome in a push-pull arrangement, sometimes called a discriminator circuit, such as that shown in Fig. 44. Because of the phase relationships between the primary and each half of the secondary of the input transformer (each half of the secondary is connected in series with the primary through capacitor C_2), the rf voltages applied to the diodes become unequal as the rf signal swings from the resonant frequency in each direction. Since the

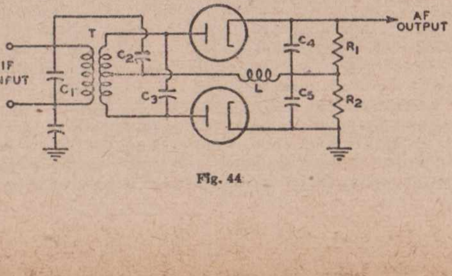


Fig. 44

swing occurs at audio frequencies (determined by the af modulation), the voltage developed across the diode load resistors, R_1 and R_2 connected in series, varies at audio frequencies. The output voltage depends on the difference in amplitude of the voltages developed across R_1 and R_2. These voltages are equal and of opposite sign when the rf carrier is not modulated and the output is, therefore, zero. When modulation is applied, the output voltage varies as indicated in Fig. 45.

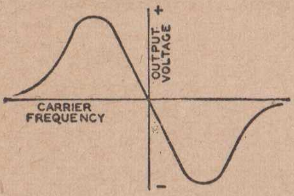


Fig. 45

Because this type of FM detector is sensitive to amplitude variations in the rf carrier, a limiter stage is frequently used to remove most of the amplitude modulation from the carrier. (See Limiters under **Amplification.**)

Another form of detector for frequency-modulated waves is called a **ratio detector.** This FM detector, unlike the previous one which responds to a difference in voltage, responds only to changes in the ratio of the voltage across the two diodes (Fig. 46) and is, therefore, insensitive to changes in the differences in the voltages due to amplitude modulation of the rf carrier.

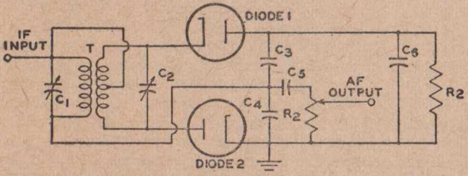


Fig. 46

The basic ratio detector is given in Fig. 46. The plate load for the final intermediate-frequency-amplifier stage is the parallel resonant circuit consisting of C_1 and the primary transformer T. The tuning and coupling of the transformer is practically the same as in the previous circuit and, therefore, the rf voltages applied to the diodes depend upon how much the rf signal swings from the resonant frequency in each direction. At this point the similarity ends.

Diode 1, R_2, and diode 2 complete a series circuit fed by the secondary of the transformer T. The two diodes are connected in series so that they conduct on the same rf half-cycle. The rectified current through R_2 causes a negative voltage to appear at the plate of diode 1. Because C_6 is large, this negative voltage at the plate of diode 1 remains constant even at the lowest audio frequencies to be reproduced. The rectified voltage across C_3 is proportional to the voltage across diode 1, and the rectified voltage across C_4 is proportional to the voltage across diode 2. Since the voltages across the two diodes differ according to the instantaneous frequency of the carrier, the voltages across C_3 and C_4 differ proportionately, the voltage across C_3 being the larger of the two voltages at carrier frequencies below the intermediate frequency and the smaller at frequencies above the intermediate frequency. These voltages across C_3 and C_4 are additive and their sum is fixed by the constant voltage across C_6. Therefore, while the ratio of these voltages varies at an audio rate, their sum is always constant. The voltage across C_4 varies at an audio rate when a frequency-modulated rf carrier is applied to the ratio detector; this audio voltage is extracted and fed to the audio amplifier.

AUTOMATIC VOLUME CONTROL

The chief purposes of automatic volume control in a receiver are to prevent fluctuations in loudspeaker volume when the signal at the antenna is fading in and out, and to prevent an unpleasant blast of loud volume when the set is tuned from a weak signal, for which the volume control has been turned up high, to a strong signal. To accomplish these purposes, an automatic volume control circuit regulates the receiver's rf and if gain so that this gain is less for a strong signal than for a weak signal. In this way, when the signal strength at the antenna changes, the avc circuit reduces the resultant change in the voltage output of the last if stage and consequently reduces the change in the speaker's output volume.

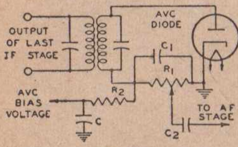


Fig. 47

The avc circuit reduces the rf and if gain for a strong signal usually by increasing the negative bias of the rf, if, and frequency-mixer stages when the signal increases. A simple avc circuit is shown in Fig. 47. On each positive half-cycle of the signal voltage, when the diode plate is positive with respect to the cathode, the diode passes current. Because of the flow of diode current through R_1, there is a voltage drop across R_1 which makes the left end of R_1 negative with respect to ground. This voltage drop across R_1 is applied, through the filter R_2 and C, as negative bias on the grids of the preceding stages. Then, when the signal strength at the antenna increases, the signal applied to the avc diode increases, the voltage drop across R_1 increases, the negative bias voltage applied to the rf and if stages increases, and the gain of the rf and if stages is decreased. Thus the increase in signal strength at the antenna does not produce as much increase in the output of the last if stage as it would produce without avc. When the signal strength at the antenna decreases from a previous steady value, the avc circuit acts, of course, in the reverse direction, applying less negative bias, permitting the rf and if gain to increase, and thus reducing the decrease in the signal output of the last if stage. In this way, when the signal strength at the antenna changes, the avc circuit acts to prevent change in the output of the last if stage, and thus acts to prevent change in loudspeaker volume.

The filter, C and R_2, prevents the avc voltage from varying at audio frequency. The filter is necessary because the voltage drop across R_1 varies with the modulation of the carrier being received. If avc voltage were taken directly from R_1 without filtering, the audio variations in avc voltage would vary the receiver's gain so as to smooth out the modulation of the carrier. To avoid this effect, the avc voltage is taken from the capacitor C. Because of the resistance R_2 in series with C, the capacitor C can charge and discharge at only a comparatively slow rate. The avc voltage therefore cannot vary at frequencies as high as the audio range but can vary at frequencies high enough to compensate for most fading. Thus the filter permits the avc circuit to smooth out variations

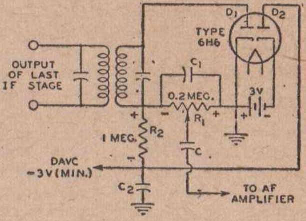


Fig. 48

in signal due to fading, but prevents the circuit from smoothing out audio modulation.

It will be seen that an avc circuit and a diode-detector circuit are much alike. It is therefore convenient in a receiver to combine the detector and the avc diode in a single stage.

In the circuit shown in Fig. 47, a certain amount of avc negative bias is applied to the preceding stages on a weak signal. Since it may be desirable to maintain the receiver's rf and if gain at the maximum possible value for a weak signal, avc circuits are designed in some cases to apply no avc bias until the signal strength exceeds a certain value. These avc circuits are known as delayed avc, or, davc circuits. A davc circuit is shown in Fig. 48. In this circuit, the diode section D_1 of the 6H6 acts as detector and avc diode. R_1 is the diode load resistor and R_2 and C_2 are the avc filter. Because the cathode of diode D_2 is returned through a fixed supply of -3 volts to the cathode of D_1, a dc current flows through R_1 and R_2 in series with D_2. The voltage drop caused by this current places the avc lead at approximately -3 volts (less the negligible drop through D_2). When the average amplitude of the rectified signal developed across R_1 does not exceed 3 volts, the avc lead remains at -3 volts. Hence, for signals not strong enough to develop 3 volts across R_1, the bias applied to the controlled tubes stays constant at a value giving high sensitivity. However, when the average amplitude of rectified signal voltage across R_1 exceeds 3 volts, the plate of diode D_2 becomes more negative than the cathode of D_2 and current flow in diode D_2 ceases. The potential of the avc lead is then controlled by the voltage developed across R_1. Therefore, with further increase in signal strength, the avc circuit applies an increasing avc bias voltage to the controlled stages. In this way, the circuit regulates the receiver's gain for strong signals, but permits the gain to stay constant at a maximum value for weak signals.

It can be seen in Fig. 48 that a portion of the -3 volts delay voltage is applied to the plate of the detector diode D_1, this portion being approximately equal to $R_1/(R_1 + R_2)$ times -3 volts. Hence, with the circuit constants as shown, the detector plate is made negative with respect to its cathode by approximately one-half volt. However, this voltage does not interfere with detection because it is not large enough to prevent current flow in the tube.

TUNING INDICATION WITH ELECTRON-RAY TUBES

Electron-ray tubes are designed to indicate visually by means of a fluorescent target the effects of a change in controlling voltage. One application of them is as tuning indicators in radio receivers. Types such as the 6U5/6G5 and the 6AB5/6N5 contain two main parts: (1) a triode which operates as a dc amplifier and (2) an electron-ray indicator which is located in the bulb as shown in Fig. 49. The target is operated at a positive voltage and therefore attracts electrons from the cathode. When the electrons strike the target they produce a glow on the fluorescent coating of the target. Under these conditions, the target appears as a ring of light.

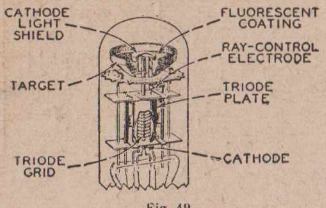


Fig. 49

A ray-control electrode is mounted between the cathode and target. When the potential of this electrode is less positive than the target, electrons flowing to the target are repelled by the electrostatic field of the electrode, and do not reach that portion of the target behind the electrode. Because the target does not glow where it is shielded from electrons, the control electrode casts a shadow on the glowing target. The extent of this shadow varies from approximately 100° of the target when the control electrode is much more negative than the target to 0° when the control electrode is at approximately the same potential as the target.

In the application of the electron-ray tube, the potential of the control electrode is determined by the voltage on the grid of the triode section, as can be seen in Fig. 50. The flow of the triode plate current through resistor R produces a voltage drop which determines the potential of the control electrode. When the voltage of the triode grid changes in the positive direction, plate current increases, the potential of the control electrode goes down because of the increased drop across R, and the shadow angle widens. When the potential of the triode grid changes in the negative direction, the shadow angle narrows.

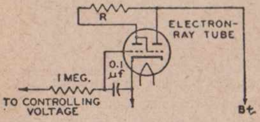


Fig. 50

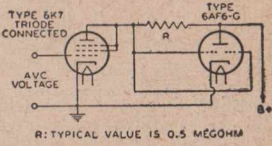


Fig. 51

Another type of indicator tube is the 6AF6-G. This tube contains only an indicator unit but employs two ray-control electrodes mounted on opposite sides of the cathode and connected to individual base pins. It employs an external dc amplifier. See Fig. 51. Thus, two symmetrically opposite shadow angles may be obtained by connecting the two ray-control electrodes together; or, two unlike patterns may be obtained by individual connection of each ray-control electrode to its respective amplifier.

In radio receivers, avc voltage is applied to the grid of the dc amplifier. Since avc voltage is at maximum when the set is tuned to give maximum response to a station, the shadow angle is at minimum when the receiver is tuned to resonance with the desired station.

The choice between electron-ray tubes depends on the avc characteristic of the receiver. The 6E5 contains a sharp-cutoff triode which closes the shadow angle on a comparatively low value of avc voltage. The 6AB5/6N5 and 6U5/6G5 each have a remote-cutoff triode which closes the shadow on a larger value of avc voltage than the 6E5. The 6AF6-G may be used in conjunction with dc amplifier tubes having either remote- or sharp-cutoff characteristics.

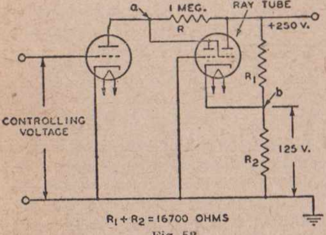


Fig. 52

The sensitivity indication of electron-ray tubes can be increased by using a separate dc amplifier to control the action of the ray-control electrode in the tuning indicator tube. This arrangement increases the maximum shadow angle from the usual 100° to approximately 180°. A circuit for obtaining wide-angle tuning is shown in Fig. 52.

OSCILLATION

As an oscillator, an electron tube can be employed to generate a continuously alternating voltage. In present-day radio broadcast receivers, this application is limited practically to superheterodyne receivers for supplying the heterodyning frequency. Several circuits (represented in Figs. 53 and 54) may be utilized, but they all depend on feeding more energy from the plate circuit to the grid circuit than is required to equal the power loss in the grid circuit. Feedback may be produced by electrostatic or electromagnetic coupling between the grid and plate circuits. When sufficient energy is fed back to more than compensate for the loss in the grid circuit, the tube will oscillate. The action consists of regular surges of power between the plate and the grid circuit at a frequency dependent on the circuit constants of inductance and capacitance. By proper choice of these values, the frequency may be adjusted over a very wide range.

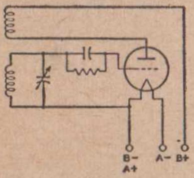


Fig. 53

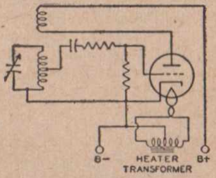


Fig. 54

The **relaxation oscillator** is an oscillator with a non-sinusoidal output. It differs from the preceding type in that the oscillations are obtained by abruptly releasing energy previously stored in the electric field of a capacitor. A **multivibrator** is a special type of relaxation oscillator used in television receivers and other electronic applications. A multivibrator may be considered as a two-stage resistance-coupled amplifier in which the output of each tube is coupled into the input of the other tube in order to sustain oscillations.

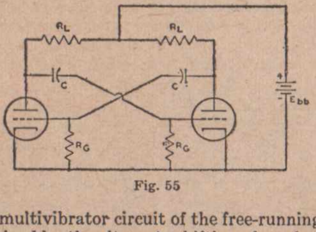
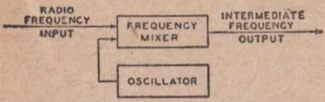


Fig. 55

Fig. 55 is a basic multivibrator circuit of the free-running type. In this circuit, oscillations are maintained by the alternate shifting of conduction from one tube to the other. The cycle starts with one tube usually at zero bias and the other at cutoff or beyond. Each tube introduces a 180° phase shift so that the energy fed back has the phase relation necessary to sustain oscillation. The frequency of oscillation is determined primarily by the constants of the resistance-capacitance coupling circuits.

FREQUENCY CONVERSION

Frequency conversion is used in superheterodyne receivers to change the frequency of the rf signal to an intermediate frequency. To perform this change in frequency, a frequency-converting device consisting of an oscillator and a frequency mixer is employed. In such a device, shown diagrammatically in Fig. 56,



FREQUENCY CONVERTER

Fig. 56

two voltages of different frequency, the rf signal voltage and the voltage generated by the oscillator, are applied to the input of the frequency mixer. These voltages beat, or heterodyne, within the mixer tube to produce a plate current having, in addition to the frequencies of the input voltages, numerous sum and difference frequencies. The output circuit of the mixer stage is provided with a tuned circuit which is adjusted to select only one beat frequency, i.e., the frequency equal to the difference betweeen the signal frequency and the oscillator frequency. The selected output frequency is known as the intermediate frequency, or if. The output frequency of the mixer tube is kept constant for all values of signal frequency by tuning the oscillator to the proper frequency.

Important advantages gained in a receiver by the conversion of signal frequency to a fixed intermediate frequency are high selectivity with few tuning stages and a high, as well as stable, overall gain for the receiver.

Several methods of frequency conversion for superheterodyne receivers are of interest. These methods are alike in that they employ a frequency-mixer tube in which plate current is varied at a combination frequency of the signal frequency and the oscillator frequency. These variations in plate current produce across the tuned plate load a voltage of the desired intermediate frequency. The methods differ in the types of tubes employed and in the means of supplying input voltages to the mixer tube.

A method widely used before the availability of tubes especially designed for frequency-conversion service and currently used in many FM, television, and standard broadcast receivers, employs as mixer tube either a triode, a tetrode, or a pentode, in which oscillator voltage and signal voltage are applied to the same grid. In this method, coupling between the oscillator and mixer circuits is obtained by means of inductance or capacitance.

A second method employs a tube having an oscillator and frequency mixer combined in the same envelope. In one form of such a tube, coupling between the two units is obtained by means of the electron stream within the tube. One arrangement of the electrodes for this type is shown in Fig. 57. Since five grids are used, the tube is called a pentagrid converter. Grids No. 1, No. 2, and the cathode are connected to an external circuit to act as a triode oscillator. Grid No. 1 is the grid of the oscillator and grid No. 2 is the anode. These and the cathode can be considered as a composite cathode which supplies to the rest of the tube an electron stream that varies at the oscillator frequency. This varying electron stream is further controlled by the rf signal voltage on grid No. 4. Thus, the variations in plate current are due to the combination of the oscillator and the signal frequencies. The purpose of grids No. 3 and No. 5, which are connected together within the tube, is to accelerate the electron stream and to shield grid No. 4 electrostatically from the other electrodes. The 6A8 is an example of a pentagrid-converter type.

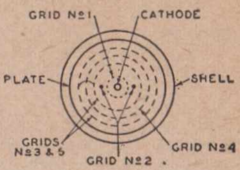


Fig. 57

Pentagrid-converter tubes of this design are good frequency-converting devices at medium frequencies but their performance is better at the lower frequencies than at the high ones. This is because the output of the oscillator drops off as the frequency is raised and because certain undesirable effects produced by interaction between oscillator and signal sections of the tube increase with frequency. To minimize these effects, several of the pentagrid-converter tubes are designed so that no electrode functions alone as the oscillator anode. In these tubes, grid No. 1 functions as the oscillator grid, and grid No. 2 is connected within the tube to the screen (grid No. 4). The combined two grids Nos. 2 and 4 shield the signal grid (grid No. 3) and act as the composite anode of the oscillator triode. Grid No. 5 acts as the suppressor. Converter tubes of this type are designed so that the space charge around the cathode is unaffected by electrons from the signal grid. Furthermore, the electrostatic field of the signal grid also has little effect on the space charge. The result is that rf voltage on the signal grid produces little effect on the cathode current. There is, therefore, little detuning of the oscillator by avc bias because changes in avc bias produce little change in oscillator transconductance or in the input capacitance of grid No. 1. Examples of the pentagrid converters discussed in this paragraph are the single-ended types 1R5 and 6BE6. A schematic diagram illustrating the use of the 6BE6 with self-excitation is given in Fig 58; the 6BE6 may also be used with separate excitation.

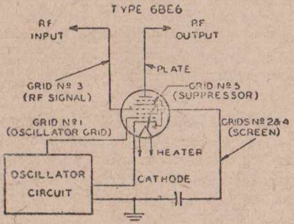


Fig. 58

Another method of frequency conversion utilizes a separate oscillator having its grid connected to the No. 1 grid of a mixer hexode. A tube utilizing this construction is the 6K8 and a top view of its electrode arrangement is shown in Fig. 59 The cathode, triode grid No. 1, and triode plate form the oscillator unit of the tube. The cathode, hexode mixer grid (grid No. 1), hexode double-screen (grids Nos. 2 and 4), hexode mixer grid (grid No. 3), and hexode plate constitute the mixer unit. The internal shields are connected to the shell of the tube and act as a suppressor for the hexode unit. The action of the 6K8 in converting a radio-frequency signal to an intermediate frequency depends on (1) the generation of a local frequency by the triode unit, (2) the transferring of this frequency to the hexode grid No. 1, and (3) the mixing in the hexode unit of this frequency with that of the rf signal applied to the hexode grid No. 3. The 6K8 is not critical to changes in oscillator-plate voltage or signal-grid bias and, therefore, finds important use in all-wave receivers to minimize frequency-shift effects at the higher frequencies.

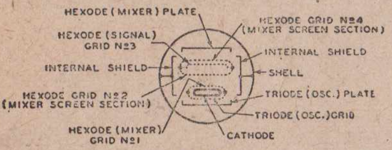


Fig. 59

A further method of frequency conversion employs a tube called a pentagrid mixer. This type has two independent control grids and is used with a separate

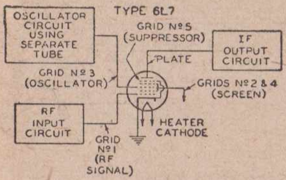


Fig. 60

oscillator tube. RF signal voltage is applied to one of the control grids and oscillator voltage is applied to the other. It follows, therefore, that the variations in plate current are due to the combination of the oscillator and signal frequencies. The arrangement of electrodes in a pentagrid-mixer tube is shown in Fig. 60. The tube contains a heater cathode, five grids, and a plate. Grids Nos. 1 and 3 are control grids. The rf signal voltage is applied to grid No. 1. This grid has a remote-cutoff characteristic and is suited for control by avc bias voltage. The oscillator voltage is applied to grid No. 3. This grid has a sharp-cutoff characteristic and produces a comparatively large effect on plate current for a small amount of oscillator voltage. Grids Nos. 2 and 4 are connected together within the tube. They accelerate the electron stream and shield grid No. 3 electrostatically from the other electrodes. Grid No. 5, connected within the tube to the cathode, functions similarly to the suppressor in a pentode. The 6L7 and 6L7-G are pentagrid-mixer tubes.

AUTOMATIC FREQUENCY CONTROL

An automatic frequency control (afc) circuit provides a means of correcting automatically the intermediate frequency of a superheterodyne receiver if, for any reason, it drifts from the frequency to which the if stages are tuned. This correction is made by adjusting the frequency of the oscillator. Such a circuit will automatically compensate for slight changes in rf carrier or oscillator frequency as well as for inaccurate manual or push-button tuning.

An afc system requires two sections: a frequency detector and a variable reactance. The detector section may be essentially the same as the FM detector illustrated in Fig. 44 and discussed under Detection. In the afc system, however, the output is a dc control voltage, the magnitude of which is proportional to the amount of frequency shift. This dc control voltage is used to control the grid bias of an electron tube which comprises the variable reactance section (**Fig. 61**). The plate current of the reactance tube is shunted across the oscillator tank circuit. Because the plate current and plate voltage of the reactance tube are almost 90° out of phase, the control tube affects the tank circuit in the same manner as a reactance. The grid bias of the tube determines the magnitude of the effective reactance and, consequently, a control of this grid bias can be used to control the oscillator frequency.

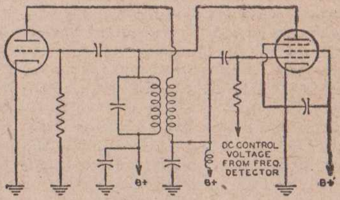


Fig. 61

Electron Tube Installation

The installation of electron tubes requires care if high-quality performance is to be obtained from the associated circuits. Installation suggestions and precautions which are generally common to all types of tubes are covered in this section. Careful observance of these suggestions will do much to help the experimenter and electronic technician obtain the full performance capabilities of radio tubes and circuits.

FILAMENT AND HEATER POWER SUPPLY

The design of electron tubes allows for some variation in the voltage and current supplied to the filament or heater, but most satisfactory results are obtained from operation at the rated values. When the voltage is low, the temperature of the cathode is below normal, with the result that electron emission is limited. This may cause unsatisfactory operation and reduced tube life. On the other hand, high cathode voltage causes rapid evaporation of cathode material and shortens tube life. To insure proper tube operation, the filament or heater voltage should be checked at the socket terminals by means of an accurate voltmeter while the receiver is in operation. In the case of series operation of heaters or filaments, correct adjustment can be checked by means of an ammeter in the heater or filament circuit.

The filament or heater voltage supply may be a direct-current source (a battery or a dc power line) or an alternating-current power line, depending on the type of service and type of tube. Frequently, a resistor (either variable or fixed) is used with a dc supply to permit compensation for battery voltage variations or to adjust the tube voltage at the socket terminals to the correct value. Ordinarily, a step-down transformer is used with an ac supply to provide the proper filament or heater voltage. Receivers intended for operation on both dc and ac power lines have the heaters connected in series with a suitable resistor and supplied directly from the power line.

DC filament or **heater operation** should be considered on the basis of the source of power. In the case of the battery supply for the 1.4-volt filament tubes, it is unnecessary to use a voltage-dropping resistor in series with the filament and a single dry-cell; the filaments of these tubes are designed to operate satisfactorily over the range of voltage variations that normally occur during the life of a dry-cell. Likewise, no series resistor is required when the 2-volt filament type tubes are operated from a single storage cell or when the 6.3-volt series are operated from a 6-volt storage battery. In the case of dry-battery supply for 2-volt filament tubes, a variable resistor in series with the filament and the battery is required to compensate for battery variations. Turning the set on and off by means of the rheostat is advised to prevent over-voltage conditions after an off-period, for the voltage of dry-cells rises during off-periods. In the case of storage-battery supply, air-cell-battery supply, or dc power supply, a non-adjustable resistor of suitable value may be used. It is well to check initial operating conditions, and thus the resistor value, by means of a voltmeter or ammeter.

The **filament** or **heater resistor** required when filaments and/or heaters are operated in parallel can be determined easily by a simple formula derived from Ohm's law.

$$\text{Required resistance (ohms)} = \frac{\text{supply volts} - \text{rated volts of tube type}}{\text{total rated filament current (amperes)}}$$

Thus, if a receiver using three 32's, two 30's, and two 31's is to be operated from dry batteries, the series resistor is equal to 3 volts (the voltage from two dry-cells in series) minus 2 volts (voltage rating for these tubes) divided by 0.56 ampere (the sum of 5 × 0.060 ampere + 2 × 0.130 ampere), i.e., approximately 1.8 ohms. Since this resistor should be variable to allow adjustment for battery depreciation, it is advisable to obtain the next larger commercial size, although any value between 2 and 3 ohms will be quite satisfactory. Where much power is dissipated in the resistor, the wattage rating should be sufficiently large to prevent overheating. The power dissipation in watts is equal to the voltage drop in the resistor multiplied by the total filament current in amperes. Thus, for the example above 1 × 0.56 = 0.56 watt. In this case, the value is so small that any commercial rheostat with suitable resistance will be adequate.

For the case where the heaters and/or filaments of several tubes are operated in series, the resistor value is calculated by the following formula, also derived from Ohm's law.

$$\text{Required resistance (ohms)} = \frac{\text{supply volts} - \text{total rated volts of tubes}}{\text{rated amperes of tubes}}$$

Thus, if a receiver having one 6SA7, one 6SK7, one 6SF7, one 25L6-GT, and one 25Z6-GT is to be operated from a 117-volt power line, the series resistor is equal to 117 volts (the supply voltage) minus 68.9 volts (the sum of 3 × 6.3 volts + 2 × 25 volts) divided by 0.3 ampere (current rating of these tubes), i.e., approximately 160 ohms. The wattage dissipation in the resistor will be 117 volts minus 68.9 volts times 0.3 ampere, or approximately 14.4 watts. A resistor having a wattage rating in excess of this value should be chosen.

It will be noted in the example for series operation that all tubes have the same current rating. If it is desired to connect in series tubes having different heater- or filament-current ratings, each tube of the lower rating should have a shunt resistor placed across its heater or filament terminals to pass the excess current. The value of this shunt resistor can be calculated from the following formula, where tube A is the tube in the series connection having the highest heater-current rating and tube B is any tube having a heater-current rating lower than tube A.

$$\begin{array}{l}\text{Heater shunt resist-}\\ \quad\text{ance (ohms), tube B}\end{array} = \frac{\text{heater volts, tube B}}{\text{rated heater amperes, tube A} - \text{rated heater amperes, tube B}}$$

For example, if a 6N7 having a 6.3-volt, 0.8-ampere heater is to be operated in a series-heater circuit employing several 6.3-volt tubes having heater ratings of 0.3 ampere, the required shunt resistance for each of the latter types would be

$$\text{Heater shunt resistance} = \frac{6.3}{0.8 - 0.3}, \text{ or } 12.6 \text{ ohms.}$$

The value of a series voltage-dropping resistor for a sequence of tubes having one or more shunt resistors should be calculated on the basis of the tube having the highest heater-current rating.

When the series-heater connection is used in ac/dc receivers, it is usually advisable to arrange the heaters in the circuit so that the tubes most sensitive to hum disturbances are at or near the ground potential of the circuit. This arrangement reduces the amount of ac voltage between the heaters and cathodes of these tubes and minimizes the hum output of the receiver. The order of heater connection, by tube function, from chassis to the rectifier-cathode side of the ac line i shown in Fig. 62.

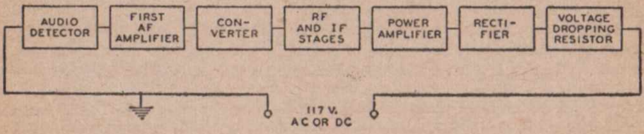


Fig. 62

AC filament or heater operation should be considered on the basis of either a parallel or a series arrangement of filaments and/or heaters. In the case of the parallel arrangement, a step-down transformer is employed. Precautions should be taken to see that the line voltage is the same as that for which the primary of the transformer is designed. The line voltage may be determined by measurement with an ac voltmeter (0-150 volts).

If the line voltage measures in excess of that for which the transformer is designed, a resistor should be placed in series with the primary to reduce the line voltage to the rated value of the transformer primary. Unless this is done, the excess input voltage will cause proportionally excessive voltage to be applied to the tubes. Any electron tube may be damaged or made inoperative by excessive operating voltages.

If the line voltage is consistently below that for which the primary of the transformer is designed, it may be necessary to install a booster transformer between the ac outlet and the transformer primary. Before such a transformer is installed, the ac line fluctuations should be very carefully noted. Some radio sets are equipped with a line-voltage switch which permits adjustment of the power transformer primary to the line voltage. When this switch is properly adjusted, the series-resistor or booster-transformer method of controlling line voltage is seldom required.

In the case of the series arrangements of filaments and/or heaters, a voltage-dropping resistance in series with the heaters and the supply line is usually required. This resistance should be of such value that, for normal line voltage, tubes will operate at their rated heater or filament current. The method for calculating the resistor value is given above.

When the filaments of battery-type tubes are connected in series, the total filament current is the sum of the current due to the filament supply and the plate and screen (cathode) currents returning to B (–) through the tube filaments. Consequently, in a series filament string it is necessary to add shunt resistors across each filament section to bypass this cathode current in order to maintain the filament voltage at its rated value.

HEATER-TO-CATHODE CONNECTION

The cathodes of heater-type tubes, when operated from ac, should be connected to the mid-tap on the heater supply winding, to the mid-tap of a 50-ohm (approximate) resistor shunted across the winding, or to one end of the heater supply winding depending on circuit requirements. If none of these methods is used, it is important to keep the heater-cathode voltage within the ratings given

Hum from ac-operated heater tubes used in high-gain audio amplifiers may frequently be reduced to a negligible value by employing a 15- to 40-volt bias between the heater and cathode elements of the tubes. The bias should be connected so that the tube cathode is negative with respect to its heater. Such bias can be obtained from either B batteries or a well-filtered rectifier. If the regular plate-supply rectifier of the amplifier is employed as the bias voltage source, it is good practice to add an additional filter stage in the bias voltage circuit to insure a hum-free bias source.

If a large resistor is used between heater and cathode, it should be bypassed by a suitable filter network or objectionable hum may develop. The hum is due to the fact that even a minute pulsating leakage current flowing between the heater and cathode will develop a small voltage across any resistance in the circuit. This hum voltage is amplified by succeeding stages. When a series-heater arrangement is used, the cathode circuits should be connected either directly or through biasing resistors to the negative side of the dc plate supply, which is furnished either by the dc power line or by the ac power line through a rectifier.

PLATE VOLTAGE SUPPLY

The plate voltage for electron tubes is obtained from batteries, rectifiers, direct-current power lines, and small local generators. Auto radios have brought about the commercial development of a number of devices for obtaining a high-voltage dc supply either from the car storage-battery or from a generator driven by the car engine.

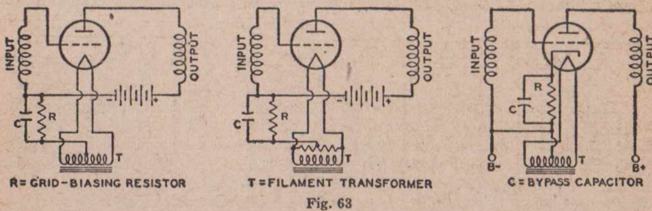
The maximum plate-voltage value for any tube type should not be exceeded if most satisfactory performance is to be obtained. Plate voltage should not be applied to a tube unless the corresponding recommended voltage is also supplied to the grid.

It is recommended that the primary circuit of the power transformer be fused to protect the rectifier tube(s), the power transformer, filter capacitor, and chokes in case a rectifier tube fails.

GRID VOLTAGE SUPPLY

The recommended grid voltages for different operating conditions have been carefully determined to give the most satisfactory performance. Grid voltage may be obtained from a separate C-battery, a tap on the voltage divider of the high-voltage dc supply, or from the voltage drop across a resistor in the cathode circuit. This last is called the ''cathode-bias'' or ''self-bias'' method. In any case, the object is to make the grid negative with respect to the cathode by the specified voltage. When a C-battery is used, the negative terminal is connected to the grid return and the positive terminal is connected to the negative filament socket terminal, or to the cathode terminal if the tube is of the heater-cathode type. If the filament is supplied with alternating current, this connection is usually made to the center-tap of a low resistance (20-50 ohms) shunted across the filament terminals. This method reduces hum disturbances caused by the ac supply. If bias voltages are obtained from the voltage divider of a high-voltage dc supply, the grid return is connected to a more negative tap than the cathode.

The **cathode-biasing** method utilizes the voltage drop produced by the cathode current flowing through a resistor connected between the cathode and the negative terminal of the B-supply. See Fig. 63. The cathode current is, of course, equal to the plate current in the case of a triode, or to the sum of the plate and screen currents in the case of a tetrode, pentode, or beam power tube. Since the voltage drop along the resistance is increasingly negative with respect to the cathode, the required negative grid-bias voltage can be obtained by connecting the grid return to the negative end of the resistance.



R= GRID-BIASING RESISTOR T =FILAMENT TRANSFORMER C = BYPASS CAPACITOR

Fig. 63

The value of the resistance for cathode-biasing a single tube can be determined from the following formula:

$$\text{Resistance (ohms)} = \frac{\text{desired grid-bias voltage} \times 1000}{\text{rated cathode current in milliamperes}}$$

Thus, the resistance required to produce 9 volts bias for a triode which operates at 3 milliamperes plate current is 9 × 1000/3 = 3000 ohms. If the cathode current of more than one tube passes through the resistor, or if the tube or tubes employ more than three electrodes, the total current determines the size of the resistor.

Bypassing of the cathode-bias resistor depends on circuit-design requirements. In rf circuits the cathode resistor should be bypassed. In af circuits the use of an unbypassed resistor will reduce distortion by introducing degeneration into the circuit. However, the use of an unbypassed resistor decreases power sensitivity. When bypassing is used, it is important that the bypass capacitor be sufficiently large to have negligible reactance at the lowest frequency to be amplified. In the case of power-output tubes of high transconductance such as the beam power tubes, it may be necessary to shunt the bias resistor with a small mica capacitor (approximately 0.001 μf) in order to prevent oscillations. The usual af bypass may or may not be used, depending on whether or not degeneration is desired. In tubes having high values of transconductance, such as the 6BA6, 12AW6, and 6AC7, input capacitance and input conductance change appreciably with plate current. When such a tube having a separate suppressor connection is used as an rf amplifier, these changes may be minimized by leaving a portion of the cathode-bias resistor unbypassed. In order to minimize feedback when this method is used, the external grid-plate (wiring) capacitances should be kept to a minimum, the screen should be bypassed to ac ground, and the suppressor should be connected to ac ground. The use of a cathode resistor to obtain bias voltage is not recommended for audio amplifiers in which there is appreciable shift of electrode currents with the application of a signal. In such amplifiers, a separate fixed supply is recommended.

Grid-bias variation for the rf and if amplifier stages is a convenient and frequently used method for controlling receiver volume. The variable voltage supplied to the grid may be obtained: (1) from a variable cathode resistor as shown in Figs. 64 and 65; (2) from a bleeder circuit by means of a potentiometer as shown in Fig. 66; or (3) from a bleeder circuit in which the bleeder current is varied by a tube used for automatic volume control. The latter circuit is shown in Fig. 47. In all cases it is important that the control be arranged so that at no time will the bias be less than the recommended minimum grid-bias voltage for the particular tubes used. This requirement can be met by providing a fixed stop on the potentiometer, by connecting a fixed resistance in series with the variable resistance, or by connecting a fixed cathode resistance in series with the variable resistance used for regulation.

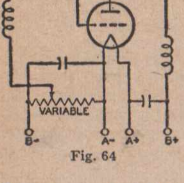


Fig. 64

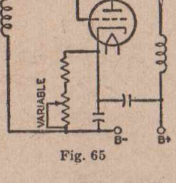


Fig. 65

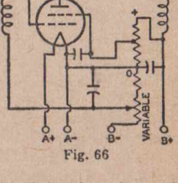


Fig. 66

Where receiver gain is controlled by grid-bias variation, it is advisable to have the control voltages extend over a wide range in order to minimize cross-modulation and modulation-distortion. A remote-cutoff type of tube should, therefore, be used in the controlled stages.

SCREEN VOLTAGE SUPPLY

The positive voltage for the screen (grid No. 2) of screen-grid tubes may be obtained from a tap on a voltage divider, from a potentiometer, or from a series resistor connected to a high-voltage source, depending on the structure of the particular tube type and its application. The screen voltage for tetrodes should be obtained from a voltage divider or a potentiometer rather than through a series resistor from a high-voltage source because of the characteristic screen-current variations of tetrodes. Fig. 67 shows a tetrode with its screen voltage obtained from a potentiometer. When pentodes or beam power tubes are operated under conditions where a large shift of plate and screen currents does not take place with the application of the signal, the screen voltage may be obtained through a series resistor from a high-voltage source. This method of supply is possible because of the high uniformity of the screen-current characteristic in pentodes and beam power tubes. Because the screen voltage rises with increase in bias and resulting decrease in screen current, the cutoff characteristic of a pentode is extended by this method of supply. The method is sometimes used to increase the range of signals which can be handled by a pentode. When used in resistance-coupled amplifier circuits employing pentodes in combination with the cathode-biasing method, it minimizes the need for circuit adjustments. Fig. 68 shows a pentode with its screen voltage supplied through a series resistor.

When power pentodes and beam power tubes are operated under conditions such that there is a large change in plate and screen currents with the application of signal, the series-resistor method of obtaining screen voltage should not be used. A change in screen current appears as a change in the voltage drop across the series resistor in the screen circuit; the result is a change in the power output and an increase in distortion. The screen voltage should be obtained from a point in the plate-voltage-supply filter system having the correct voltage, or from a separate source.

It is important to note that the plate voltage of tetrodes, pentodes, and beam power tubes should be applied before or simultaneously with the screen voltage. Otherwise, with voltage on the screen only, the screen current may rise high enough to cause excessive screen dissipation.

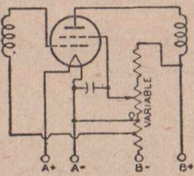


Fig. 67

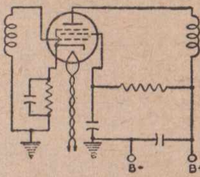


Fig. 68

Screen-voltage variation for the rf amplifier stages has sometimes been used for volume control in older-type receivers. Reduced screen voltage lowers the transconductance of the tube and results in reduced gain per stage. The voltage variation is obtained by means of a potentiometer shunted across the screen voltage supply. See Fig. 67. When the screen voltage is varied, it is essential that the screen voltage never exceed the rating of the tube. This requirement can be met by providing a fixed stop on the potentiometer.

SHIELDING

In high-frequency stages having high gain, the output circuit of each stage must be shielded from the input circuit of that stage. Each high-frequency stage also must be shielded from the other high-frequency stages. Unless shielding is employed, undesired feedback may occur and may produce many harmful effects on receiver performance. To prevent this feedback, it is a desirable practice to shield separately each unit of the high-frequency stages. For instance, in a superheterodyne receiver, each if and rf coil may be mounted in a separate shield can.

Baffle plates may be mounted on the ganged tuning capacitor to shield each section of the capacitor from the other sections. The oscillator coil may be especially well shielded by being mounted under the chassis. The shielding precautions required in a receiver depend on the design of the receiver and the layout of the parts. In all receivers having high-gain high-frequency stages, it is necessary to shield separately each tube in high-frequency stages. When metal tubes, and in particular the single-ended types, are used, complete shielding of each tube is provided by the metal shell which is grounded through its grounding pin at the socket terminal. The grounding connection should be short and heavy. Many modern tubes of glass construction have internal shields connected usually to the cathode and where present are indicated in the socket diagram.

DRESS OF CIRCUIT LEADS

At high frequencies such as are encountered in FM and television receivers, lead dress, that is, the location and arrangement of the leads used for connections in the receiver, is very important. Because even a short lead provides a large impedance at high frequencies, it is necessary to keep all high-frequency leads as short as possible. This precaution is especially important for ground connections and for all connections to bypass capacitors and hf filter capacitors. The ground connections of plate and screen bypass capacitors of each tube should be kept short and made directly to cathode ground.

Particular care should be taken with the lead dress of the input and output circuits of an hf stage so that the possibility of stray coupling is minimized. Unshielded leads connected to shielded components should be dressed close to the chassis. As the frequency increases, the need for paying careful attention to lead dress becomes increasingly important.

In high-gain audio amplifiers, these same precautions should be taken to minimize the possibility of self-oscillation.

FILTERS

Feedback effects also are caused in radio receivers by coupling between stages through common voltage-supply circuits. Filters find an important use in minimizing such effects. They should be placed in voltage-supply leads to each tube in order to return the signal current through a low-impedance path direct to the tube cathode rather than by way of the voltage-supply circuit. Fig. 69 illustrates several forms of filter circuits. Capacitor C forms the low-impedance path, while the choke or resistor assists in diverting the signal through the capacitor by offering a high-impedance to the power-supply circuit.

The choice between a resistor and a choke depends chiefly upon the permissible dc voltage drop through the filter. In circuits where the current is small (a few milliamperes), resistors are practical; where the current is large or regulation important, chokes are more suitable.

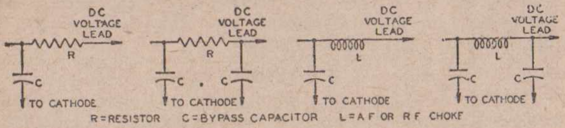


Fig. 69

The minimum practical size of the capacitors may be estimated in most cases by the following rule: The impedance of the capacitor at the lowest frequency amplified should not be more than one-fifth of the impedance of the filter choke or resistor at that frequency. Better results will be obtained in special cases if the ratio is not more than one-tenth. Radio-frequency circuits, particularly at high frequencies, require high-quality capacitors. Mica capacitors are preferable. Where stage shields are employed, filters should be placed within the shield.

Another important application of filters is to smooth the output of a rectifier tube. See **Rectification.** A smoothing filter usually consists of capacitors and iron-core chokes. In any filter-design problem, the load impedance must be considered as an integral part of the filter because the load is an important factor in filter performance. Smoothing effect is obtained from the chokes because they are in series with the load and offer a high impedance to the ripple voltage. Smoothing effect is obtained from the capacitors because they are in parallel with the load and store energy on the voltage peaks; this energy is released on the voltage dips and serves to maintain the voltage at the load substantially constant. Smoothing filters are classified as choke-input or capacitor-input according to whether a choke or capacitor is placed next to the rectifier tube. See Fig. 70.

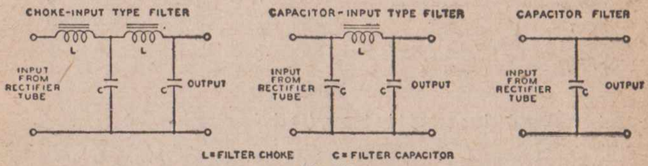


Fig. 70

If an input capacitor is used, consideration must be given to the instantaneous peak value of the ac input voltage. This peak value is about 1.4 times the RMS value as measured by an ac voltmeter. Filter capacitors, therefore, especially the input capacitor, should have a rating high enough to withstand the instantaneous peak value if breakdown is to be avoided. When the input-choke method is used, the available dc output voltage will be somewhat lower than with the input-capacitor method for a given ac plate voltage. However, improved regulation together with lower peak current will be obtained.

Mercury-vapor and gas-filled rectifier tubes occasionally produce a form of local interference in radio receivers through direct radiation or through the power line. This interference is generally identified in the receiver as a broadly tunable 120-cycle buzz (100 cycles for 50-cycle supply line, etc.). It is usually caused by the formation of a steep wave front when plate current within the tube begins to flow on the positive half of each cycle of the ac supply voltage. There are several ways of eliminating this type of interference. One is to shield the tube. Another is to insert an rf choke having an inductance of one millihenry or more between each plate and transformer winding and to connect high-voltage, rf bypass capaci-

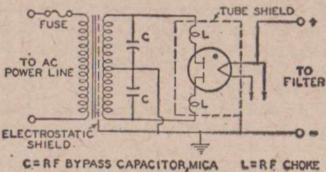


Fig. 71

tors between the outside ends of the transformer winding and the center tap. See Fig. 71. The rf chokes should be placed within the shielding of the tube. The rf bypass capacitors should have a voltage rating high enough to withstand the peak voltage of each half of the secondary, which is approximately 1.4 times the RMS value. Transformers having electrostatic shielding between primary and secondary are not likely to transmit rf disturbances to the line. Often the interference may be eliminated simply by making the plate leads of the rectifier extremely short. In general, the particular method of interference elimination must be selected by experiment for each installation.

OUTPUT-COUPLING DEVICES

An output-coupling device is used in the plate circuit of a power output tube to keep the comparatively high dc plate current from the winding of an electromagnetic speaker and, also, to transfer power efficiently from the output stage to a loudspeaker of either the electromagnetic or dynamic type.

Fig. 72

Output-coupling devices are of two types, (1) choke-capacitor and (2) transformer. The choke-capacitor type includes an iron-core choke with an inductance of not less than 10 henrys which is placed in series with the plate and B-supply. The choke offers a very low resistance to the dc plate current component of the signal voltage but opposes the flow of the fluctuating component. A bypass capacitor of 2 to 6 μf supplies a path to the speaker winding for the signal voltage. The transformer type is constructed with two separate windings, a primary and a secondary wound on an iron core. This construction permits designing each winding to meet the requirements of its position in the circuit. Typical arrangements of each type of coupling device are shown in Fig. 72. Examples of transformers for push-pull stages are shown in several of the circuits given in the CIRCUIT SECTION.

Interpretation of Tube Data

The tube data given include ratings, typical operation values, characteristics, and characteristic curves.

The values for grid-bias voltages, electrode voltages, and electrode supply voltages are given with reference to a specified **datum point** as follows: For types having filaments heated with dc, the negative filament terminal is taken as the datum point to which other electrode voltages are referred. For types having filaments heated with ac, the mid-point (i.e., the center tap on the filament-transformer secondary, or the mid-point on a resistor shunting the filament) is taken as the datum point. For types having unipotential cathodes indirectly heated, the cathode is taken as the datum point.

Electrode voltage and current **ratings** are in general self-explanatory, but a brief explanation of other ratings will aid in the understanding and interpretation of tube data.

Plate dissipation is the power dissipated in the form of heat by the plate as a result of electron bombardment. It is the difference between the power supplied to the plate of the tube and the power delivered by the tube to the load.

Screen dissipation is the power dissipated in the form of heat by the screen as a result of electron bombardment. With tetrodes and pentodes, the power dissipated in the screen circuit is added to the power in the plate circuit to obtain the total B-supply input power.

Peak heater-cathode voltage is the highest instantaneous value of voltage that a tube can safely stand between its heater and cathode. This rating is applied to tubes having a separate cathode terminal and used in applications where excessive voltage may be introduced between heater and cathode.

Maximum peak inverse plate voltage is the highest instantaneous plate voltage which the tube can withstand recurrently in the direction opposite to that in which it is designed to pass current. For mercury-vapor tubes and gas-filled tubes, it is the safe top value to prevent arc-back in the tube operating within the specified temperature range. Referring to Fig. 73, when plate A of a full-wave rectifier tube is positive, current flows from A to C, but not from B to C, because B is negative. At the instant plate A is positive, the filament is positive (at high voltage) with respect to plate B. The voltage between the positive filament and the negative plate B is in inverse relation to that causing current flow. The peak value of this voltage is limited by the resistance and nature of the path between plate B and filament. The maximum value of this voltage at which there is no danger of breakdown of the tube is known as maximum peak inverse voltage. The relations between peak inverse voltage, RMS value of ac input voltage, and dc output voltage depend largely on the individual characteristics of the rectifier circuit and the power supply. The presence of line surges or any other transient, or wave-form distortion may raise the actual peak voltage to a value higher than that calculated for sine-wave voltages. Therefore, the actual inverse voltage, and not the calculated value, should be such as not to exceed the rated maximum peak inverse voltage for the rectifier tube. A calibrated cathode-ray oscillograph or a peak-indicating electronic voltmeter is useful in determining the actual peak inverse voltage. In single-phase, full-wave circuits with sine-wave input and with no capacitor across the output, the peak inverse voltage on a rectifier tube is approximately 1.4 times the RMS value of the plate voltage applied to the tube. In single-phase, half-wave circuits with sine-wave input and with capacitor input to the filter, the peak inverse voltage may be as high as 2.8 times the RMS value of the applied plate voltage. In polyphase circuits, mathematical determination of peak inverse voltage requires the use of vectors.

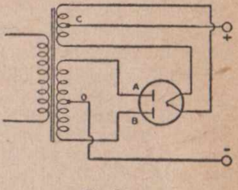


Fig. 73

Maximum peak plate current is the highest instantaneous plate current that a tube can safely carry recurrently in the direction of normal current flow. The safe value of this peak current in hot-cathode types of rectifier tubes is a function of the electron emission available and the duration of the pulsating current flow from the rectifier tube in each half-cycle.

The value of peak plate current in a given rectifier circuit is largely determined by filter constants. If a large choke is used at the filter input, the peak plate current is not much greater than the load current; but if a large capacitor is used at the filter input, the peak current may be many times the load current. In order to determine accurately the peak plate current in any rectifier circuit, measure it with a peak-indicating meter or use an oscillograph.

Maximum dc output current is the highest average plate current which can be handled continuously by a rectifier tube. Its value for any rectifier tube type is based on the permissible plate dissipation of that type. Under operating conditions involving a rapidly repeating duty cycle (steady load), the average plate current may be measured with a dc meter.

Typical Operation Values. Values for typical operation are given for many types These values should not be confused with ratings, because a tube can be used under any suitable conditions within its maximum ratings, according to the application.

The power output value for any operating condition is an approximate tube output—that is, plate input minus plate loss. Circuit losses must be subtracted from tube output in order to determine the useful output.

Characteristics are covered in the ELECTRON TUBE CHARACTERISTICS SECTION and such data should be interpreted in accordance with the definitions given in that section. **Characteristic curves** represent the characteristics of an average tube. Individual tubes, like any manufactured product, may have characteristics that range above or below the values given in the characteristic curves.

Although some curves are extended well beyond the maximum ratings of the tube, this extension has been made only for convenience in calculations. Do NOT operate a tube outside of its maximum ratings.

All tubes are rated according to the "**design-center system**" as given in RMA Standard M8-210. This standard takes into account the normal voltage variations of the various power-supply sources used for modern radio receivers. The Standard M8-210, used with permission of the Engineering Department of the Radio Manufacturers Association, follows:

It shall be standard to interpret the ratings on receiving types of tubes according to the following conditions:

1. CATHODE—The heater or filament voltage is given as a normal value unless otherwise stated. This means that transformers or resistances in the heater or filament circuit should be designed to operate the heater or filament at rated value for full-load operating conditions under average supply-voltage conditions. A reasonable amount of leeway is incorporated in the cathode design so that moderate fluctuations of heater or filament voltage downward will not cause marked falling off in response; also moderate voltage fluctuations upward will not reduce the life of the cathode to an unsatisfactory degree.

A. 1.4-Volt Battery Tube Types.—The filament power supply may be obtained from dry-cell batteries, from storage batteries, or from a power line. With dry-cell battery supply, the filament may be connected either directly across a battery rated at a terminal potential of 1.5 volts, or in series with the filaments of similar tubes across a power supply consisting of dry cells in series. In either case, the voltage across each 1.4-volt section of filament should not exceed 1.6 volts. With power-line or storage-battery supply, the filament may be operated in series with the filaments of similar tubes. For such operation, design adjustments should be made so that, with tubes of rated characteristics, operating with all electrode voltages applied and on a normal line voltage of 117 volts or on a normal storage-battery voltage of 2.0 volts per cell (without a charger) or 2.2 volts per cell (with a charger), the voltage drop across each 1.4-volt section of filament will be maintained within a range of 1.25 to 1.4 volts with a nominal center of 1.3 volts. In order to meet the recommended conditions for operating filaments in series from dry-battery, storage-battery, or power-line sources it may be necessary to use shunting resistors across the individual 1.4-volt sections of filament.

B. 2.0-Volt Battery Tube Types—The 2.0-volt line of tubes is designed to be operated with 2.0 volts across the filament. In all cases the operating voltage range should be maintained within the limits of 1.8 volts to 2.2 volts.

2. POSITIVE POTENTIAL ELECTRODES—The power sources for the operation of radio equipment are subject to variations in their terminal potential. Consequently, the maximum ratings shown on the tube-type data sheets have been established for certain Design Center Voltages which experience has shown to be representative. The Design Center Voltages to be used for the various power supplies together with other rating considerations are as given below:

A. AC or DC Power Line Service in U.S.A. The design center voltage for this type of power supply is 117 volts. The maximum ratings of plate voltages, screen-supply voltages, dissipations, and rectifier output currents are design maximums and should not be exceeded in equipment operated at a line voltage of 117 volts.

B. Storage-Battery Service—When storage-battery equipment is operated without a charger, it should be designed so that the published maximum values of plate voltages, screen-supply voltages, dissipations, and rectifier output currents are never exceeded for a terminal potential at the battery source of 2.0 volts per cell. When storage-battery equipment is operated with a charger, it should be designed so that 90% of the same maximum values is never exceeded for a terminal potential at the battery source of 2.2 volts.

C. "B"-Battery Service—The design center voltage for "B" batteries is the normal voltage rating of the battery block, such as 45 volts, 90 volts, etc. Equipment should be designed so that under no condition of battery voltage will the plate voltages, the screen-supply voltages, or dissipations ever exceed the recommended respective maximum values shown in the data for each tube type by more than 10%.

D. Other Considerations—

a. Class A_1 Amplifiers—The maximum plate dissipation occurs at the "Zero-Signal" condition. The maximum screen dissipation usually occurs at the condition where the peak-input signal voltage is equal to the bias voltage.

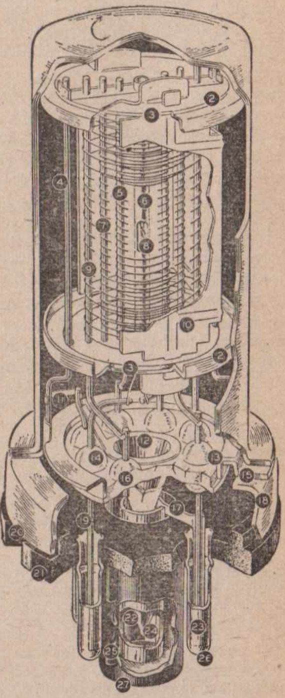
b. Class B Amplifiers—The maximum plate dissipation theoretically occurs at approximately 63% of the "Maximum-Signal" condition, but practically may occur at any signal voltage value.

c. Converters—The maximum plate dissipation occurs at the "Zero-Signal" condition and the frequency at which the oscillator-developed bias is a minimum. The screen dissipation for any reasonable variation in signal voltage must never exceed the rated value by more than 10%.

d. Screen Ratings—When the screen voltage is supplied through a series voltage-dropping resistor, the maximum screen voltage rating may be exceeded, provided the maximum screen dissipation rating is not exceeded at any signal condition, and the maximum screen voltage rating is not exceeded at the maximum-signal condition. Provided these conditions are fulfilled, the screen-supply voltage may be as high as, but not above, the maximum plate voltage rating.

3. TYPICAL OPERATION—For many receiving tubes, the data show typical operating conditions in particular services. These typical operating values are given to show concisely some guiding information for the use of each type. They are not to be considered as ratings, because the tube can be used under any suitable conditions within its rating limitations.

1 – Metal Envelope
2 – Spacer Shield
3 – Insulating Spacer
4 – Mount Support
5 – Control Grid
6 – Coated Cathode
7 – Screen
8 – Heater
9 – Suppressor
10 – Plate
11 – Batalum Getter
12 – Conical Stem Shield
13 – Header
14 – Glass Seal
15 – Header Insert
16 – Glass-Button Stem Seal
17 – Cylindrical Base Shield
18 – Header Skirt
19 – Lead Wire
20 – Crimped Lock
21 – Octal Base
22 – Exhaust Tube
23 – Base Pin



1¾ times actual size

24 – Exhaust Tip
25 – Aligning Key
26 – Solder
27 – Aligning Plug

Structure of a Metal Tube

Electron Tube Testing

The electron tube user—service man, experimenter, or non-technical radio listener—is interested in knowing the condition of his tubes, since they govern the performance of the device in which they are used. In order to determine the condition of a tube, some method of test is necessary. Because the operating capabilities and design features of a tube are indicated and described by its electrical characteristics, a tube is tested by measuring its characteristics and comparing them with values established as standard for that type. Tubes which read abnormally high with respect to the standard for the type are subject to criticism just the same as tubes which are too low.

Certain practical limitations are placed on the accuracy with which a tube test can be correlated with actual tube performance. These limitations make it unnecessary for the service man and dealer to employ complex and costly testing equipment having laboratory accuracy. Because the accuracy of the tube-testing device need be no greater than the accuracy of the correlation between test results and receiver performance, and since certain fundamental characteristics are virtually fixed by the manufacturing technique of leading tube manufacturers, it is possible to employ a relatively simple test in order to determine the serviceability of a tube.

In view of these factors, dealers and service men will find it economically expedient to obtain adequate accuracy and simplicity of operation by employing a device which indicates the status of a single characteristic. Whether the tube is satisfactory or unsatisfactory is judged from the test result of this single characteristic. Consequently, it is very desirable that the characteristic selected for the test be one which is truly representative of the tube's overall condition.

The following information and circuits are given to describe and illustrate general theoretical and practical tube-tester considerations and not to provide information on the construction of a home-made tube tester. In addition to the problem of determining what tube characteristic is most representative of performance capabilities in all types of receivers, the designer of a home-made tester faces the difficult problem of determining satisfactory limits for his particular tester. The obtaining of information of this nature, if it is to be accurate and useful, is a tremendous job. It requires the testing of a large number of tubes of each type, the testing of many types, and the correlation of these readings with performance in many kinds of equipment.

SHORT CIRCUIT TEST

The fundamental circuit of a short-circuit tester is shown in Fig. 74. Although this circuit is suitable for tetrodes and types having less than four electrodes, tubes of more electrodes may be tested by adding more indicator lamps to the circuit. Voltages are applied between the various electrodes with lamps in series with the electrode leads. The value of the voltages applied will depend on the type of tube being tested. Any two shorted electrodes complete a circuit and light one or more lamps. Since two electrodes may be just touching to give a high-resistance short, it is desirable that the indicating lamps operate on very low current. It is also desirable to maintain the filament or heater of the

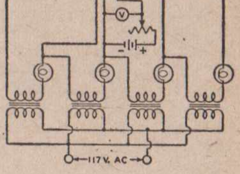


Fig. 74

tube at its operating temperature during the short-circuit test, because short-circuits in a tube may sometimes occur only when the electrodes are heated.

SELECTION OF A SUITABLE CHARACTERISTIC FOR TEST

Some charcteristics of a tube are far more important in determining its operating worth than are others. The cost of building a device to measure any one of the more important characteristics may be considerably higher than that of a device which measures a less representative characteristic. Consequently, three methods of test will be discussed, ranging from relatively simple and inexpensive equipment to more elaborate, more accurate, and more costly devices.

An emission test is perhaps the simplest method of indicating a tube's condition. (Refer to **Diodes,** in ELECTRONS, ELECTRODES, AND ELECTRON TUBES SECTION, for a discussion of electron emission.) Since emission falls off as the tube wears out, low emission is indicative of the end of tube serviceability. However, the emission test is subject to limitations because it tests the tube under static conditions and does not take into account the actual operation of the tube. On the one hand, coated filaments, or cathodes, often develop active spots from which the emission is so great that the relatively small grid area adjacent to these spots cannot control the electron stream. Under these conditions, the total emission may indicate the tube to be normal although the tube is unsatisfactory. On the other hand, coated types of filaments are capable of such large emission that the tube will often operate satisfactorily after the emission has fallen far below the original value.

Fig. 75 shows the fundamental circuit diagram for an emission test. All of the electrodes of the tube, except the cathode, are connected to the plate. The filament, or heater, is operated at rated voltage; after the tube has reached constant temperature, a low positive voltage is applied to the plate and the electron emission is read on the meter. Readings which are well below the average for a particular tube type indicate that the total number of available electrons has been so reduced that the tube is no longer able to function properly.

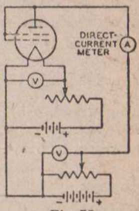


Fig. 75

A transconductance test takes into account a fundamental operating principle of the tube. (This will be seen from the definition of transconductance in the Section on ELECTRON TUBE CHARACTERISTICS.) It follows that transconductance tests when properly made, permit better correlation between test results and actual performance than does a straight emission test.

There are two forms of transconductance test which can be utilized in a tube tester. In the first form (illustrated by Fig. 76 giving a fundamental circuit with a tetrode under test), appropriate operating voltages are applied to the electrodes of the tube. A plate current depending upon the electrode voltages, will then be indicated by the meter. If the bias on the grid is then shifted by the application of a different grid voltage, a new plate-current reading is obtained. The difference between the two plate-current readings is indicative of the transconductance of the tube. This method of transconductance testing is commonly called the "grid-shift" method, and depends on readings under static conditions. The fact that this form of test is made under static conditions imposes limitations not encountered in the second form of test made under dynamic conditions.

The dynamic transconductance test illustrated in Fig. 77 gives a fundamental circuit with a tetrode under test. This method is superior to the static transconductance test in that ac voltage is applied to the grid. Thus, the tube is tested

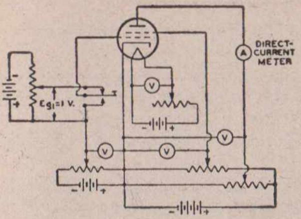


Fig. 76

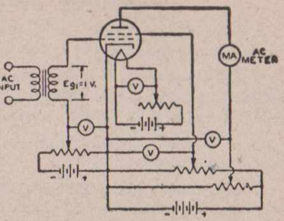


Fig. 77

under conditions which approximate actual operating conditions. The alternating component of the plate current is read by means of an ac ammeter of the dynamometer type. The transconductance of the tube is equal to the ac plate current divided by the input-signal voltage. If a one-volt RMS signal is applied to the grid, the plate-current-meter reading in milliamperes multiplied by one thousand is the value of transconductance in micromhos.

The **power-output test** probably gives the best correlation between test results and actual operating performance of a tube. In the case of voltage amplifiers, the power output is indicative of the amplification and output voltages obtainable from the tube. In the case of power-output tubes, the performance of the tube is closely checked. Consequently, although more complicated to set up, the power-output test will give closer correlation with actual performance than any other single test.

Fig. 78 shows the fundamental circuit of a power-output test for class A operation of tubes. The diagram illustrates the method for a pentode. The ac output voltage developed across the plate-load impedance (L) is indicated by the current meter. The current meter is isolated as far as the dc plate current is concerned by the capacitor (C). The power output can be calculated from the current reading and known load resistance. In this way, it is possible to determine the operating condition of the tube quite accurately.

Fig. 79 shows the fundamental circuit of a power-output test for class B operation of tubes. With ac voltage applied to the grid of the tube, the current in the plate circuit is read on a dc milliammeter. The power output of the tube is approximately equal to:

$$\text{Power output (watts)} = \frac{(\text{dc current in amperes})^2 \times \text{load resistance in ohms}}{0.405}$$

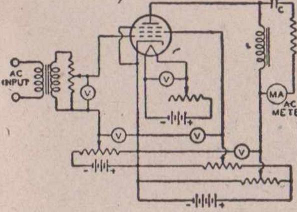


Fig. 78

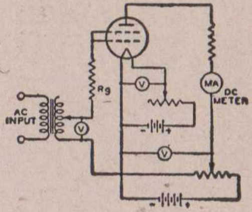


Fig. 79

ESSENTIAL TUBE-TESTER REQUIREMENTS

1. It is desirable that the tester provide for a short-circuit test to be made prior to measurement of the tube's characteristics.

2. It is important that some means of controlling the voltages applied to the electrodes of the tube be provided. If the tester is ac operated, a line-voltage control permits the supply of proper electrode voltages.

3. It is essential that the rated voltage applied to the filament or heater be maintained accurately.

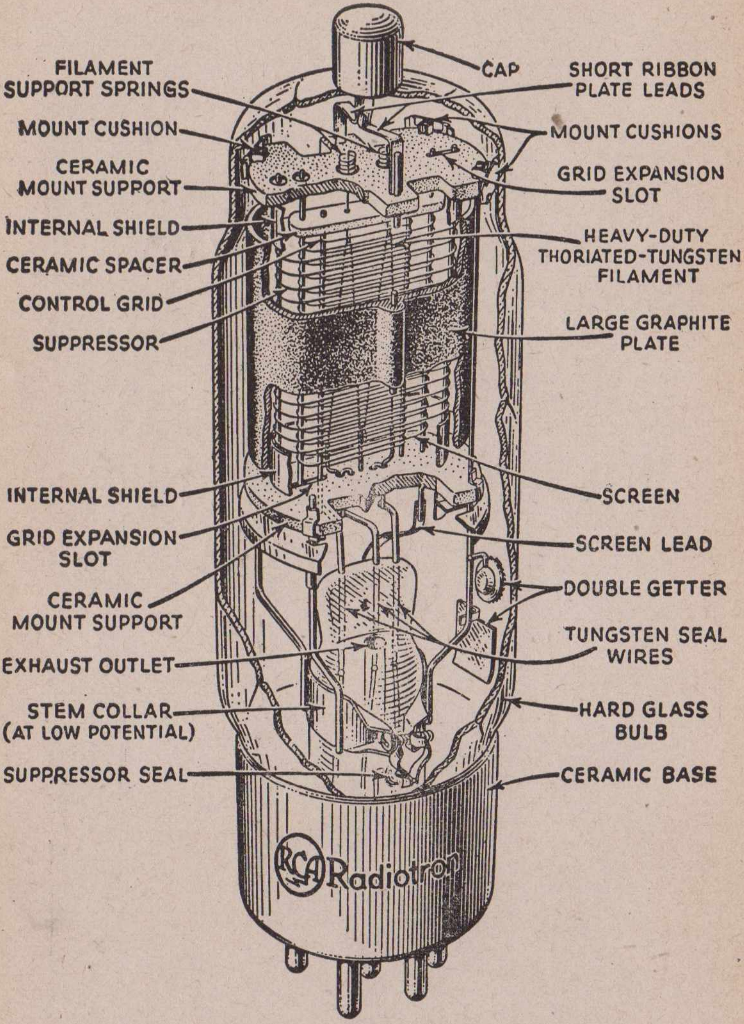
4. It is suggested that the characteristics test follow one of the methods described. The method selected and the quality of the parts used in the test will depend upon the requirements of the user.

TUBE-TESTER LIMITATIONS

A tube-testing device can only indicate the difference between a given tube's characteristics and those which are standard for that particular type. Since the operating conditions imposed upon a tube of a given type may vary within wide limits, it is impossible for a tube-testing device to evaluate tubes in terms of performance capabilities for all applications. The tube tester, therefore, cannot be looked upon as a final authority in determining whether or not a tube is always satisfactory. Actual operating test in the equipment in which the tube is to be used will give the best possible indication of a tube's worth.

SECTION TWO

TRANSMITTING TUBES



STRUCTURE OF TRANSMITTING PENTODE

GENERAL VACUUM TUBE CONSIDERATIONS

A radio vacuum tube, whether designed for receiving or transmitting service, consists of a cathode and one or more additional electrodes — all contained in an evacuated enclosure — with their electrical connections brought out to external terminals. The evacuated enclosure may be made of glass, metal, or a combination of glass and metal. The cathode supplies electrons while the other electrodes control and collect them.

CATHODES

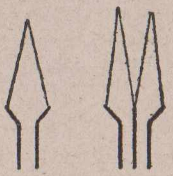
A **cathode** is an essential part of a radio tube, because it supplies the electrons necessary for tube operation. In general, heat energy is applied to the cathode to cause it to release electrons. The method of heating the cathode may be used to identify different forms of cathodes. For example, a directly heated cathode, or **filament cathode,** is a wire heated by the passage of an electric current. An indirectly heated cathode, or **heater cathode,** consists of a filament (heater) enclosed by and insulated from a closely fitting metal sleeve (cathode) which is coated with electron-emitting material. The cathode is heated by radiation and conduction from the heater.

A filament, or directly heated cathode, can be further classified by identifying the filament or electron emitting material. The materials in regular use are tungsten, thoriated tungsten, and metals which have been coated with alkaline-earth oxides.

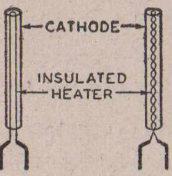
A very important characteristic of any cathode is its electron-emitting ability for a given amount of heat energy. This characteristic, called **emission efficiency,** is the electron space current in amperes per watt of filament or heater power. For convenience, emission efficiency is usually expressed in milliamperes per watt.

Tungsten Cathodes

Directly heated tungsten-filament cathodes are made from the pure metal. Because tungsten filaments must operate at a high temperature (a dazzling white) to emit electrons in useful quantity, tungsten requires a relatively large amount of filament-heating power; in other words, its emission efficiency is low. The large filament power dissipation requires a relatively large bulb for a fixed plate dissipation, or reduces the permissible plate dissipation for a bulb of fixed size.



DIRECTLY HEATED CATHODES
(FILAMENT TYPE)



INDIRECTLY HEATED CATHODES
(HEATER TYPE)

Advantages of tungsten as a cathode material are its ruggedness and its ability to withstand relatively heavy positive-ion bombardment in high-voltage tubes. This bombardment, resulting from the presence of minute amounts of residual gas, is naturally more severe at higher plate voltages. Cathode materials which depend on a thin, active surface layer for their emission may quickly have this layer sputtered away by positive ions, with a resulting loss in emissivity. In the case of tungsten, the emission is an inherent property of the metal itself, so that there is no loss in emission even if some of the surface is sputtered away by positive-ion bombardment.

Coated Cathodes

Coated cathodes are of two general types—the directly heated filament cathode and the indirectly heated cathode. The coated-filament type of cathode consists usually of a nickel-alloy wire or ribbon coated with a mixture containing certain alkaline earth oxides. This coating, consisting of a substantial layer on the filament wire, requires a very low temperature (a dull red) to produce a copious supply of electrons. Coated-filament cathodes, therefore, require relatively little heat energy, and have a high emission efficiency—many times that of tungsten.

A heater cathode comprises an assembly of a thin metal sleeve, coated with an active material similar to that employed on coated-type filaments, and a heater element contained within and insulated from the sleeve. The heater is usually made of tungsten wire, or of a tungsten-molybdenum alloy, and is used solely for the purpose of heating the coated sleeve (actual cathode) to an electron-emitting temperature. The sleeve is heated by conduction and radiation from the heater. Due to the fact that the coated cathode is isolated electrically from the filament heating source, it is also called an **unipotential cathode**; unlike filament-type cathodes, it has no voltage drop along its length due to a heating current.

Advantages of the coated cathode are its high emission efficiency, relative freedom from filament or heater burn-out, low operating temperature, and its comparatively low hum level (especially in the unipotential-cathode type).

A disadvantage of the coated cathode is its tendency to contaminate adjacent electrodes with small quantities of active emitting material, so that emission from these electrodes may take place at relatively low temperatures. Despite their high emission efficiency, coated cathodes have been used in transmitting tubes principally in small, low-voltage types where operating temperatures of the electrodes are relatively low.

Thoriated-Tungsten Cathodes

Thoriated-tungsten-filament cathodes are drawn from tungsten slugs which have been impregnated with thoria. In processing, a surface layer of thorium is formed; as a result, these cathodes liberate electrons at a medium temperature (a bright yellow). They have an emission efficiency between that of pure tungsten and coated cathodes.

Thoriated-tungsten filaments are suitable for use in tubes operating at a fairly high voltage. They are not used in tubes operating at extremely high voltages because the surface layer of thorium may be sputtered off by positive-ion bombardment; this results in loss of emission. Thoriated-tungsten filaments are substantially free from grid-emission effects and possess the unique capability of being reactivated (in many cases) after their emission has been lost because of temporary tube overloads. Information regarding the reactivation of thoriated-tungsten filaments is given under TRANSMITTING-TUBE INSTALLATION.

The choice of cathode material for a transmitting tube depends upon the service for which the tube is designed. The plate voltage to be used on the tube is an important factor, as is also the cathode emission required. In general, coated cathodes have been employed in small, low-voltage tubes; thoriated-tungsten filaments have been used in medium power tubes operating at fairly high voltages, and tungsten filaments have been used in large, high power tubes operating at very high voltages. However, design requirements control the choice of cathode material for specific tube types.

ANODES

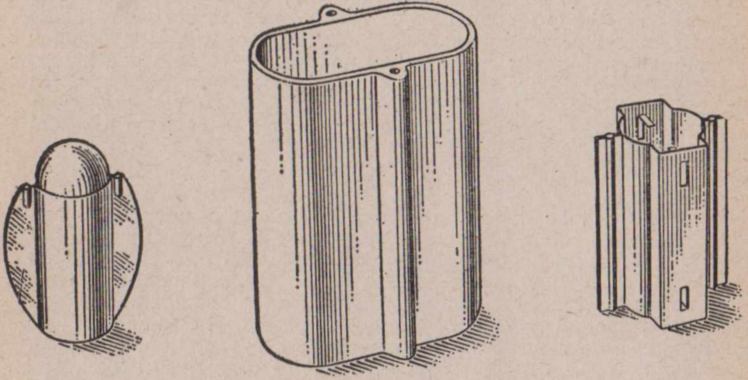
For any tube there is a maximum amount of power that can be dissipated safely by the anode, or plate, if reasonable tube life is to be obtained. The safe anode dissipation of a transmitting tube is one of the most important factors controlling the amount of power the tube will deliver. Anodes can be classified according to the principal method of cooling employed. In some types of tubes the anodes are cooled almost entirely by radiation; in others, by conduction. Only the first type will be considered here.

In a radiation-cooled tube, the anode is operated at a fairly high temperature and heat is radiated directly by the anode to and through the walls of the bulb (generally of glass). It is usually necessary to operate such anodes at fairly high temperatures in order to keep their physical dimensions commensurate with the desired electrical characteristics of the tubes.

Operation of anodes at such high temperatures brings up numerous problems. The liberation of gases from the anode itself is one of the most important. In the raw state, all materials suitable for anodes contain gases—mainly hydrogen, nitrogen, carbon monoxide, and carbon dioxide—which are present throughout the body of the material. The major portion of these gases must be driven out of the anode during the manufacture of a tube so that in subsequent normal operation no appreciable quantities of gas are liberated. The assembled tube is sealed to a vacuum system where the glass bulb can be "baked" to free it of adsorbed gases. The anodes are heated in two ways. One method is to supply a high positive voltage to the anode and bombard it with electrons from the cathode. Another method is to place around the glass bulb a coil carrying high-frequency currents. The anode then acts as a short-circuited secondary of a transformer and is heated to a high temperature by induced currents.

Some of the most important considerations in the choice of an anode material for radiation-cooled tubes are its thermal emissivity, its mechanical properties, and its vapor pressure.

The thermal emissivity should approach as nearly as possible the ideal of a black body, in order to obtain the highest dissipation rating for a given anode design and anode operating temperature (the temperature being determined by gas liberation). At first thought it might appear that the size of the anode could be increased to get the desired dissipation rating for an anode of a given material. However, this usually results in an increase in the electrostatic capacitance between the anode and the other tube electrodes; it also increases the weight of the anode which means heavier mounting supports and a larger mass of material from which gases must be removed. Because of the pronounced trend to higher frequencies in radio communication, it is important to keep interelectrode capacitances to a minimum so that capitance charging currents, which entail losses, can be limited to reasonable values.



Typical Anode Structures.

The mechanical properties of an anode material are very important. The material must be capable of being worked readily into the desired shapes and must maintain these shapes at the high temperatures employed during tube manufacture. Only a very small amount of warping can be tolerated at the normal operating temperature, because warping may produce a change in the electrical characteristics of a tube.

The vapor pressure of an anode material must be low enough so as not to cause appreciable metallic deposits in a tube during manufacture. Such deposits on the insulators in a tube may result in excessive interelectrode leakage or in excessive radio-frequency losses in the insulators.

Various materials have been used for transmitting-tube anodes. A brief description of the materials which have been most widely used is given in the following paragraphs.

Tungsten

Tungsten was one of the first materials employed for anodes in air-cooled tubes. From the standpoint of gas content, ease of degassing, vapor pressure, and maintenance of mechanical shape at high temperatures, tungsten is a satisfactory material for anodes. However, from the standpoint of workability, tungsten has a serious disadvantage. It is difficult to fabricate into the desired shapes and is, therefore, little used at present as an anode material.

Molybdenum

The characteristics of the metal molybdenum make it suitable for use as an anode material. Although its thermal emissivity is rather low, molybdenum degases readily and is much more workable than tungsten. The heat-dissipating ability of molybdenum anodes is improved by the addition of fins (e.g., such as in type 852), which increase the radiating area of the anode. Further improvement is obtained when the anode surface is roughened by means of carborundum blasting.

Graphite

Graphite is used as an anode material in many radiation-cooled tube types. Although graphite contains considerably more adsorbed gases than either tungsten or molybdenum, these gases can be largely removed by suitable manufacturing technique. This includes pretreatment of graphite anodes before the tubes are assembled.

The thermal emissivity of graphite depends on the treatment the surface has received. Compared with molybdenum anodes, graphite anodes operate at a visibly lower temperature for the same power dissipation. Some users of transmittting tubes find it convenient to judge the operating efficiency of a tube by observing the color temperature of the anode. With tungstem, molybdenum, and tantalum anodes this is easily possible, because at the normal operating temperature the anodes are distinctly cherry- or orange-red in color. With graphite, however, practically no color can be seen in normal operation so that it is very difficult to judge visually how much energy is being dissipated by the anode.

Graphite anodes are made with relatively thick walls for mechanical strength. They are not subject to warping and have the further advantage that their good heat conductivity, due to the thick walls, prevents "hot spots." The absence of hot spots means that the graphite anode radiates heat almost uniformly over its entire surface. Because graphite, as ordinarily termed, is a complex mixture of a variety of carbon forms, some of which produce undesirable effects in anodes, careful selection and processing of graphite anode material is essential.

Mechanically, graphite presents no serious problems. It is a soft material and, therefore, can readily be formed into the desired shapes. The vapor pressure of graphite is low enough that bulb blackening can be avoided during the exhausting of a tube.

Nickel

Because of the relatively low melting point of nickel, this anode material is used principally in tubes where the anode operating temperature is moderate. Although the thermal emissivity of nickel is not high, this material lends itself readily to a process called carbonizing. In this process, a well-adhering layer of amorphous carbon is deposited on the nickel anode to provide a thermal emissivity approaching that of a black body. Nickel is formed readily into the shapes desired for anodes. Care must be exercised in the design of the anode to avoid warping during exhaust. Like other metal anode materials, nickel has the advantage of light weight, so that elaborate supporting structures are not needed.

Tantalum

A metal which is finding increasing use as an anode material is tantalum. Although the properties of this material have been known for many years, it has been used commercially in transmitting tubes for a relatively short time. The appearance and many of the characteristics of tantalum are similar to those of molybdenum. Tantalum has the same metallic luster, a slightly higher melting point, a lower vapor pressure, and is more easily worked into various mechanical shapes. The principal advantage of tantalum is that it will clean up gases and, thus, is capable of helping to maintain a high vacuum in a tube during normal operation. Sudden tube overloads of short duration do not cause tantalum anodes to liberate appreciable gas.

Tantalum anodes are usually made with fins and with a rough surface to increase the effective heat-radiating area. Under conditions of maximum rated plate dissipation, tantalum anodes will show a red to orange-red color. They will normally show some color even when the tubes are lightly loaded. The color characteristic of tantalum anodes serves as a rough indication of the power being dissipated.

Tubes such as the 808, 833, and 861 are examples of tantalum-anode construction.

GRIDS

The metals and alloys suitable for anode material are, in general, also useful for grid structures. Like anode materials, a good grid material should have resonably low gas content, should be easy to degas, and should have sufficient mechanical strength to hold its shape while operating at very high temperatures. A very small change in the shape of a control-grid structure results in a relatively large change in tube characteristics. Grid material should be suited for drawing into wire, because grids are often formed of spirally wound wire supported by metal side rods.

An important consideration in the choice of grid material is the electron-emitting characteristic of the material, especially in the presence of other elements which may be used in tube manufacture. In most types of r-f service the grid is driven positive part of the time, so that the grid is bombarded by electrons and must dissipate some power. If the grid material is active enough, or the grid temperature gets high enough, primary grid emission may take place. This effect should be minimized in tube operation because it may result in loss of grid bias if a grid leak is employed. Grid structures are sometimes pretreated in various manners to reduce primary grid emission.

When the control grid is driven positive, the primary electrons which bombard it may dislodge secondary electrons. This effect called **secondary emission**, may also cause a loss of grid bias, and must be minimized by proper choice of grid materials and by suitable processing methods.

Some of the metals used for grids are tungsten, molybdenum, tantalum, and also nickel alloys, such as magno-nickel. The latter is an alloy of nickel and manganese. Alloys of molybdenum and tungsten are also employed. Grid materials in some cases are coated with carbon to reduce secondary-emisssion effects and to increase thermal emissivity.

BULBS

The kind of glass used in the manufacture of bulbs for transmitting tubes must meet specific requirements. It must have good mechanical strength, be a good electrical insulator, stand high temperatures and should be easily freed of adsorbed gases.

Where heat-dissipation requirements are moderate and where bulb size is not especially important, so-called "soft" glass is a suitable material. If the bulb size must be kept small, "hard" glass is employed. The important physical distinction between soft glass and hard glass is that the latter has an appreciably higher softening point (about 750°C compared to 625°C). Hard glass is generally employed for the larger air-cooled tube types, where bulb size is an important factor.

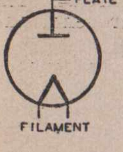
BASES

Base materials are of two general types—**ceramic** and **plastic.** Ceramics include glass (usually Pyrex) and various silicates, of which porcelain is an example. The plastic material in common use is Bakelite. Some tube bases are composed of metal shells with an insulating bottom disc.

The better grades of ceramic insulators cause less radio-frequency losses at high frequencies than most plastics suitable for use in bases. However, the use of ceramic bases is generally limited to tubes where fairly high r-f voltages appear between some of the base pins.

GENERIC TUBE TYPES

DIODES



The simplest form of radio vacuum tube is the two-electrode type consisting of a cathode and an anode, or plate. This type, called a **diode,** is used in transmitting service mainly as a rectifier to convert low-frequency a-c voltages from the power line to d-c voltages for plate, screen, and grid-bias supplies. Simple diodes, such as the 866, are called **half-wave** rectifiers because they rectify but one-half of each alternating voltage cycle. When two diodes are enclosed in a single envelope, the tube is called a **full-wave** rectifier because it rectifies both halves of each a-c cycle. The receiving types 5Z3 and 83 are typical examples.

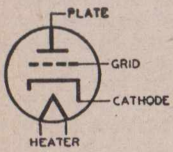
Both half- and full-wave rectifiers are of two general types—high-vacuum and mercury-vapor. The latter type, represented by the 866 and the 83, is characterized by a very low and approximately constant internal voltage drop, amounting to about 15 volts. This drop is practically independent of d-c load current, but depends to some extent upon the temperature of the mercury vapor within the bulb. Mercury-vapor rectifiers, in operation, have a characteristic bluish glow which fills a considerable portion of the bulb. The extent of the glow depends on the value of the d-c load current.

Due to their low and relatively constant internal voltage drop, mercury-vapor retifiers are very useful in applications where excellent voltage regulation of the d-c power supply is desired. Class B modulators represent one such application.

High-vacuum rectifiers have an internal voltage drop which is proportional to the d-c load current being drawn. With varying d.c. load currents they do not, in general, provide the good voltage regulation obtained from mercury-vapor rectifiers. Some high-vacuum rectifiers, such as the 836, are designed with close-spaced electrodes, so that a voltage regulation almost as good as that of a mercury-vapor type is obtained.

Additional information on rectifiers is given under RECTIFIERS AND FILTERS.

TRIODES



When a third electrode, called the **control grid,** or simply **grid,** is placed between the cathode and the plate, the tube is known as a triode. The grid usually consists of a wire mesh, spiral, or grating, the appearance of which suggests its name.

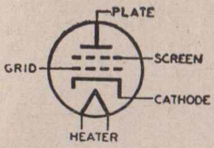
When the grid of a triode is made positive or negative with respect to the cathode, the plate current correspondingly increases or decreases. This action makes possible the use of a triode as an amplifier. The electrical impulse to be amplified is applied to the grid of the tube and thus controls electrostatically the flow of electrons from the cathode to the plate. The energy required to draw the electrons to the plate comes from a high-voltage d.c. supply in the plate circuit. The power required to vary the electron stream from the cathode to the plate ordinarily is only a fraction of the power flowing in the plate circuit. Therefore, the action of the tube is that of a valve, the d.c. power of the high-voltage plate supply being converted by the grid-voltage variations into a.c. power in the plate load circuit. The efficiency of this energy conversion is never 100 per cent., and some power is dissipated by the plate of the tube.

Triodes are used in transmitters as oscillators, frequency multipliers, r-f power amplifiers, a-f amplifiers, modulators, and for various special purposes. Some types are especially designed for audio power-amplifier service, but most types can be used in either r-f or a-f applications.

The grid, plate, and cathode of a triode form an electrostatic system, each electrode acting as one plate of a small condenser. The capacitances are those existing between the grid and plate, plate and cathode, and grid and cathode. These capacitances, as well as those of tubes having additional electrodes, are known as **interelectrode capacitances.** Generally, the grid-plate capacitance is the most important. In radio-frequency amplifier circuits, this capacitance may act to produce undesired coupling between the input and output circuits and cause uncontrolled regeneration or oscillation.

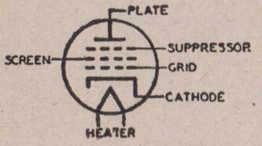
TETRODES AND PENTODES

The effect of grid-plate capacitance in causing excess regeneration can be eliminated in a number of ways. One scheme requires the use of special circuit arrangements which set up counteracting effects to balance out the action of the grid-plate coupling. This method is known as **neutralization.** A second and preferable method is to reduce the grid-plate capacitance in the tube itself to a negligible value. This is accomplished by employing a fourth electrode in the tube which is known as the **screen.** The screen is placed between the plate and the grid and thus makes a four-electrode tube—hence the name tetrode. With this type of tube, intricate circuits and balancing difficulties can be eliminated.

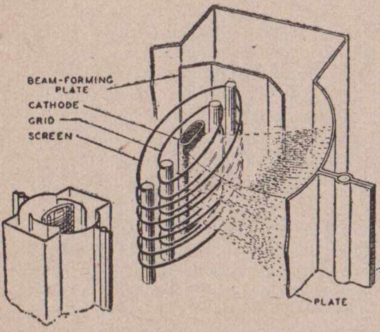


The screen is constructed so that the flow of electrons to the plate is not materially obstructed, yet it serves to establish an electrostatic shield between the plate and the grid. The screen is usually operated at some positive voltage lower than that of the plate and is by-passed to the cathode through a condenser having low impedance at the operating frequency. This by-pass condenser effectively grounds the screen for high-frequency currents and assists in reducing the effective grid-plate capacitance to a minimum value. This reduction permits tetrodes to provide a high order of stable amplification with relatively simple circuits. The 865 and 860 are representative tetrodes.

In all radio tubes, electrons striking a positive electrode may, if moving at sufficient speed, dislodge or "splash out" other or secondary electrons. In diodes and triodes, such secondary electrons produced at the plate usually do not cause any trouble because no positive electrode other than the plate itself is present to attract them. These electrons, therefore, are eventually drawn back to the plate. In tetrodes, the screen (operating at a positive potential) offers a strong attraction to secondary electrons when the plate voltage swings lower that the screen voltage. This effect limits the permissible plate swing for tetrodes because the major portion of the space current then goes to the screen rather than to the plate. The plate-swing limitation can be substantially removed when a fifth electrode, known as the **suppressor,** is placed in the tube between the screen and the plate. Such five-electrode types are called pentodes.



The suppressor in a pentode is usually connected to the cathode, or to a low positive or negative voltage, depending on the tube application. Because of its negative potential (in any case) with respect to the plate, the suppressor retards the flight of secondary electrons and diverts them back to the plate, where they cause no undesirable effects. Thus, in pentodes, the plate voltage may swing below the screen voltage.



In a beam power tube (e.g., type 807), the function of the suppressor grid is performed by a potential minimum which exists between the screen and the plate, suppresses secondary emission from the plate, and which gives the tube pentode characteristics.

In general, pentodes and beam tetrodes have high **power sensitivity**. This means that very little driving power is required in comparison with the power output obtained. For this reason, such tubes are especially useful in multistage transmitters as buffer amplifiers and frequency multipliers. The use of pentodes and beam tetrodes reduces the total number of stages required to obtain a specific power gain. These tubes also find useful application in certain types of oscillator circuits.

A pentode in radio-telephony service can be modulated by means of the suppressor. Under proper operating conditions, modulation of almost 100 per cent. can be obtained with good linearity. Because the suppressor is usually operated at a negative potential over most of the a-f cycle, very little modulating power is required.

TRANSMITTING-TUBE INSTALLATION

Information regarding the required type of socket or mounting is given in the data under each individual tube type. In most cases, the socket is mounted to hold the tube in a vertical position with the base down, although some tubes may be operated in a horizontal position. Exceptions are described under the respective tube types. Where the tube is subjected to vibration or shock, a shock-absorbing suspension should be employed.

The **bulb** becomes very hot during continuous operation of a tube; therefore, free circulation of air around the tube should be provided. Care should be taken that the bulb does not come in contact with any metallic object nor be subjected to the spray of any liquid. The installation of all wires and connections should be made so that they will not be close to or touch the bulb, in order to avoid possible puncture of the glass due to peak voltage effects. In the case of tubes with metal cap terminals, such as the **806, 808,** and **866**, flexible leads should be used to make connections to these terminals in order to minimize strains placed on the glass bulb at the base of the caps. It is important that the caps should not be used to support coils, condensers, chokes, or other circuit parts. Under no circumstances should anything be soldered to the caps, because the heat of the soldering may crack the bulb seals. The flexible leads should be big enough to carry, without notice-able heating, the large circulating r-f currents which flow in the circuits at high frequencies.

The **cathodes** used in transmitting tubes are of several types, as described in GENERAL VACUUM-TUBE CONSIDERATIONS. Filament-type cathodes include thoriated-tungsten filaments and oxide-coated filaments. Indirectly heated oxide-coated cathodes are employed in some tube types.

Thoriated-tungsten filaments, in general, may be operated from either an a.c. or a d.c. source. Except where a d.c. source is necessary to avoid hum, an a.c. filament supply is generally used because of its convenience and economy. Where d.c. is used for the filament supply, the grid and plate returns should be made to the negative filament terminal rather than (as in the case of an a.c. filament supply) to the mid-tap of the filament circuit. For the larger tube types, a suitable voltmeter should be connected permanently across the tube filament terminals to provide a ready check of the filament voltage. This voltage should not vary more than plus or minus 5% from the rated value; otherwise, a loss of filament emission may result. When the apparatus in which the tube is used is idle for short periods of time, the filament should be maintained at its rated voltage during the "stand-bys." When an a.c. filament supply is used, rheostat control is placed preferably in the primary circuit of the filament transformer.

Overheating, by severe overload, of tubes employing thoriated-tungsten filaments may decrease filament emission. The activity of the filament can sometimes be restored by operating the filament at rated voltage for ten minutes or more with no voltages applied to the other electrodes. This process may be accelerated by raising the filament voltage a small amount above its rated value for a few minutes. The maximum voltage which should be used is 9 volts for 7.5-volt types, 12 volts for 10-volt types, and 13 volts for 11-volt types.

Oxide-coated filaments may be operated from either an a.c. or a d.c. source. An a.c. filament supply is generally used because of its convenience and economy. When d.c. is employed, the grid and plate returns should be made to the negative filament terminal, rather than to the electrical centre of the filament circuit as in the case of a.c. filament operation. The voltage across the filament terminals should be checked periodically and should be maintained within plus or minus 5% of the rated value. An oxide-coated filament should be allowed to come up to normal operating temperature before voltage is applied to the plate; otherwise, a loss of filament emission may result. In radio transmitters during "standby" periods, the filament should be kept at its rated voltage to avoid a delay in the resumption of transmission. Data relating to the filament operation of specific tube types (especially rectifiers) are given in the text following the tabulated data on those types.

The **heaters** of those tubes employing indirectly heated cathodes may be operated from either an a.c. or a d.c. supply. A.c. is usually employed because of its convenience and economy. The voltage across the heater terminals at the socket should be checked periodically. In radio transmitters, during "standby" periods, the heater should be maintained at its rated voltage in order that transmissions can be promptly resumed.

The **cathode** should be connected to the electrical mid-point of the heater circuit when the heater is operated from an a.c.

source. Where cathode bias is used, the cathode should be connected to the same point through the cathode-bias resistor. When the heater is operated from a d.c. source, the cathode circuit may be connected to either heater-supply lead. In circuits where the cathode is not tied directly to the heater, the potential difference between them should be kept as low as possible. Recommended values for heater-cathode potential differences are given in the data under the tube types. Where a large resistance is necessary between heater and cathode in some circuit designs, the resistor should be by-passed for both r-f and a-f frequencies, to avoid the possibility of hum and circuit losses.

The **plate dissipation (the difference between plate input and power output) should never exceed the maximum values given under MAXIMUM RATINGS and TYPICAL OPERATING CONDITIONS.**

A d.c. milliammeter should always be used in the plate circuit to provide a continuous check of plate current. Under no condition should the d.c. plate current exceed the maximum values given under MAXIMUM RATINGS and TYPICAL OPERATING CONDITIONS. A d.c. meter placed in the grid-return circuit is an invaluable aid in checking r-f grid excitation as well as in making tuning and neutralizing adjustments. If a d.c. milliammeter is placed in the filament-to-ground return lead, or in the negative high-voltage supply lead, the meter should be shunted by a suitable resistor having about 100 times the resistance of the meter. This arrangement will prevent the r-f amplifier stage or the framework of the rectifier from assuming a high d.c. potential with respect to ground in the event that the meter should develop an open circuit from any cause. With a ratio of external resistance to meter resistance of 100, the effect of the external resistor on the meter reading is very small—about one per cent.

The **control-grid bias voltage** can be obtained by any one of three general methods, or by a combination of these methods, depending on the class of service in which the tube is used. The three methods for obtaining grid bias are: (1) from a fixed-voltage supply, such as a battery, or a rectifier having good regulation; (2) from a grid-leak resistor; and (3) from a cathode resistor (self-bias). Some types of bias supply are not suitable for some classes of tube operation. The recommended types of bias supply for each class of service are given under TRANSMITTING-TUBE APPLICATION. For additional information on biasing methods, refer to TRANSMITTER DESIGN CONSIDERATIONS.

The **screen voltage** for pentodes and tetrodes may be obtained from a separate source, from a potentiometer, or from the plate supply through a series resistor. The method employed depends on the service in which the tube is used and on the tube type (see TRANSMITTING-TUBE APPLICATION.) Where the series screen-resistor method is used, the resistor should have a value sufficient, under load conditions, to drop the high voltage to a d.c. value which is within the maximum screen-voltage rating given under each tube type. In those classes of service where screen-voltage regulation is not an important factor, the series-resistance method of obtaining screen voltage is desirable, because of its simplicity and because it serves to limit the d.c. power input to the screen. With this method, however, it is important that the high-voltage supply switch be opened before the filament or heater or cathode circuit is opened; otherwise, the full supply voltage will be placed on the screen. When the screen voltage is obtained from a separate source, or from a potentiometer, plate voltage should be applied before the screen voltage, or simultaneously with it; otherwise, with voltage on the screen only, the screen current may be large enough to cause excessive screen dissipation. A d.c. milliammeter should be used in the screen circuit in most cases, so that the screen current and the d.c. power input to the screen can be determined. The screen input should never be allowed to exceed the maximum rated value.

Suppressor voltage for pentodes may be obtained from any fixed-voltage d.c. supply. In cases where the suppressor draws current, the supply should be a battery or other source having good voltage regulation.

The use of a **protective device** in each transmitting-tube circuit is usually advisable to safeguard the tube against accidental overloads. This device preferably should remove the d.c. plate voltage when the d.c plate current reaches a value about 50 per cent. greater than normal. For small, low-power tubes, a high-voltage fuse placed in series with the **positive** plate-voltage lead is usually satisfactory. For the larger transmitting tubes, an instantaneous d.c. overload relay should be employed. In r-f amplifier stages employing low- or medium-mu tubes with grid-leak-bias, it is especially important that a protective device be used to safeguard the tube against a heavy d.c. plate-current overload in case the r-f grid excitation should fail. Such failure, with grid-leak-biased tubes, results in a total loss of the d.c. grid bias. Additional information on protective devices is given in TRANSMITTER DESIGN CONSIDERATIONS.

Adequate **shielding** and isolation of the input circuit and the output circuit of pentodes and tetrodes are necessary if optimum results are to be obtained. The impedance between the screen and filament (or cathode) must be kept low, usually by means of a suitable by-pass condenser. When the screen voltage is obtained from the plate supply through a series resistor, the screen by-pass condenser should have a voltage rating at least equal to the d.c. plate voltage applied to the tube. The capacitance value of the condenser may be in the order of 0.01 to 0.1 µf. In telephony service where the screen voltage is modulated, a smaller capacitance may have to be used in order to avoid excessive a-f by-passing. If the screen by-pass condenser is made too small in value, however, r-f feedback from plate to control grid may result, depending on the circuit layout, operating frequency, and power gain of the stage. A-f by-passing difficulties can be largely eliminated if the screen by-pass condenser is replaced by a series-tuned circuit resonant at the operating frequency. The series-tuned circuit presents a high impedance to audio frequencies, but a very low impedance to its resonant frequency.

Heavy leads and conductors together with suitable insulation should be used in all parts of the r-f plate tank circuit so that losses due to r-f voltages and currents can be kept at a minimum. Because proper circuit design becomes very important at the higher frequencies, it is essential that short, heavy leads and circuit returns be used in order to minimize lead inductance and losses.

In order that the maximum ratings will not be exceeded, changes in electrode voltages due to line-voltage fluctuation, load variation, and manufacturing variation of the associated apparatus should be determined. An average value of voltage for each electrode should then be chosen so that under the usual voltage variations the maximum rated voltages will not be exceeded.

When a new circuit is tried or when adjustments are made, the plate voltage should be reduced in order to prevent damage to the tube or associated apparatus in case the circuit adjustments are incorrect. It is advisable to use a protective resistance in series with the high-voltage plate lead during such adjustments. The value of this resistance can be obtained with sufficient accuracy by taking one-half of the tube's plate resistance, as determined by Ohm's law from the typical operating conditions to be used. For example, a single 834 operating with a d.c. plate voltage of 1000 volts and a d.c. plate current of 100 milliamperes represents a resistive load of 10000 ohms (1000/0.1). The protective resistance should be about 5000 ohms, the exact value not being critical. Suitable meters should be provided for measuring tube voltages and currents as well as for making transmitter adjustments. When modulation is employed, a cathode-ray oscillograph also is recommended to assist in the making of final adjustments for optimum performance. Under no conditions should the maximum values be exceeded.

The rated plate voltage of practically all transmitting tubes is high enough to be dangerous to the user. Great care should be taken during the adjustment of circuits, especially those in which the exposed circuit parts are at a high d.c. potential. In the design of apparatus, precautions should include the enclosing of all high-potential circuit elements and the use of "interlock" switches to open the primary circuit of the high-voltage power supply when access to the apparatus is required.

TRANSMITTING-TUBE APPLICATION

Radio tubes are used in transmitters in a number of different ways, depending on the results to be achieved. Four distinct classes of amplifier service recognized by engineers are covered by definitions standardized by the Institute of Radio Engineers. This classification depends primarily on the fraction of input cycle during which plate current is expected to flow under rated full-load conditions. The four principal modes of operation are identified as class A, class AB, class B, and class C.

A **class A amplifier** is an amplifier in which the grid bias and alternating grid voltages are such that plate current in a specific tube flows at all times.

A **class AB amplifier** is an amplifier in which the grid bias and alternating grid voltages are such that plate current in a specific tube flows for appreciably more than half but less than the entire electrical cycle.

A **class B amplifier** is an amplifier in which the grid bias is approximately equal to the cut-off value so that the plate current is approximately zero when no exciting grid voltage is applied, and so that plate current in a specific tube flows approximately one-half of each cycle when an alternating grid voltage is applied.

A **class C amplifier** is an amplifier in which the grid bias is appreciably greater than the cut-off value so that the plate current in each tube is zero when no alternating grid voltage is applied, and so that plate current flows in a specific tube for appreciably less than one-half of each cycle when an alternating grid voltage is applied.

To denote that grid current does not flow during any part of the input cycle, the suffix 1 may be added to the letter or letters of the class identification. The suffix 2 may be used to denote that grid current flows during some part of the cycle.

For radio-frequency amplifier tubes which operate into selective tuned circuits, as in radio transmitter applications, or under requirements where distortion is not an important factor, any class of amplification may be used, in either a single-ended or a push-pull stage. For audio-frequency amplifiers in which distortion is an important factor, only class A amplifiers permit single-tube operation. For class AB or class B audio service, a balanced amplifier stage using at least two tubes is required.

CLASS A AUDIO AMPLIFIERS

An ideal class A amplifier is one in which the output wave shape is an exact reproduction of the input wave shape. In a practical class A amplifier, the grid is usually not driven positive (with respect to the cathode) by the input signal and is never driven negative so far that plate current is cut off. The average d.c. plate current is substantially constant between the conditions of no signal and full signal. The plate efficiency, or ratio of a.c. power output to average d.c. power input, is relatively low for triodes—about 20 to 30 per cent at full output, depending on the design of the tube and on the operating conditions. Fig. 1 illustrates class A amplifier operation.

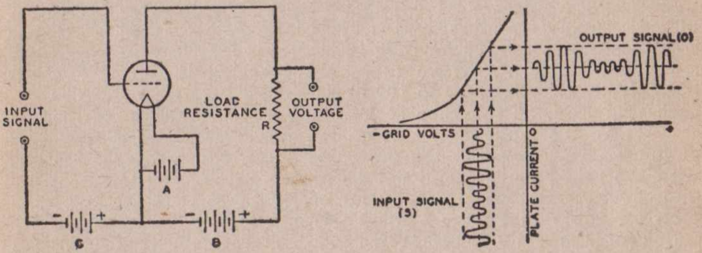


Fig. 1

Specially designed tubes of the triode type are frequently used as class A audio-frequency power amplifiers to modulate radio-frequency carriers. These tubes, which are usually driven by class A voltage amplifiers, require a relatively large input signal even though practically no power is required by the grid circuit. Class A audio power tubes, such as the 845 and 849, are generally characterized by a low or medium amplification factor.

Grid bias for class A service may be obtained from a separate d.c. voltage source or by means of a cathode-bias resistor shunted by a condenser. This condenser should be large enough to minimize degenerative effects at low audio frequencies. When the cathode-resistor method of bias is used, the proper value of the cathode resistor can be determined by the equation $R = 1000\ E/I$, where R is the cathode-bias resistance in ohms, E is the rated d.c. grid-bias voltage, and I is the *cathode current* in milliamperes. For a triode, the cathode current is simply the plate current; for tetrodes and pentodes, it is the sum of plate and screen currents.

If more audio power output is desired than can be obtained from a single tube, two or more tubes can be operated in parallel or in push-pull. The parallel connection provides twice the output of a single tube with the same input-signal voltage. The push-pull connection requires twice the input-signal voltage, but has, in addition to the increase in power, a number of important advantages over single-tube operation. Distortion due to even-order harmonics and hum due to plate-supply ripple voltages are either eliminated or decidedly reduced through cancellation in the output circuit. Because harmonic distortion is reduced, appreciably more than twice single-tube output can be obtained by using a plate-to-plate load resistance only slightly larger than the value for single-tube operation.

If the bias for two tubes in push-pull is supplied by a single cathode resistor, a large by-pass condenser should be used across the resistor to minimize distortion. With either the parallel or the push-pull circuit, the d.c. grid bias is the same as for a single tube. Where a number of tubes are operated in parallel or in push-pull, it may be necessary to provide individual adjustment of grid bias to insure that the plate dissipation of each tube does not exceed the maximum rated value. This can be accomplished by means of a tapped C-supply, or by means of a variable cathode-bias resistor for each tube. A separate filament-supply winding and a separate cathode-resistor by-pass condenser are necessary for each tube that is individually biased with a cathode resistor. Where tubes are operated in parallel, a non-inductive resistance of 10 to 100 ohms should be placed in series with each grid lead, at the tube socket, to prevent parasitic oscillations.

Where the input circuit of an a.f. power amplifier is resistance- or impedance-coupled to the preceding stage, the resistance in series with the grid circuit should not be made too high. The permissible grid-circuit resistance is usually larger for tubes that are self-biased than for tubes that have a fixed-bias supply, due to the protective action of the cathode-bias resistor. The recommended maximum value of grid-circuit resistance is given in the tabulated tube data.

Operation of audio power amplifiers so that the grids are driven positive on any portion of the input-signal cycle is inadvisable except under conditions discussed in the sections on class AB and class B amplifiers.

The power output of triodes as class A amplifiers can be calculated graphically without serious error from the plate family curves. The proper plate current, grid bias, and optimum load resistance, as well as the per cent. second-harmonic distortion, can also be determined. The method of calculation is not within the scope of this book.

CLASS AB AUDIO AMPLIFIERS

A class AB audio power amplifier consists of a push-pull stage in which the tubes are operated with a negative grid bias larger than that used for class A operation. With this larger grid bias, the plate (and screen) voltage can usually be made higher than the value used for class A operation because the increased negative bias reduces the d.c. plate current at zero signal to a value such that the plate-dissipation of the tube is not exceeded. A class AB amplifier will deliver more power output than a class A amplifier because of the higher voltages employed and because of its higher efficiency.

Class AB amplifiers are divided into two groups—class AB_1 and class AB_2. In a class AB_1 amplifier there is no flow of grid current because the peak signal voltage applied to each grid does not exceed the negative grid-bias voltage. Since the grids are never driven positive, grid rectification does not occur. In class AB_2 service, the peak signal voltage does exceed the grid bias with the result that the grids are driven positive and draw current on a portion of the positive half-cycle of signal voltage. The efficiency and power output of a class AB_2 amplifier are somewhat higher than for a class AB_1 amplifier.

Because of the flow of grid current in a class AB_2 amplifier, there is a loss of power in the grid circuit. The sum of this loss and the loss in the input transformer is equal to the total driving power required by the grid circuit. The driver stage should be capable of giving a power output considerably larger than this required power in order that distortion introduced in the grid circuit can be kept low. The input transformer used in a class AB_2 amplifier usually has a step-down turns ratio.

The d.c. plate current in a class AB_2 amplifier varies over a considerable range and increases with the input signal. Because of this variation, the plate-voltage supply should have good regulation; otherwise, fluctuations in the voltage output of the power supply cause a decrease in power output and an increase in distortion. To obtain satisfactory regulation, it is usually advisable to use a choke-input filter in the power supply. A mercury-vapor rectifier tube is generally preferable to a high-vacuum rectifier because of the better regulation of mercury-vapor tubes. In all cases, the resistance of the filter chokes and power transformer should be as low as practical.

The negative **grid bias** for either a class AB_1 or a class AB_2 amplifier should be obtained from a fixed-voltage supply if the maximum power output capabilities of the class AB stage are to be realized. Cathode-resistor bias can be employed with a class AB_1 amplifier, although this bias method reduces power output and may increase distortion. The cathode resistor should be by-passed by a very large condenser in order to minimize distortion. It is often advisable to provide for individual adjustment of grid bias for each tube in a push-pull class AB stage. If separate bias supplies are used, they should each be by-passed by suitably large condensers to minimize degenerative effects.

CLASS B AMPLIFIERS

The ideal **class B** amplifier is one in which the alternating component of plate current is an exact replica of the alternating grid voltage for the half-cycle when the grid is positive with respect to the bias voltage. The power output is proportional to the square of the exciting grid voltage. In class B service, the tube is operated so that the plate current is relatively low with no grid excitation. When excitation is applied, there is no plate-current flow over a substantial part of the negative half-cycle. Plate current flows only during the least negative excursions of the exciting voltage. A considerable amount of second-harmonic and higher even-order-harmonic distortion is thus introduced into the power output of a single tube. However, with two tubes in a balanced push-pull circuit, the even harmonics are eliminated from the output. In such a circuit, therefore, two tubes can be employed as class B amplifiers to supply power output with very low distortion. Class B amplifiers are characterized by medium power output, medium plate efficiency, and a moderate ratio of power amplification. They are used for both radio- and audio-frequency amplification.

In **class B audio amplifier service,** the tubes must be used in a balanced circuit so that harmonic distortion can be kept sufficiently low. Figs. 2 and 3 illustrate class B audio operation. It is possible to drive the grids of the amplifier tubes positive by a certain amount and still obtain virtually undistorted output, provided sufficient driving power is available. This power is conveniently supplied by a class A or class AB power amplifier driving the grids of the output tubes through a suitable push-pull transformer. Where class B amplifier tubes are designed with a sufficiently high amplification factor, it is possible and convenient to operate them with zero grid bias, and so avoid the problem of providing a grid-bias supply having good voltage regulation. A modified remote-cut-off plate-current characteristic in such tubes is an important factor in obtaining low distortion.* The 805 is an example of this type of tube design.

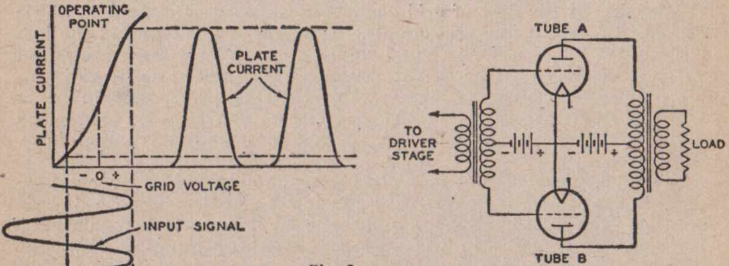


Fig. 2

Distinguishing features of class B audio service are: High power output of good quality can be obtained with relatively small tubes operating at a fairly low plate voltage; and unusual overall economy of power consumption is possible because the average d.c. plate current is low when no signal is applied to the grids. To give these advantages, a class B power amplifier requires the use of a driver stage capable of supplying considerable undistorted audio power and the use of a plate-voltage supply capable of maintaining good voltage regulation regardless of the variation of average plate current with signal voltage. It should be noted that the distortion present in the output of class B amplifiers is usually somewhat higher for the ordinary range of signals than that obtained with class A audio amplifiers employing much larger tubes capable of the same maximum power output.

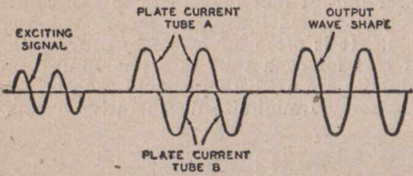


Fig. 3

Because the average d.c. plate current in a class B audio amplifier fluctuates considerably between no-signal and full-signal conditions, the plate supply should have adequate voltage regulation to take care not only of the average power requirements but also of the peak power demands. When an a.c. operated power supply is used, the rectifier tube itself should have good regulation—a requirement which is usually met by the use of mercury-vapor rectifiers. The filter chokes and transformer windings should have low resistance.

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* L. E. Barton, "Recent Developments of the Class B Audio- and Radio-Frequency Ampifiers" Proc. I.R.E., July 1936.

The grid of a class B audio amplifier tube is usually operated sufficiently positive to cause current to flow in the grid circuit. Therefore, the driver stage must supply not only the necessary input voltage to the class B stage, but it must be capable of doing so under conditions where considerable power is taken by the grids of the class B amplifier tubes. Because the power necessary to swing the grids positive is partially dependent on the plate load of the class B tubes, and because the efficiency of power transfer from the driver stage is dependent on transformer characteristics, the design of a class B audio power amplifier requires more than ordinary attention to effects produced by the component parts of the circuit. For this reason, the design of a class B audio amplifier with its driver stage is more involved than that of a class A system.

The interstage transformer is the coupling link between the driver and the class B stage. It is usually made with a step-down ratio of primary to one-half secondary. This means that the primary voltage is higher than the secondary voltage applied to the grid of either class B tube. The step-down ratio depends on the following factors: Type of driver tube; type of class B power tube; load on class B power tube; permissible distortion; and transformer peak-power efficiency. In practice, the ratio of primary to one-half secondary may range between 1 to 1 and 5 to 1.

The class B input transformer should be designed to give good frequency response when operated into an open circuit, such as that represented by the class B stage when the signal amplitude is very small. It should have fairly high power efficiency so that it can deliver the required power when the signal amplitude is large. The power output and distortion of the class B stage are often critically dependent on the circuit constants, which should be made as nearly independent of frequency as possible. This applies particularly to the class B input transformer. Because it is difficult to compensate for the effects of leakage inductance in this transformer without excessive loss of high-frequency response, its leakage inductance should be as low as possible.

The type of tube chosen for the driver stage should be capable of supplying sufficient undistorted power to operate the class B stage at full output. Allowance should be made for the efficiency of the interstage transformer. Two low-impedance tubes are frequently used in a push-pull class A circuit for the driver stage. This arrangement not only delivers relatively large amounts of undistorted power but, because of the bucking action of the d.c. current flowing in each half of the primary, also frees the interstage transformer of undesirable d.c. magnetization effects. It is often necessary, in order that distortion may be kept low, to work the driver tube into a load resistance higher than the normal value. The higher load reduces the distortion in the output of the driver stage, and consequently helps to reduce the distortion in the output of the class B stage.

In radio-telephone transmitters, a class B audio amplifier is generally used to modulate the plate voltage of a class C r-f amplifier, which may be either the final (output) stage, or some low-power stage preceding the final r-f amplifier. Coupling between the modulator and the class C stage is generally made by means of an output transformer, which should be designed so that the resistance load on the secondary, presented by the class C stage, is reflected into the primary circuit as the plate-to-plate load specified in the modulator tube data. The output transformer should have low leakage inductance and should be designed with a core sufficiently large to avoid magnetic saturation effects which would impair the quality of the output. For best low-frequency response, it is preferable not to allow the d.c. plate current of the r-f amplifier to flow through the secondary winding of the class B output transformer. Coupling between the secondary and the r-f stage to be modulated can be made through a series condenser and a parallel choke. If the secondary is to carry d.c. plate current, the transformer core should be made larger and should include a suitable air gap to prevent magnetic saturation due to d.c. magnetization.

The proper turns ratio for the output transformer is determined by the plate voltage and plate current of the class C stage to be modulated, together with the recommended plate-to-plate load of the class B modulator. For example, it is desired to operate two 805's as class B modulators with a plate supply of 1250 volts. The rated tube output is 300 watts and the recommended plate-to-plate load is 6700 ohms. If the efficiency of the class B output transformer is assumed to be 90 per cent, there will be 0.9 x 300, or 270 watts of useful audio power available. Because the power input to the class C r-f stage can be twice this value, for 100 per cent sinusoidal modulation, the class C amplifier can be operated at 2000 volts and 270 milliamperes, 1000 volts and 540 milliamperes, or at any other voltage and current providing an input of 540 watts. For the 2000-volt conditions, the equivalent resistance (sometimes called **modulation impedance**) of the class C stage is 2000/0.270, or 7400 ohms. The turns ratio of the output transformer (total secondary to total primary) is equal to the square root of the impedance ratio: thus, $\sqrt{7400/6700} = 1.1$. This is a step-up ratio, because the load on the secondary is higher than the desired plate-to-plate load for the modulator.

The **plate-circuit efficiency** of a class B a-f amplifier is in the order of 50 to 65 per cent at full output.

Grid bias for tubes operated in class B a-f service should be obtained from a battery or other d.c. source of good regulation. It should not be obtained from a high-resistance supply, such as a grid leak or a cathode resistor, nor from a rectifier, unless the latter is designed to have exceptionally good voltage regulation.

As a **class B radio-frequency amplifier,** any tube rated for such service may be operated in single-ended as well as in push-pull circuits. Either kind of operation is practical, because harmonic distortion in a class B r-f amplifier is largely filtered out by the "fly-wheel" action of the tuned output circuit.

Where the final r-f stage of a transmitter is modulated, the term **high-level modulation** is used to describe the system because modulation takes place in the stage operating at the highest power level. Where modulation takes place in some intermediate stage preceding the final r-f amplifier, the term **low-level modulation** is employed. In the latter system, the plate of the final amplifier is supplied with unmodulated d.c. voltage and the grid is excited by r-f voltage modulated at audio frequency in some preceding stage. The final amplifier is known as a linear amplifier and is operated under class B conditions so that the power output is proportional to the square of the exciting voltage Thus, when the r-f grid voltage is doubled, the output of the class B r-f amplifier is increased four times and 100 per cent modulation is obtained.

Because the input impedance of a class B linear r-f amplifier varies considerably with variation in the modulated r-f grid voltage, it is essential that the r-f stage driving the linear amplifier have good regulation. This requirement can be met by means of a capacitive or inductive step-down of r-f voltage between the plate circuit of the modulated class C stage and the input circuit of the class B amplifier.

The use of a low-impedance modulator together with a fairly large voltage step-down from the plate tank circuit of the modulated class C amplifier is an aid in obtaining satisfactory regulation.* Another, but less efficient, way of obtaining good regulation is by means of a non-inductive resistor of suitable value shunted across the input circuit of the class B r-f amplifier. This grid-regulation resistor (see circuit No. 21 in the CIRCUIT SECTION) should be of adequate size to dissipate a considerable portion of the exciting amplifier's power output. Adjustment of this resistance value, of grid bias, of grid excitation, and of antenna loading are important factors in obtaining proper operation. The average d.c. plate current of a class B r.f. amplifier should remain substantially constant as the modulation is varied between zero and 100 per cent.

Pentodes, tetrodes, and triodes can be used in class B r-f amplifier service. In the case of pentodes and tetrodes, the screen voltage should be obtained from a separate source, or from a potentiometer or voltage divider connected across the plate supply. The suppressor voltage for pentodes may be obtained from any fixed d.c. supply. In cases where the suppressor draws current, the supply should be a battery or other d.c. source of good regulation.

The **plate-circuit efficiency** of an unmodulated class B r-f amplifier is in the order of 30 per cent. At 100 per cent modulation, the efficiency rises to approximately 60 per cent. Because the plate dissipation is greatest when the carrier is unmodulated, care should be taken to limit the plate dissipation for the unmodulated condition to the maximum rating of the tube in this class of service.

Grid bias for class B r-f service may be obtained in the same manner as for class B a-f service, or by means of a cathode resistor (self-bias). Bias should not be obtained from a high-resistance source, such as a grid leak, nor from a power supply having poor voltage regulation. When self-bias is employed, the cathode resistor should be by-passed for both audio and radio frequencies.

CLASS C AMPLIFIERS

A class C amplifier is one in which high plate-circuit efficiency and high power output are the primary considerations. In an ideal case, the alternating component of plate current is directly proportional to plate voltage, so that within wide limits the power output varies as the square of plate voltage. The tube is operated with a negative grid bias considerably higher than the value necessary to cause plate-current cut-off. An r-f grid voltage of sufficient amplitude is applied so that large amplitudes of plate current flow during a small fraction of the least-negative half-cycle of the exciting voltage. The grid is usually swung sufficiently positive to cause plate-current saturation. The resulting harmonics in the output waves are, to a large degree, filtered out by the "fly-wheel" action of the tuned plate circuit. Fig. 4 illustrates class C operation.

Distinguishing characteristics of class C amplification are high plate-circuit efficiency, high power output, and relatively low power amplification. Because power output varies as the square of plate voltage, a class C amplifier is capable of being modulated linearly by variation of plate voltage at audio frequency. In class C telephony service, the negative grid bias employed is usually two or more times the value required to reduce the plate current to zero with no r-f grid excitation. The cut-off value of grid bias for a particular plate voltage

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* See footnote on page 78.

can be obtained from the plate characteristics curves. Class C amplifiers are at present used almost exclusively as radio-frequency power amplifiers.

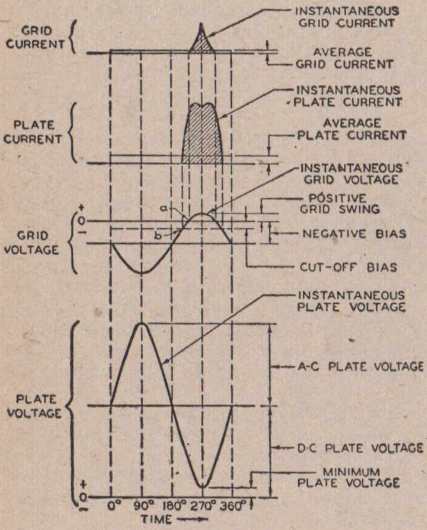


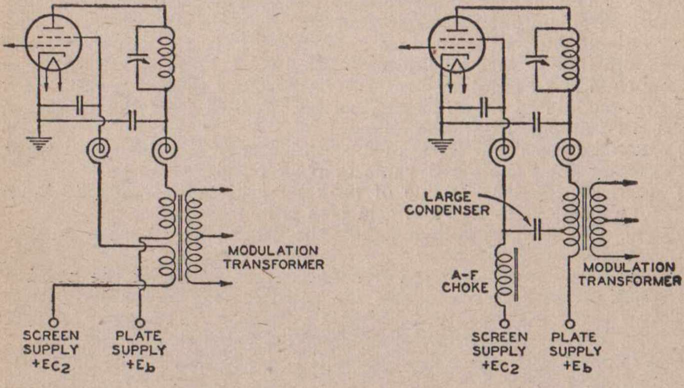
Fig. 4

In **plate-modulated class C telephony service,** a tube is operated with a d.c. plate voltage on which has been superimposed an audio-frequency voltage. The amplitude of this a-f voltage varies with the intensity of the modulating signal. The largest a.c. voltage that may be superimposed without introducing serious distortion is one whose peak amplitude just equals the d.c. plate voltage. This is the condition necessary for 100 per cent. modulation. Thus, when the r-f carrier is fully modulated, the modulating voltage drives the instantaneous plate voltage up to twice its normal d.c. value and down to zero during each audio cycle. The ratio of the peak audio modulating voltage to the d.c. plate voltage is called the **modulation factor.**

In order to have distortionless modulation, it is essential that a linear relation exist between currents and voltages. Thus, as the instantaneous plate voltage e_p is doubled, the r-f output voltage and current must also double. Likewise, as e_p is driven to zero on the negative half-cycle of the modulating voltage, the input and output currents must fall to zero. Averaged over an audio cycle, however, the d.c. supply voltage and current (E_b and I_b) remain constant, because the superimposed audio variations are symmetrical about the d.c. values. Since, at 100 per cent moduation, the peak modulating voltage and current equal the d.c. supply volatge and current, the RMS values of the audio components are equal to $E_b/\sqrt{2}$ and $I_b/\sqrt{2}$. Therefore, the audio-frequency modulating power, being the product of the RMS voltage and the RMS current, is equal to $E_bI_b/2$; this means that the modulator must be able to supply audio power equal to one-half of the d.c. plate input to the class C r-f amplifier.

When an r-f amplifier is modulated 100 per cent, the total input power is the sum of the d.c. power input and the a-f power input, E_bI_b plus $E_bI_b/2$, or $3E_bI_b/2$. The total input power, therefore, is increased 50 per cent when the amplifier is modulated. The radio-frequency modulated carrier power is also increased 50 per cent, since the energy in the side bands is then 50 per cent of the carrier power. The plate losses likewise rise 50 per cent, because the efficiency of a class C amplifier is almost constant whether it is modulated or unmodulated. In order to allow for this level of plate dissipation, it is necessary for the plate losses under unmodulated-carrier conditions to be limited to 2/3 of the maximum rated plate dissipation of the tube. Then, with sustained modulation at the 100 per cent level, the maximum rated plate dissipation will not be exceeded. These considerations account for the lower plate-dissipation ratings of tubes in plate-modulated class C service.

Triodes, tetrodes, and pentodes can be plate-modulated 100 per cent. To effect 100 per cent modulation of tetrodes and pentodes, it is necessary to modulate their screen voltage as well as their plate voltage. The screen voltage may be obtained from a fixed supply or from a voltage-dropping resistor in series with the plate supply. The screen voltage should be modulated simultaneously with the plate voltage so that the percentage changes in both voltages are approximately equal. Modulation of a fixed screen-voltage supply can be accomplished either by connecting the screen to a separate winding on the modulation transformer or by connecting it through a blocking condenser to a tap on the modulation transformer or choke. With the latter method, an a-f choke of suitable impedance for low audio frequencies should be connected in series with the screen-supply lead. Fig. 5 shows these connections. Where the series-screen-resistor method is used to obtain the screen voltage for pentodes, the screen resistor should be connected to the *modulated* plate supply ; for tetrodes, to the *unmodulated* plate supply. In the case of tetrodes, self-modulation of the screen voltage occurs due to variations in screen current as the plate voltage is modulated. The suppressor voltage for pentodes in plate-modulated service may be obtained from any fixed supply. Pentodes can also be used as tetrodes in this class of service, with the suppressor tied to the screen. The screen resistor for plate-modulated beam power tubes should be connected the same as for pentodes.



TWO METHODS OF MODULATING THE PLATE AND SCREEN VOLTAGE OF A TETRODE WHEN A SEPARATE, FIXED VOLTAGE IS USED FOR THE SCREEN.

Fig. 5

The **plate-circuit efficiency** of plate-modulated class C amplifiers is usually in the order of 65 to 75 per cent, although a higher efficiency can be obtained.

Grid bias for plate-modulated amplifiers is usually higher than for unmodulated amplifiers. Furthermore the bias must change with modulation in the plate circuit, if linear operation over the entire audio-frequency cycle is to be obtained. It follows, therefore, that a bias supply having poor voltage regulation is desirable for plate-modulated class C amplifiers. In practice, this poor regulation can be obtained quite easily by the use of a grid-leak resistor to develop the bias voltage. The control-grid bias may also be obtained from a combination of either grid leak and fixed supply, or of grid leak and cathode resistor. A suitably designed bias rectifier may also be employed to give a bias voltage with the poor regulation desired. If a cathode resistor is used to supply part of the bias voltage, the resistor should be by-passed for both audio and radio frequencies. Grid-bias voltage for class C service is not critical, so that correct adjustment can be obtained with values differing widely from those shown under typical operation for each tube type in tube manuals.

In **grid-modulated class C telephony service,** a tube is operated with an unmodulated r-f grid excitation voltage and with a d.c. grid bias on which has been superimposed an audio-frequency signal. The plate is supplied with unmodulated d.c. voltage. The operating conditions with an unmodulated carrier should be adjusted so that the r-f voltage in the plate circuit can be made to double at the crest of the audio cycle. Because the d.c. plate voltage is the same under carrier and modulated conditions, the developed plate-voltage swing under carrier conditions can utilize only about half of the d.c. supply voltage. The limited plate-voltage swing under carrier conditions causes the r-f output to be low and the plate-circuit efficiency to be poor—about one-half that of an unmodulated class C amplifier. The maximum tube ratings for grid-modulated class C service are the same as for class B r-f amplifier service. Satisfactory operating conditions for grid-modulated r-f amplifiers can be obtained from the tabulated class B r-f amplifier data, as follows:

(1) Increase the listed value of d.c. grid bias by a value equal to or greater than the listed value of peak r-f grid voltage.
(2) Increase the listed value of peak r-f grid voltage by the same number of volts that the grid bias is increased.
(3) The peak a-f grid voltage equals the listed (class B) peak r-f grid voltage.
(4) The grid current through the modulating source at the positive peak of the a-f cycle equals the listed driving power divided by two times the listed peak r-f grid voltage. This current consists of a d.c. component having one-half the value given above and an a-f component whose peak value is equal to that of the d.c. component.
(5) The carrier power output is approximately the same as the listed value of power output, although the d.c. plate current is somewhat less than the listed plate current.
(6) The r-f driving power at the crest of the a-f cycle is approximately the same as the listed class B value.

The audio power required for grid-modulated service is relatively low, because modulation takes place in the control-grid circuit. However, the modulator must be capable of supplying the necessary peak power taken by the grid of the class C amplifier on the positive crest of the signal and should not produce distortion under the varying load of the grid circuit during the remainder of the cycle. The r-f excitation voltage and the d.c. bias supply should have good regulation. The grid bias should not be obtained from a high-resistance supply, such as a grid leak or a cathode resistor. The plate-circuit losses are at a maximum under carrier conditions ; therefore, the plate dissipation under these conditions should not be allowed to exceed the maximum rated value. The efficiency increases and the plate loss decreases when the carrier is modulated.

For grid-modulated pentodes and tetrodes, the screen voltage should be obtained from a separate source or from a potentiometer connected across the plate supply. The suppressor voltage for pentodes may be obtained from any fixed supply.

In **suppressor-modulated class C r-f amplifier service,** pentodes may be operated as shown in the tabulated data under each type. The plate is supplied with unmodulated d.c. voltage, the control grid (grid No. 1) with unmodulated r-f voltage, and the suppressor (grid No. 3) with a negative d.c. voltage modulated at audio frequency. The voltage for the screen (grid No. 2) should be obtained from the plate supply through a series resistor. The suppressor bias may be taken from any fixed-voltage d.c. supply ; this supply should have good regulation in circuits where the suppressor draws current. Control-grid bias may be obtained by any of the methods given under TRANSMITTING-TUBE INSTALLATION. If cathode-resistor bias is employed, the resistor should be by-passed for both audio and radio frequencies. As in other types of class C service, the control-grid bias is not particularly critical.

The **plate-circuit efficiency** of a suppressor-modulated amplifier is in the order of 30 to 35 per cent. This moderate efficiency is due to the fact that the plate voltage is fixed and that the tube must be operated so as to allow the r-f plate voltage and current to double at the crest of the audio cycle. In this respect, operation is similar to that of a class B linear r-f amplifier.

Suppressor modulation has the advantage of requiring very little audio power for 100 per cent. modulation. For example, a modulator delivering about one watt of audio power is capable of fully modulating one -803. The suppressor is operated with sufficient negative bias so that, under carrier conditions, the r-f output voltage and current equal half the values reached at the crest of the a-f cycle. As a result, the suppressor does not draw current except on a portion of the positive half-cycle of modulating voltage. The modulator, which may be either transformer or impedance coupled to the suppressor, must be capable of delivering sufficient audio power to supply that required by the suppressor on the positive half-cycles, and to supply it without introducing serious distortion during the time that suppressor current flows.

In **class C r-f amplifier or oscillator service for telegraphy,** a tube is operated with an unmodulated d.c. plate voltage. The control grid is supplied with a negative bias voltage and is excited by an unmodulated r-f voltage. The screen of a tetrode or a pentode is supplied with a positive d.c. voltage. The suppressor of a pentode may be operated with a small positive d.c. voltage or it may be tied to the cathode and thus operated at zero potential. In the former case, the power output of a pentode is slightly increased. Screen, suppressor, and control-grid voltages may be obtained by any of the methods described under TRANSMITTING-TUBE INSTALLATION.

Because the output of a class C amplifier in telegraph service must be interrupted so as to form dots and dashes for the communication of intelligence, the subject of keying is of considerable importance.

Satisfactory keying is accomplished when the power output of the amplifier is reduced to zero almost instantaneously with the opening of the key and when full power output is delivered almost instantaneously with the closing of the key.

The power output of a vacuum-tube r-f amplifier can be controlled by either of two general methods, each of which is capable of a number of variations. These general methods are : direct control of the d.c. plate input by switching the plate voltage off and on ; and control of the excitation supplied to the control grid of the amplifier. The design of a satisfactory keying system involves many problems, the solutions of which are not within the scope of this book. The keying circuit selected should operate so that when the key is opened, no voltage, current, or dissipation rating of the tube will be exceeded.

When a tetrode or a pentode is to be keyed, the screen voltage is preferably obtained from a separate source or from a voltage divider. However, the series-screen-resistor method may be used with some tubes, as shown in the data under the tube type in tube manuals.

The grid excitation of a triode (except one having a sufficiently high mu) should not be interrupted when grid-leak bias is employed ; otherwise, the plate dissipation rating of the tube will be exceeded due to the resultant rise in d.c. plate current. To avoid this difficulty, a suitable value of fixed-bias voltage should be used.

Frequency Multipliers

Because the plate-current waves of a class C amplifier contain a relatively high percentage of harmonics, an amplifier of this type can readily be employed to double or triple the frequency of the r-f exciting voltage. The harmonic output can be increased by using a bias voltage higher than for class C amplifier service. It is common practice to employ a low-frequency crystal oscillator whose frequency has a submultiple relation to the desired operating frequency, in conjunction with one or more class C frequency multipliers. Thus, a 3500-kilocycle crystal oscillator can be used with several frequency doublers to provide an r-f voltage having a frequency of 7000 kc. 14000 kc, 28000 kc, etc. The plate circuit of a frequency multiplier is tuned to the frequency of the harmonic which is to be amplified. Triodes, tetrodes, and pentodes can be used in this class of service. Pentodes as frequency multipliers generally provide more output for a given input than triodes or tetrodes ; high-mu triodes are somewhat better than low-mu triodes. Frequency quadrupling is often not satisfactory, because the amplitude of the fourth harmonic is usually quite small. The loss in power at the fourth harmonic is usually great enough to necessitate the use of an additional amplifier stage, unless special circuit arrangements are used. The efficiency of a tube used as a class C plate-circuit frequency multiplier is considerably less than when it is used as a class C amplifier. An efficiency of 50 to 60 per cent is typical for doublers ; the value decreases rapidly as the harmonic frequency is increased. Neutralization of frequency multipliers is not essential, because the plate circuit does not operate at the same frequency as the grid circuit. The use of a neutralizing circuit, however, provides somewhat higher power output due to the feedback thus introduced.

A frequency doubler having better regulation is obtained by operating two tubes in a balanced-input circuit with the grids in push-pull and the plates in parallel. The plate circuit, tuned to twice the frequency of the exciting voltage, receives two pulses of plate current for each complete cycle of grid excitation voltage; the power output obtained is about twice that of a single-tube doubler.

Crystal-Controlled Oscillators

Because of their general use in controlling the frequency of radio transmitters of many types, crystal-controlled oscillators are of considerable importance. Due to the fragile nature of crystals, especially those ground for high-frequency operation, and to the small amount of power they are capable of handling, it is general practice to use them in conjunction with oscillator tubes of relatively low power. Triodes, tetrodes, and pentodes can be used as crystal-controlled oscillators. In the case of a triode, such as the 801, the plate voltage should be reduced to about one-third of its normal value, to prevent overloading the crystal by excessive feedback and heavy r-f currents. Pentodes, such as the 802, and beam power tubes, such as the 807, are especially suitable for crystal-oscillator service. They cause relatively little loading of the crystal in properly designed circuits, even when operated at full plate voltage. In addition, they will deliver considerably more power output than triodes of similar size, due partly to the higher d.c. plate input at which they can be operated and partly to their higher power sensitivity. In the case of tetrodes and pentodes, which have sufficient screening between the control grid and the plate, it is usually necessary to introduce some external grid-plate capacitance in circuits where oscillation depends upon the feedback produced by this capacitance. The external feedback may be obtained by means of a small adjustable condenser (usually not larger than 2 or 3 $\mu\mu$f) connected between the grid terminal and the plate terminal. The extra capacitance should not be made larger than necessary, because an excessive value may cause sufficient feedback to overload and destroy a crystal. In high-frequency transmitters where a low-frequency crystal is employed, special crystal-oscillator circuits are frequently used wherein frequency doubling or tripling is accomplished in the oscillator plate circuit. Such circuits have the advantage of reducing the number of frequency-multiplier stages needed.

OTHER CONSIDERATIONS

In those classes of operation where d.c. grid current is drawn, it will be found that the grid current will vary with individual tubes. Under no condition of operation should the grid-current values under MAXIMUM RATINGS be exceeded.

If more radio-frequency power output is required than can be obtained from a single tube, the push-pull, parallel, or push-pull parallel connection can be used. For example, two tubes connected in push-pull or in parallel will give approximately twice the power output of one tube. The parallel connection requires no increase in exciting voltage; the push-pull connection requires twice the exciting voltage necessary for a single tube. With either connection, the driving power required is approximately twice that for single-tube operation, while the d.c. grid bias is the same as for a single tube. The push-pull arrangement has the advantage of cancelling the even-order harmonics from the output and of simplifying the balancing of high-frequency circuits. Where two or more tubes are operated in push-pull or in parallel, a non-inductive resistance of 10 to 100 ohms should be placed in series with the grid lead of each tube, close to the socket terminal, to prevent parasitic oscillations. Additional information on the application of transmitting tubes is given in the chapter on TRANSMITTER DESIGN CONSIDERATIONS.

TRANSMITTING TUBE RATINGS

HOW RATINGS ARE DETERMINED

During the development of a tube, tentative designs are constructed to meet desired ratings. For these designs, the materials chosen, the dimensions used, and the structures employed are based on the chemical and physical properties of materials, research work, and the experience of engineers with other tube types, both in the laboratory and in the field. Sample tubes of the new designs are then checked for compliance with the desired ratings and characteristics. Destructive overload tests are made to determine if there is a reasonable margin of safety in the designs. Life tests, however, are most important of all in the selection of the final design and the determination of final ratings. Groups of tubes are placed on life-test racks and operated under maximum rated conditions. At intervals they are removed for electrical measurements, but life testing is continued until the tubes fail. When the life tests indicate that the design is satisfactory for good tube performance at the tentative maximum ratings, these ratings are established for the tube type.

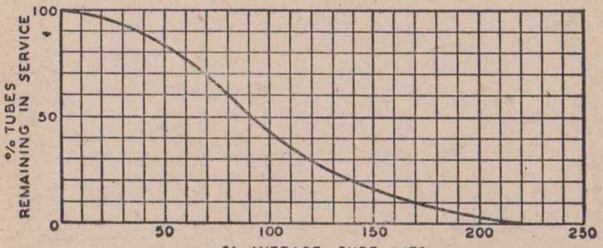


Fig 6

If the results of life tests on a large number of tubes of a given type are examined, some interesting facts will be found. The curve in Fig. 6 shows what occurs. The rate of tube failures is low initially, but after a prolonged period increases rather rapidly for a while. Finally, the rate again becomes low and a few tubes give an exceedingly long life. This curve is typical of many mortality relationships, and is particularly comparable to the human mortality curves from which life insurance companies compute their rates. It is apparent that although the life of a single tube, even under rigidly specified conditions, cannot be predicted, the average life of a group of tubes can be predicted when the tubes are operated under rated conditions. Therefore, if the operation of tubes is confined within well-established ratings, satisfactory service and life can be expected.

CONSIDERATIONS INFLUENCING RATINGS

When a tube is manufactured, it is not known in what field of radio service it will be used. Accordingly, ratings must be established so that the tube will give long, reliable service in any field. Long tube life is capable of a number of interpretations, depending on the viewpoint of the user. A broadcasting station, for example, operates tubes on an average of 18 hours a day. Tube failures are expensive both in themselves and because of interrupted programs. Consequently, the broadcaster insists that his tubes operate for more than a thousand hours without failures. Reliability is the keyword.

On the other hand, aviation companies often operate transmitting tubes only 15 minutes each day. On this basis, a tube life of 1000 hours would seem unnecessary. However, it is imperative that the tubes be ready for operation when necessary, because failures at the wrong moment may mean damage to an expensive airplane or even loss of human life. Again, reliability is the keyword.

The radio amateur has different requirements. He does not usually demand the full measure of reliability that some other services require, nor, relatively speaking, does he require the extremely long tube life needed by others. It has been estimated that the average amateur transmitter is in operation 300 hours, or less, a year. On an average, therefore, an amateur requires at least 3½ years to obtain a thousand hours of operation from his transmitting tubes. Because of this, amateurs may feel that they can overload their tubes a certain amount, shorten the life to one year, and thus obtain economy in the operation of their stations (on the basis that an overloaded small tube can be made to do the work of a larger and more expensive type). The flaw in this reasoning is that not even the manufacturer can predict how much overloading an individual tube will stand and yet give a desired fraction of its probable life under normal operating conditions. A tube costing $5 which delivers an output of 100 watts for 300 hours is not as economical as a larger tube costing $10 which delivers an output of 100 watts for 1000 hours. Furthermore, there is no guarantee that the overloaded $5 tube will give even 30 per cent. of its probable normal life. The important conclusion for almost all users of transmitting tubes is that it is highly desirable to operate them within the manufacturer's ratings.

INTERPRETATION OF TUBE RATINGS

A thorough understanding of the significance of published ratings is necessary if optimum results are to be obtained. The following explanation is intended to clarify the meaning of the ratings tabulated under each individual tube type in tube manuals.

The filament or heater voltage given in the tabulations is a normal value unless otherwise stated. Transformers and resistances in the filament circuit should be designed to operate the filament or heater at the rated value for full-load operating conditions with an average line voltage. Variations from the rated value due to line-voltage fluctuations or other causes should not exceed plus or minus 5 per cent, unless otherwise stated under the tube type.

In general, the filament of a transmitting tube may be operated with either an a.c. or a d.c. supply. An a.c. source is usually employed because of its convenience and economy, unless a d.c. source is necessary to avoid hum. With a.c. operation, the grid return and the plate return should be connected to the mid-point of the filament circuit. This point may be the centre tap of the filament winding or of a low resistance shunted across the filament circuit. When direct current is used, the return leads should be connected to the negative filament terminal.

Where it is found desirable to use d.c. filament excitation on any filament-type tube for which data are given on an a.c. basis, the grid-bias values as shown in the tabulated data should be decreased by an amount equal to approximately one-half the rated filament voltage. The grid-bias voltage should be measured from the negative filament terminal.

In the rating of transmitting tubes, certain tabulated values are given as maximum. These are limiting values above which the serviceability of the tube will be impaired from the standpoint of life and satisfactory performance. If these limiting values are not to be exceeded, it is necessary to determine the amount of voltage fluctuation due to line-voltage variation, load variation, and manufacturing variation in the apparatus itself. Average design values can then be chosen so that the maximum ratings will never be exceeded under the usual operating conditions.

Each maximum rating should be considered in relation to all other maximum ratings, so that under no condition of operation will any maximum rating be exceeded. If the product of the maximum rated plate voltage and d.c. plate current exceeds the maximum rated d.c. plate input, then either or both the plate voltage and plate current should be reduced an appropriate amount. For example, the 808 in class C telegraphy service has the following ratings: 1500 max. plate volts; 150 max. plate milliamperes; and 200 max. d.c. plate input watts. It is apparent that when the maximum plate voltage of 1500 volts is used, the d.c. plate current must be reduced so that the maximum d.c. plate input will not be exceeded. If the maximum plate current of 150 milliamperes is used, then the plate voltage should be reduced accordingly.

The data tabulations also show typical operating values for each respective tube type in the classes of service for which the tube is recommended. These values should not be considered as ratings, because the tube can be used under any suitable conditions within its maximum ratings, according to the application. The output value for any operating condition is an approximate tube output—that is plate input minus plate loss. Circuit losses must be subtracted from tube output in order to determine the useful output. Output values are approximate and are not to be considered as output ratings. The actual output in any case depends on a number of variable factors, important among which are circuit efficiency and operating frequency.

TRANSMITTING-TUBE RATINGS VERSUS OPERATING FREQUENCY

Because circuit and tube losses increase with frequency, it is apparent that for each tube type there will be a limiting maximum frequency above which the tube cannot be expected to operate safely within its maximum power dissipation ratings when the maximum rated d.c. plate input is employed. However, safe operation can be obtained at the higher frequencies if the d.c. plate voltage and power input are appropriately reduced. The following table lists the recommended operating conditions in per cent of maximum rated plate volts and d.c. plate input. For frequencies between the tabulated values, interpolation may be employed. For example, in the case of an 800 operating at 80 megacycles, the maximum d.c. plate voltage and input that should be used are 87 per cent of the maximum rated values shown in the tabulated data for any given class of service. The maximum plate voltage for class C telegraphy service at 80 megacycles is 1090 volts (approximately), this being 87 per cent. of the maximum rated value of 1250 volts. The maximum rated d.c. plate current may remain the same.

In the fifth column of the accompanying table are given the resonant frequencies of the tubes alone. Each of the resonant values is obtained with the shortest practical connection between grid and plate.

TRANSMITTING TUBE RATINGS VERSUS OPERATING FREQUENCY

Tube Type	Max. Freq. for 100% Max. Rated Plate Volts & Plate Input *Megacycles*	Max. Freq. for 75% Max. Rated Plate Volts & Plate Input *Megacycles*	Max. Freq. for 50% Max. Rated Plate Volts & Plate Input *Megacycles*	Resonant Frequency of Tube Only *Megacycles*
203-A	15	30	80	100
204-A	3	10	30	50
211	15	30	80	100
800	60	100	180	300
801	60	75	120	170
802	30	55	110	150
803	20	35	70	115
804	15	35	80	140
805	30	45	85	115
806	30	50	100	197
807	60	80	125	155
808	30	60	130	272
809	60	70	100	140
814	30	50	100	190
830-B	15	30	60	90
831	20	30	60	100
834	100	170	350	500
837	20	35	80	125
838	30	50	120	140
841	6	45	170	170
843	6	50	200	200
844	8	45	155	155
849	3	10	30	40
850	13	35	100	130
851	3	7	15	28
852	30	70	120	210
860	30	70	120	195
861	20	30	60	100
865	15	30	70	125
1602	6	45	170	170
1608	45	70	150	150
1610	20	110	——	215

CHOICE OF TUBE TYPES

In the design of a radio transmitter, the choice of the number and types of transmitting tubes is of paramount importance. Engineers, radio amateurs, and others interested in transmitter design are fortunate in having available a large variety of power tubes with which to work. The very number of tubes types may even seem to be a source of confusion, but the problem, if approached logically, represents no great difficulty. The designer can, by the simple process of elimination, reduce the number of tube types suitable for a specific application to a small group from which a final choice can readily be made.

Most modern transmitters are of the crystal-oscillator power-amplifier type. In almost every case, however, the ultimate design revolves around the final stage—the r-f power amplifier which develops useful r-f energy and supplies it to the radiating system. The following considerations are important in the choice of power tubes for the final amplifier stages: (1) power capability, (2) frequency capability, (3) design suitability, and (4) economic suitability.

Power capability. The tube or tubes used in the r-f power amplifier should be capable of delivering the desired power output when operated (with a practicable value of efficiency) within the maximum ratings. The efficiency of the final stage depends on a number of factors, chief of which are the class of amplification and the operating frequency. Typical efficiencies to be expected in the various classes of amplification are given in the chapter on TRANSMITTING-TUBE APPLICATION.

Frequency capability. The final amplifier tube or tubes should be capable of operating at the desired radio frequency with sufficient d.c. plate input so that, with a practicable value of efficiency, the required power output can be obtained. In this connection, the table TRANSMITTING TUBE RATINGS vs. OPERATING FREQUENCY is valuable. The problems introduced by the operating frequency are increasingly important as the frequency becomes higher.

Design suitability. Under this broad heading is included a large number of miscellaneous factors which the designer should consider. Some of these are:

(1) Power supply. This factor is important in the choice of tube types. In portable designs, it may be necessary to use tubes which can be economically operated from a heavy-duty, low-voltage battery supply. In fixed-station service, where a source of a.c. power is available, the problem of d.c. voltage supplies is greatly simplified through the use of suitable rectifiers and filters.

(2) Power sensitivity. In those cases where the total number of stages in a transmitter must be kept to a minimum, tubes having high power sensitivity should be employed. Power pentodes and beam power tubes, such as the 803, 807, and 814, require very little driving power compared to triodes of equivalent power output. For low-power frequency multipliers and intermediate amplifier stages, the 802 pentode and the 807 beam power amplifier are very useful.

(3) Circuit flexibility. Where a transmitter must be capable of operating on a number of widely different frequencies with a minimum of time required for changing frequencies, the use of tetrodes or pentodes (in preference to triodes) is indicated. Because tetrode and pentode amplifiers do not, in general, require neutralization, the problems that are sometimes encountered with neutralized triode amplifiers are avoided.

(4) Mechanical considerations. The size and shape of the tube may be important in some transmitter designs because of space or weight requirements. The arrangement of the electrode terminals is sometimes of importance because it affects circuit wiring and the mounting of circuit components.

(5) Electrical considerations. It is frequently convenient to use certain tube types together because they can be operated from a common filament supply, from a common plate-voltage source, or because they make practical other simplifications in design and maintenance.

Economic suitability. This factor includes not only initial tube cost but also the costs of auxiliary equipment, maintenance, and operation. An analysis of these costs will often indicate that it is desirable to modify the design to meet the requirements of a particular installation.

Most of these considerations have dealt with the choice of tube type for the r-f power amplifier stage. Where modulated service is contemplated, additional factors which influence the choice are introduced : these, however, are explained in the chapter on TRANSMITTING-TUBE APPLICATION.

An important problem in transmitter design is the choice of tube types for the intermediate amplifier, multiplier (if any), and oscillator stages. In practice, it is generally convenient to begin with the r-f power amplifier stage and work "backward", toward the master- or crystal-oscillator stage. The driving power necessary for the final tube (or tubes) can be obtained, for a specified class of service, from the tabulated tube data. This power, as shown for triodes and tetrodes in class B r-f service and in class C service, is subject to wide variations, depending on the impedance of the output or load circuit. High-impedance load circuits require more driving power to obtain the desired output. Low-impedance circuits need less driving power, but cause a sacrifice of plate-circuit efficiency.

The driver stage should have a tank circuit of good regulation and should be capable of delivering considerably more than the rated driving power of the final amplifier tube. For example, if the final amplifier has a rated driving power of 10 watts in class C telegraphy service, the driver stage may have to be capable of delivering 15 to 25 watts of r-f power in order to compensate for circuit losses and to have suitable regulation. The actual value will depend on several variable factors, so that some actual experience is frequently necessary before the designer of a transmitter can choose the most logical tube type for the driver stage. In general, however, it is advisable to have available some surplus driving power, because class C amplifiers do not operate efficiently when under-excited. An important advantage of pentodes and beam power tubes is that they require very little driving power, so that the choice of a suitable driver stage for such tubes usually presents no great problem. In most cases, the driver should be operated as an amplifier rather than as a plate-circuit multiplier, because the efficiency and power output of the latter are relatively low.

The choice of tube types for the stages preceding the last intermediate amplifier depends, of course, on considerations of frequency and power. A typical arrangement for a high-frequency, multi-stage transmitter includes a crystal-controlled oscillator and one or more frequency-multiplier stages. The number of multiplier stages (usually frequency doublers) depends on the frequency of the crystal and on the desired operating frequency. In many cases, special oscillator circuits are used so that frequency multiplication initially takes place in the oscillator stage itself. These circuits usually reduce the number of multiplier stages necessary to reach a specified operating frequency with a crystal whose fundamental frequency is a sub-harmonic of the operating frequency.

Pentodes and beam power tubes, such as the 802 and 807, respectively, are very useful as frequency multipliers and low-power intermediate amplifiers. These tubes, when used in properly designed and shielded circuits, ordinarily require no neutralization in r-f amplifier service. This advantage is very worth while in multi-stage transmitters which necessarily require numerous controls and adjustments. The last intermediate amplifier is often driven by the last frequency-doubler stage. This arrangement is quite satisfactory provided the output of the doubler is sufficient to excite adequately the amplifier stage.

GRID-BIAS CONSIDERATIONS

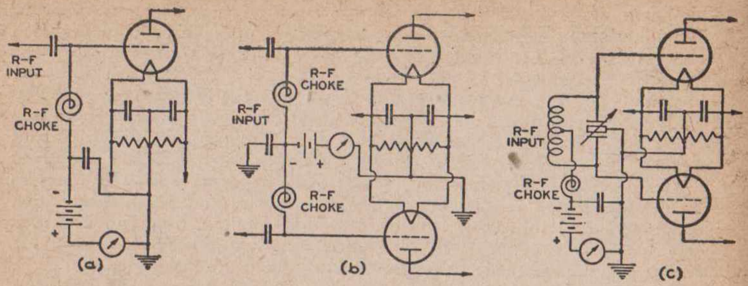
There are three general methods of obtaining negative grid bias for vacuum-tube amplifiers. Not all of these methods are suitable for every class of service, as explained in TRANSMITTING-TUBE APPLICATION. The three methods are : (1) fixed source, (2) grid-lead resistor, and (3) cathode resistor (self-bias).

Fig. 7 illustrates the use of fixed bias in several types of r-f amplifier circuits. The voltage source may be a battery, a d.c. generator, or a rectifier designed to have good regulation. An r-f choke and by-pass condenser serve to exclude the r-f grid voltage from the bias-voltage supply. Where a tuned grid circuit is employed, the r-f choke is often not essential and may sometimes even be detrimental to the operation of the circuit. An r-f choke of the wrong value in the grid circuit may cause trouble from parasitic oscillations, especially where a similar r-f choke is used in the plate circuit. A bias voltage from a fixed source serves to protect the tube against accidental removal of the r-f grid excitation, provided the bias is large enough to reduce the d.c. plate current to cut-off, or to a low value.

If two tubes are used in parallel or in push-pull, the d.c. grid current of both tubes may flow through a common grid leak. In this case, the value of the grid-leak resistance will be one-half that for a single tube.

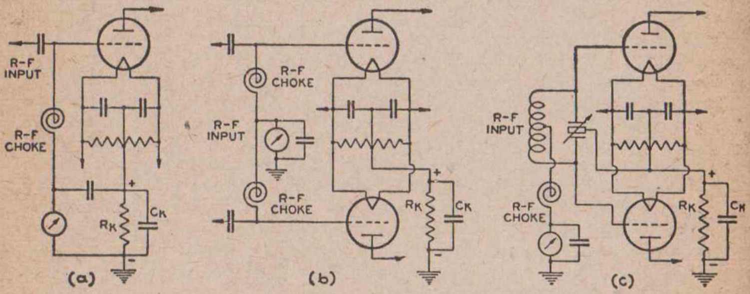
The grid-leak bias method has the advantage of simplicity and of automatically biasing the grid in proportion to the excitation voltage available. Because of this automatic action, the bias voltage developed across a grid leak is not critically dependent on the value of the grid-leak resistance. Therefore, considerable variation in the resistance of the leak can usually be tolerated. Special care must be observed when grid-leak bias is used because accidental removal of the r-f grid excitation will cause the grid bias to fall to zero and (in the case of a tube having a low or medium amplification factor) the plate current to rise to an excessive value. The use of a protective device designed to remove the plate voltage (and screen voltage, in the case of tetrodes and pentodes) on excessive rises of plate current will minimize the danger of destructive overloads (see PROTECTIVE DEVICES).

Fig. 8 illustrates the use of cathode-resistor bias. In these circuits, the cathode current flowing through R_k builds up a voltage drop which makes the cathode positive with respect to ground. Since the grid is at ground potential with respect to all d.c. voltage, the grid is biased negatively with respect to the cathode. The cathode current for triodes is the sum of the d.c. plate current and the d.c. grid current. For tetrodes and pentodes, the screen current must also be added.



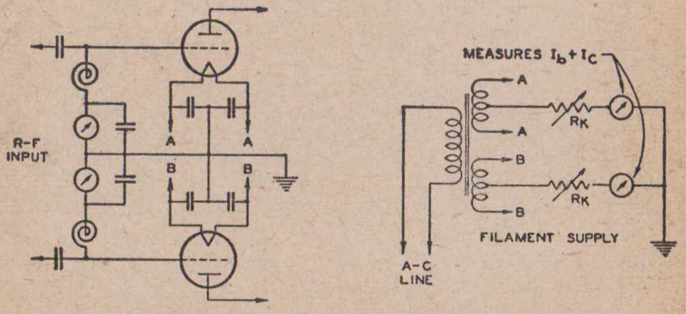
CONNECTIONS FOR FIXED BIAS SUPPLY

Fig. 7



CONNECTIONS FOR CATHODE-RESISTOR BIAS SUPPLY

Fig. 8



CONNECTIONS FOR INDIVIDUALLY-BIASED TUBES USING THE CATHODE-RESISTOR METHOD.

Fig. 9

Cathode-resistor bias, or self-bias, is advantageous in that it tends to protect the tube against heavy d.c. plate-current overloads; that is, when the plate current increases, the bias voltage across the cathode resistor also increases so that the rise in plate current is automatically opposed. A disadvantage of self-bias is that the effective d.c. plate voltage is reduced by the amount of the bias voltage. Thus, the voltage output of the plate supply must equal the desired plate voltage plus the required bias voltage.

The value of cathode resistor R_k can be determined by Ohm's law, $R = E/I$, where R is in ohms, E is the required bias in volts, and I is the total cathode current in amperes. For example, assume that the total d.c. plate current (under normal load) is 100 milliamperes, that the total d.c. grid current is 20 milliamperes, and that the required bias is –240 volts. Then, $R_k = 240/0.120 = 2000$ ohms. The power dissipated by R_k is equal to EI, or $(240)(0.120) = 28.8$ watts. A 50-watt resistor is a logical choice, because it is desirable to operate a resistor at less-than-rated power in order to provide a suitable factor of safety.

Where two or more filament-type tubes are individually self-biased, the use of a separate cathode resistor and a separate filament-supply winding is necessary for each tube so biased (see Fig. 9). This arrangement provides a method of adjusting individually the bias of each tube in a push-pull amplifier stage.

Various combinations of biasing methods are sometimes desirable. In a plate-modulated amplifier, the use of grid-leak bias combined with either cathode bias or fixed bias improves the linearity of the amplifier and thereby reduces distortion in the audio component of the modulated carrier.

The performance of a transmitting tube definitely depends on the characteristics of the circuit in which it is used. Because parallel-tuned circuits are almost universally employed for the plate, or output, circuit of vacuum-tube r-f amplifiers, except at ultra-high radio frequencies, considerations involving inductance (L) and capacitance (C) are very important in transmitter design.

The resonant frequency of the parallel-tuned circuits used in transmitters is given by the relation,

$$f = \frac{10^6}{2\pi\sqrt{LC}} \qquad (1)$$

where f is frequency in kilocycles per second (kc)
L is inductance in microhenrys (μh)
C is capacitance in micro-microfarads (μμf)

This relation can be further simplied so that

$$f = \frac{159160}{\sqrt{LC}} \quad \text{or} \qquad (2)$$

$$L = \frac{(159160)^2}{f^2C} = \frac{25.33 \times 10^9}{f^2C} \qquad (3)$$

Equation (3) can be used to determine the inductance necessary to tune to a specified frequency f with a known value of capacitance C. The product of L and C is a constant for a given frequency; the frequency of a resonant circuit varies inversely as the square root of the product of inductance and capacitance. Doubling both L and C halves the resonant frequency; reducing both L and C to one-half doubles the frequency. In actual circuits, of course, the effect of stray inductances and capacitances of the circuit wiring and of the tubes must be taken into account, especially at the higher radio frequencies.

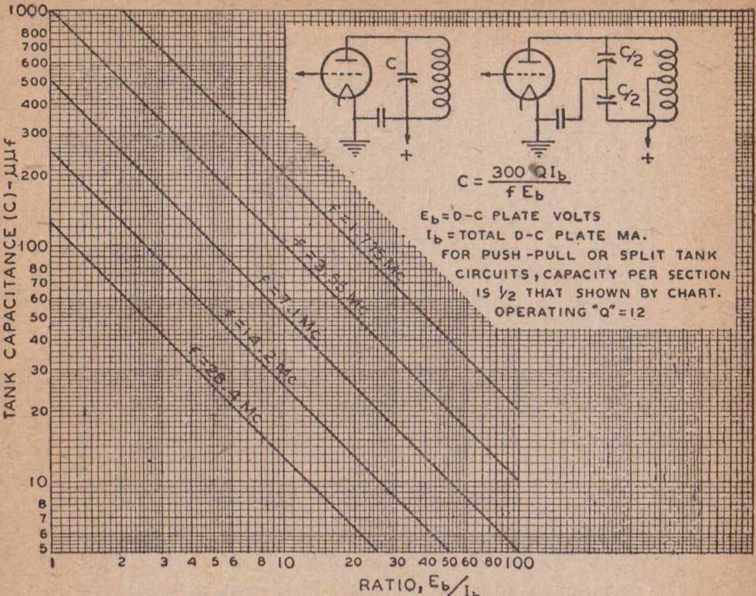


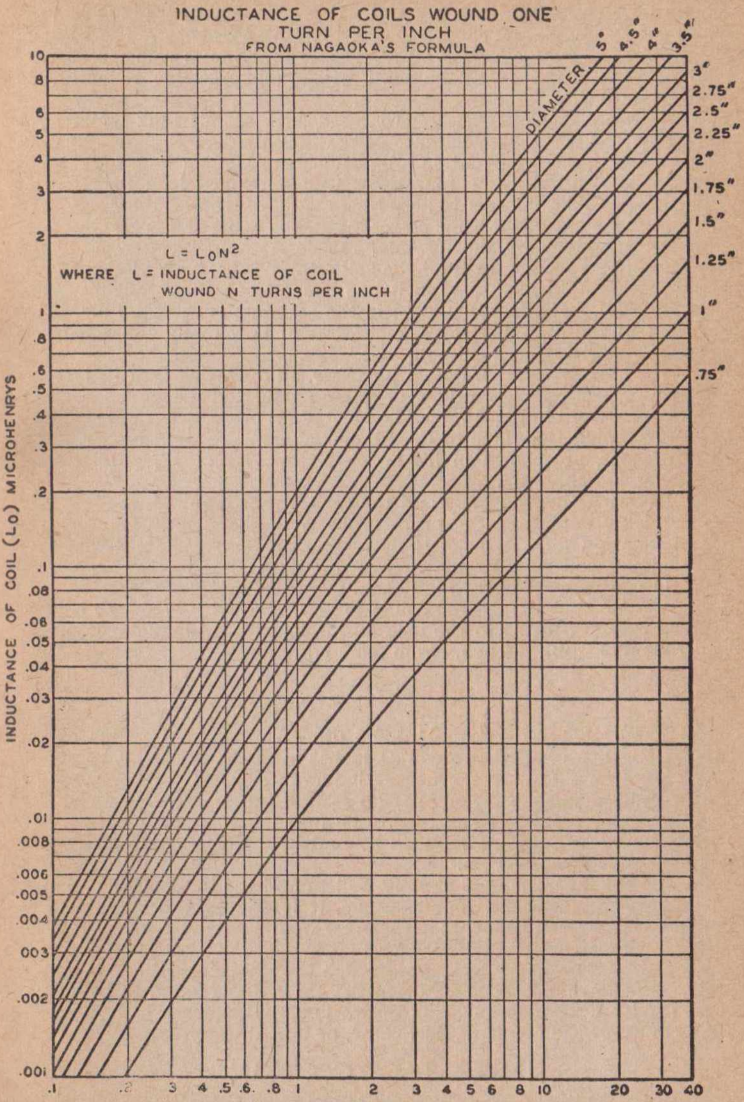
Fig. 10

The value of L and C should be chosen with considerable care. Because an r-f amplifier tube supplies power only during a fraction of each cycle, the tank circuit must function as a "fly-wheel" to carry on the oscillation to the next plate-current pulse. A measure of this fly-wheel effect is the ratio of volt-amperes in the tank circuit to the power delivered by the tube. This ratio is defined as the operating Q.

It is common practice to employ an operating Q of 10 to 15 for either telegraphy or telephony service. If the value of Q is much lower, there will be considerable distortion of the r-f waveform with resultant power output at harmonic frequencies. Harmonic output from the power amplifier is very undesirable because it represents wasted power and may lead to radiation at harmonic frequencies which will cause interference to other radio services. A value of Q which is too high will result in excessive losses in the tank circuit due to the large circulating r-f current in a high-Q circuit. This condition is evidenced by high plate current even when the tank circuit is not loaded. Other factors being equal, the Q is proportional to the tuning capacity in the tank circuit. The capacitance needed for the tuned circuit of an r-f amplifier can be determined approximately from the following relation :

$$C = \frac{300QI_b}{fE_b} \qquad (4)$$

where Q is a constant (about 10 to 15)
I_b is the total of d.c. plate current in milliamperes
f is the frequency in megacycles
E_b is the d.c. plate voltage in volts
C is the total capacitance, in micro-microfarads (µµf), placed across the tank inductance.



Data by courtesy of Electronics

Fig. 11

This value of C is for an amplifier of the single-ended type employing a tank circuit which is not split. It is the capacitance in actual use and not the maximum capacitance of the tank condenser. The value of C determined from equation (4) represents a minimum value; a slightly larger value can usually be used without appreciable reduction in power output.

Where a single-ended stage is used with a split tank circuit, the value of C (the total capacitance across the inductance) should be one-fourth that given by equation (4). The corresponding tank inductance should be approximately four times that employed in a tank circuit which is not split, in order to keep the product of L and C the same. For a push-pull stage of the same power input, the value of C is also but one-fourth that given by the formula. Because the condenser used in a push-pull stage is genreally of the split-stator type, each section of the condenser should have a capacitance equal to one-half that given by equation (4). The factor I_b used in the equation is the total d.c. plate current of the amplifier stage, regardless of how many tubes may be used in parallel or in push-pull.

For amateur-station design purposes, an operating Q of 12 is satisfactory for either telegraphy or plate-modulated telephone service. The chart shown in Fig. 10, based on a Q of 12, presents a simple method of determining the value of C. Similar charts, prepared by Mr. John L. Reinartz, are shown in his article "How Much C?", published in QST for March, 1937.

Knowing the frequency and the capacitance required, the designer can quickly determine the proper value of inductance in microhenrys from equation (3). In order to determine the approximate design of a single-layer coil to give the desired inductance, the chart shown in Fig. 11 can be employed as indicated in the following example.

Assume that the desired coil is to be wound with 3/16-inch copper tubing spaced 3 turns to the inch and is to have an inductance of 4.5 microhenrys (μh). Then, from the equation

$$L = L_o N^2, \text{ or } L_o = \frac{L}{N^2}, \qquad (5)$$

it is found that $L_o = 4.5/(3)^2 = 0.5$ μh. Applying this value of L_o to the chart, we find that a coil 2½ inches in diameter should be about 4.2 inches long to give the proper inductance. The total number of turns necessary is 4.2 N, or (4.2) (3) = 12.6 turns. The length of the coil for other diameters can readily be found from the chart, and the total number of turns determined by multiplying the length by N, the number of turns per inch.

The chart can be used equally well to find the inductance of a coil of known specifications. For example, it it desired to determine the inductance of a coil 2½ inches in diameter wound with 90 turns of No. 24 D.C.C. wire. The wire tables show that this size of wire has a winding factor of 33.6 turns per inch, from which the length of the coil is found to be 90/33.6 = 2.68 inches. From the chart, L_o is found to be about 0.29 μh for a 2½ inch coil 2.68 inches long. Because $L = L_o N^2$, the inductance of the coil is $(0.29)\ (33.6)^2$, or 327 μh (approximately).

INTERSTAGE COUPLING

In transmitter design, the coupling of the r-f amplifier grid circuit to the plate circuit of the driver stage is of considerable importance. In most cases, the amplifier grid is driven so that grid rectification occurs and, as a result, a direct current flows in the amplifier grid circuit. The amount of d.c. grid current and driving power required depend principally on the tube type used in the amplifier, the class of service, the operating frequency, and on the plate load impedance of the amplifier. Where considerable power must be transferred from the driver to the amplifier, the interstage coupling system should be capable of transferring this power efficiently.

There are two general methods of coupling r-f stages, namely, capacitive and inductive. The latter method may consist of two directly coupled inductances, or of two inductances indirectly coupled through a low-impedance transmission line.

The grid condenser should be connected to a tap on the plate inductance of the driver stage. This tap should be chosen so that the required peak r-f voltage is applied to the grid of the amplifier tube. The higher the peak r-f voltage required, the closer the excitation tap should be placed to the plate end of the driver tank. This coupling method has the advantage of extreme simplicity, because it requires a minimum of parts and of circuit adjustments. It has the disadvantage that the use of a tap on the driver plate tank may form auxiliary tuned circuits which invite spurious, parasitic oscillations.

Direct inductive coupling between the driver plate tank and the amplifier grid tank provides an efficient coupling system. The grid circuit of the amplifier may be either tuned or untuned, the former being more efficient but more critical of adjustment. This system has the disadvantage that more circuit parts and adjustments are necessary than with capacitive coupling. In addition, the driver and the amplifier must necessarily be placed close together due to the importance of short leads at radio frequencies.

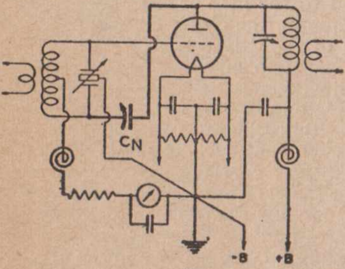
The advantages of inductive coupling can be retained, without the necessity of the coupled stages being in close proximity, by means of a low-impedance transmission line. The most common form, known as "link coupling," consists of two tuned circuits coupled by means of a twisted pair terminated at each end by a coupling coil of a few turns. This system is capable of transferring power efficiently and permits the amplifier to be placed at a considerable distance from the driver stage. Link coupling has the disadvantage of requiring additional circuit parts and adjustments, and is not particularly flexible where operation on several widely different frequencies is required. The coupling "links" should always be coupled to the associated tuned circuits at a point of zero or low r-f potential.

Other types of transmission lines can be used if desired. Two-wire spaced lines are more efficient than ordinary twisted pair, but are more difficult to handle and require more space. Co-axial-cable lines are most efficient, but, if made of considerable length, are costly and in many cases rather unflexible. Co-axial lines are, therefore, little used for coupling between stages.

NEUTRALIZING

A triode used as an r-f amplifier will oscillate because of r-f feedback through the grid-plate capacitance of the tube, unless the effect of this feedback is eliminated. In tetrodes and pentodes, the grid-plate capacitance is practically eliminated by means of a screen grid placed between the grid and the plate. Feedback between grid and plate in a triode is nullified by a circuit arrangement which takes some of the r-f voltage from one circuit and feeds it back into the other circuit so that it effectively cancels the r-f voltage operating through the grid-plate capacitance of the tube. This procedure, known as **neutralization,** makes it impossible for a triode to operate in a self-excited condition. For proper neutralization, the neutralizing voltage must be opposite in phase and equal in amplitude to the feedback voltage between the grid and the plate.

A typical **grid-neutralized circuit** is shown in Fig. 12. In a balanced-input circuit of this type, the neutralizing condenser C_n should theoretically have a capacitance equal to the grid-plate capacitance (C_{gp}) of the tube. Actually, however, the correct value for C_n may vary somewhat from the value of C_{gp}, due to the effects of stray capacitance in the circuit. The circuit from which the neutralizing voltage is obtained is sometimes not of the balanced type. If the tap on the coil is placed more than half the total number of turns from the "tube end," the capacitance required at C_n will increase about in proportion to the relative number of turns in the two portions of the coil. In most cases, it is desirable that C_n should have a small range which is adequate to extend beyond both sides of the calculated value, to take care of circuit and tube variations.



GRID-NEUTRALIZED CIRCUIT.

Fig. 12.

Two triodes in a push-pull circuit are neutralized by means of two neutralizing condensers connected in the so-called "criss-cross" circuit. The grid of each tube is connected through a neutralizing condenser to the plate of the other tube.

Neutralizing Procedure

The technique in neutralizing an r-f amplifier is essentially the same irrespective of the type of tube or circuit employed. As the first step, the positive high-voltage plate lead should be disconnected from the amplifier. The filament of the tube should be lighted and the r-f grid excitation (from the driver stage) applied. Next, a fairly sensitive r-f indicator should be loosely coupled to the plate tank coil. Suitable r-f indicators are a neon bulb, a flashlight bulb or a thermogalvanometer connected in series with a one- or two-turn loop of insulated wire, a vacuum-tube voltmeter, or a cathode-ray oscillograph. The simple indicators are usually more convenient to use than the more complicated instruments. The plate tank circuit of the amplifier should be tuned to resonance, which will be shown by a maximum "reading" on the r-f indicator. The neutralizing condenser is now adjusted until the r-f indicator shows a minimum reading. This operation may detune the plate tank of the driver stage slightly, so that the latter should be carefully returned to resonance. The plate tank of the amplifier should again be tuned to resonance. The r-f indicator will usually show another maximum reading, but one of considerably less magnitude than the original reading. The neutralizing condenser is again adjusted for minimum (or zero) r-f indication. After this procedure has been repeated several times, a setting of the neutralizing condenser should have been found which shows no r-f voltage in the plate tank circuit of the amplifier. As the point of correct neutralization is more closely approached, the coupling of the r-f indicator will usually have to be tightened, because there is less r-f voltage available to operate the indicator. After each adjustment of the neutralizing condenser, the driver tank and the amplifier tank should be retuned to resonance. When the r-f indicator shows zero r-f voltage in the amplifier tank, the stage is properly neutralized. If a push-pull stage is to be neutralized, both neutralizing condensers should be adjusted simultaneously. They will not, however, always have exactly the same setting when neutralization is reached, because of slight differences in stray capacitance, and because the tuned tank circuit may not be electrically symmetrical.

A very sensitive neutralizing indicator is a d.c. milliammeter connected in the grid-return circuit of the amplifier which is being neutralized so as to measure rectified grid current. With the plate-voltage lead disconnected as before, the driver tank circuit is tuned until the d.c. meter in the amplifier grid circuit shows a maximum reading. If the amplifier is not properly neutralized initially, tuning its plate tank circuit through resonance will cause the d.c. grid current to vary. The neutralizing condenser should be adjusted slowly while the plate tank circuit of the amplifier is tuned gradually back and forth through resonance. As the point of correct neutralization is approached, the flicking of the needle of the d.c. grid meter will gradually decrease in amplitude. If the amplifier is perfectly neutralized, tuning the plate circuit through resonance will not change the meter reading even slightly. During these adjustments, the driver plate circuit should occasionally be retuned to resonance, as indicated by a dip in its d.c. plate current or by a maximum in the d.c. grid current of the amplifier.

Because the rectified d.c. grid current is a measure of the r-f excitation applied to the amplifier, the use of a d.c. grid meter is usually advisable. The grid meter is not only useful for neutralizing adjustments, but it also provides a continuous check on the operation of the amplifier and the driver stage as well.

In some cases it may be found that, while a setting of the neutralizing condenser can be made which will give a definite minimum r-f indication, no adjustment will entirely elimintae r-f voltage from the tank circuit. This effect is sometimes due to stray coupling between the amplifier and driver plate tanks or to stray capacitances between various parts of the amplifier which tend to unbalance the neutralizing circuit. Adequate shielding between grid and plate circuits and between stages will often eliminate neutralizing difficulties. Shielding may actually cause trouble, however, if it is placed too close to the tuned circuits or to the neutralizing condensers. It is important that the ground lead from the rotor of a split-stator condenser be made direct (and as short as possible) to the filament circuit.

OUTPUT COUPLING

There are numerous methods of coupling an r-f amplifier to an antenna or feeder system. The method best suited to a particular system depends on a number of factors which vary with different installations. Either capacitive or inductive coupling can be employed, regardless of whether the tank circuit of the final stage is of the balanced or unbalanced type.

Capacitive coupling has the advantage of simplicity, but does not attenuate harmonics which may be present in the output of the transmitter. The d.c. blocking condenser should have a voltage rating high enough to take care of the peak plate voltage applied to the plate tank circuit.

Inductive coupling of the r-f amplifier to the antenna has many advantages and is often preferable to capacitive coupling. A well-designed inductive-coupling arrangement reduces the transfer of power at harmonic frequencies. In addition, inductive coupling effectively isolates the load circuit from the high d.c. plate voltage, provides a flexible means of varying the load on the r-f amplifier, and, in conjunction with a low-impedance transmission line, permits the antenna tuning controls to be located at a distance from the transmitter.

When a tuned antenna tank circuit is inductively coupled to the tank circuit of the amplifier, the antenna coil should be coupled at a point of low r-f potential. This point is located at the "filament end" of a single-ended tank circuit and at the centre of a split tank circuit of the balanced type. The popular "link" coupling arrangement employing a low-impedance transmission line is well suited for coupling to a balanced tank circuit. The turns ratio, primary to secondary, is equal to $\sqrt{Z_p/Z_s}$, where Z_p is the plate-circuit load impedance of the amplifier and Z_s is the impedance of the transmission line. This is a step-down ratio, because the impedance of the plate tank circuit is higher than that of the transmission line.

The plate-circuit load impedance Z_p can be determined approximately from the following relations:

$Z_p = 500\ E_b/I_b$ (for class C amplifiers)

$Z_p = 250\ E_b/I_b$ (for class B r-f amplifiers and for grid- or suppressor-modulated amplifiers)

where E_b is d.c. plate voltage in volts
I_b is d.c. plate current in milliamperes
Z_p is in ohms.

These values of Z_p are for unbalanced, single-ended output circuits. For split-tank or push-pull circuits, the values of Z_p as determined from the equations given above should be multiplied by four.

TUNING A CLASS C R-F AMPLIFIER

In general, the same adjustments are made in tuning different class C r-f amplifiers, irrespective of the type of tube or circuit used. Although the tuning of a triode r-f amplifier is described in the following paragraphs, the procedure applies almost equally well to tetrode and pentode amplifiers. In the following explanation, it is assumed that the triode has been correctly neutralized.

The filament of the amplifier tube is lighted, the positive plate-supply lead disconnected,* and r-f excitation from the driver stage applied. The plate circuit of the driver is tuned to resonance, which is indicated by a dip in the driver plate current or by maximum d.c. grid current in the amplifier stage. If the amplifier has a tuned grid circuit, the latter must also be tuned to resonance (indicated by the grid-current reading). After a maximum amplifier grid current has been obtained by these tuning processes, the coupling between the driver and the amplifier may be adjusted to give still more amplifier grid current, if this can be done without overloading the driver stage. The plate circuit of the driver should be retuned to resonance every time the coupling is changed, because of the interaction between the various circuits.

After the interstage-coupling adjustments have been made, the amplifier plate tank should be set as near to resonance as possible. A

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* The screen voltage should also be removed if the tube is a tetrode or a pentode.

protective resistance of adequate size should then be placed in series with the positive plate-supply lead, as explained in TRANSMITTING-TUBE INSTALLATION. In the case of large, high-power tubes which are protected by d.c. overload relays, this protective resistor can be omitted, especially in those installations where the d.c. plate voltage can be reduced to about 50 per cent of its rated value by means of taps in the primary circuit of the plate-supply transformer. The plate voltage is now applied and the plate tank circuit quickly tuned to resonance (indicated by a sharp dip in the d.c. plate current of the amplifier). The plate current at resonance will usually drop to a value between 10 and 20 per cent of the rated full-load value (see Fig. 13), if no load is coupled to the plate circuit. In case the plate tank condenser does not have an adequate voltage rating, the high r-f voltage developed across the unloaded plate tank circuit may cause the condenser to flash over. This effect should not occur with the d.c. plate voltage reduced 50 per cent, if the condenser is suitable for the purpose. If it does occur, however, the load circuit can be coupled to the plate tank in order to reduce the r-f voltage developed.

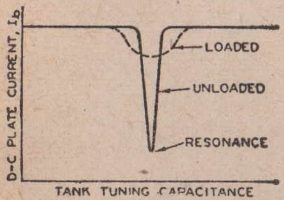


Fig. 13

If the plate tank cannot be tuned to resonance, the reason will usually be found in improper tuned-circuit constants. Either the tank inductance L, or the tank capacitance C, or both, may have to be increased or reduced, depending on whether the circuit is found to tune higher or lower than the desired frequency. An absorption-type wave-meter is useful in checking trouble of this kind. The "off-resonance" plate current of an amplifier may be quite high, even with a protective resistor in the plate-supply lead. For this reason, a tube *should not be operated with its plate circuit out of resonance*, except for the very short time required to make the proper tuning adjustment. If the plate current does not dip normally with no load coupled to the plate tank, the trouble may be due to insufficient r-f grid excitation, to excessive tank-circuit losses, or to improper neutralization. Because the minimum plate current under no-load conditions depends on the Q of the tank circuit, on the biasing method used, and on the excitation voltage, the minimum plate-current value should not be considered a definite indication of the efficiency of an amplifier.

When the tuning procedure described has been completed, the load circuit may be coupled to the amplifier. The load may be an antenna, a dummy antenna (for test purposes), or the grid circuit of a following r-f amplifier stage. When the load is applied, the amplifier plate current will rise. The plate circuit of the amplifier should be retuned to resonance to guard against the possibility that the load has caused detuning. The plate current will still dip, but its minimum value will be considerably higher than under no-load conditions. Full plate voltage should now be applied and the coupling of the load made tighter, until the minimum plate current (at the dip) reaches the normal value given in the typical operating conditions tabulated under the tube type. Of course, if the required power output can be obtained with a lower value of plate current, the load-circuit coupling can be loosened or the d.c. plate voltage reduced. In no case should the d.c. plate input exceed the value given under MAXIMUM RATINGS for the particular class of service involved.

Pentodes and tetrodes are tuned in the same manner as triodes. Because neutralization is ordinarily not required for screen-grid tubes, the circuits of these tubes are relatively simple and easy to adjust. It is quite important in a screen-grid r-f amplifier to prevent stray coupling between the input and output circuits. Although the use of a screen grid in a tube substantially eliminates internal feedback within the tube, self-oscillation and unstable operation may be caused by external feedback due to stray capacitances. Complete shielding of the input and output circuits from each other, and in some cases from the tube itself, is generally advisable.

The value of the d.c. potential on the screen usually has an important effect on power output ; adjustment of this voltage after the circuit has been tuned may result in better efficiency and more power output. Care should be observed, however, that the maximum rated d.c. power input to the screen is not exceeded.

As the load on an r-f amplifier is increased, the d.c. grid current will decrease, more so for triodes than for tetrodes and pentodes. After the load has been adjusted to the desired value, the d.c. grid current should be checked. If it has dropped substantially lower than the normal value, insufficient r-f grid excitation or excessive d.c. grid bias may be the cause.

The process of tuning other types of amplifiers will vary somewhat, depending on the class of service in which the tube is used.

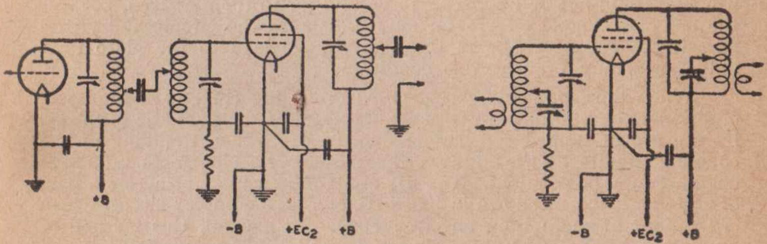
PARASITIC OSCILLATIONS

A **parasitic,** as the term is used in radio work, is any spurious oscillation taking place in a vacuum-tube circuit other than the normal oscillation for which the circuit is designed. Parasitic oscillations may occur in either audio- or radio-frequency amplifiers.

Parasitics, like normal oscillations, are generated when the conditions necessary for oscillations exist and may be of either audio or radio frequency. In many cases, circuit troubles which may be attributed to other causes are actually due to parasitics. They may cause the radiation of spurious carriers and side bands, voltage flashover, loss of efficiency, instability, and premature failure of vacuum tubes and other circuit elements.

Unfortunately, parasitic oscillations cannot always be foreseen and eliminated in the design of a new type of radio transmitter. It is usually necessary to remove any existing parasitics after a transmitter has been constructed. The location of the parasitic circuit often requires considerable study and may involve the use of "cut-and-try" methods. Detuning and damping of the offending circuit to stop the oscillation are often quite simple, once the undesired oscillating circuit has been located. The occurrence of parasitics during the development of a complex, modern transmitter, especially one of high power using several tubes in push-pull or in parallel, is not necessarily indicative of poor design. Such an occurrence is often to be expected.

The most detrimental parasitics are probably those which cause flashovers, spurious radiations, and low amplifier efficiency. The tubes and associated circuits in a transmitter may have damped or undamped parasitics, depending on the feedback coupling, the circuit losses, and the grid and plate potentials, as well as on the reactance and tuning of the parasitic circuit. Damped oscillations, or "trigger" parasitics, occur as the result of modulation transients, keying transients, or flashovers in vacuum tubes due to peak voltage effects. These parasitics may exist only during a part of the modulation cycle, when the plate or grid voltage is at a high positive value. When one parasitic is eliminated, it is quite possible that an entirely different one may start. Vacuum tubes can oscillate simultaneously on more than one frequency, but one oscillation may prevent one or more other oscillations from starting.



(A) LOADING TAPS

(B) TUNING TAPS

Fig. 14

The tuned-plated-tuned-grid oscillator circuit has been found to be the basic circuit for the most common forms of parasitic oscillations. To satisfy the conditions for oscillation, there must be a grid circuit and a plate circuit tuned approximately to the same frequency together with capacitive feedback through the grid-plate capacitance of the tube. Oscillation can usually be stopped by heavy damping or by detuning of the circuits. It is generally preferable to detune a grid parasitic circuit to a much higher frequency than the corresponding plate parasitic circuit in order to stop the spurious oscillation.

Ultra-high-frequency parasitics may be generated if the leads from the amplifier tube to the plate tank condenser are long. This type of oscillation can be eliminated in a number of ways. Resistors in the order of 10 to 50 ohms may be inserted in the grid lead, plate lead, or both, close to the socket terminal. The resistors should be of the non-inductive, wire-wound type, or preferably of the carbon-stick type. When large tubes are employed, especially in class B r-f service, it is not desirable to add very much series resistance in the grid circuit. Too much resistance tends to limit the positive modulation peaks, due to the flow of grid current through the grid resistor. A suitable method is the use of a grid resistor shunted by a low-resistance r-f choke ; the latter carries the d.c. grid current.

Ultra-high-frequency parasitics can also be eliminated by tuning a grid parasitic circuit to a much higher frequency than the corresponding plate parasitic circuit. This detuning can be accomplished by mounting the grid tank capacitor close to the tube in order to make the grid-to-filament circuit as short as possible. Small r-f chokes placed in series with the plate lead, next to the socket, are often helpful. In some cases, resistors should be shunted across the chokes.

Spurious oscillations are sometimes caused if the leads to the neutralizing capacitor are long. At high frequencies, long leads may have considerable inductance. A non-inductive resistor of low value placed in the lead from the tube to the neturalizing capacitor may remedy trouble from this source.

It is common practice to use a split-stator capacitor with the rotor grounded, in push-pull circuits and in single-ended circuits of the balanced type. If the capacitor is not grounded for r-f potentials, a parasitic oscillation may be the result. In such a circuit, with the rotor grounded for r-f voltages, the centre tap on the tank inductance usually should not be by-passed to ground (or to the filament), because the use of a double r-f ground may unbalance the circuit and create parasitics. An r-f choke in the high-voltage lead to the plate tank inductance may prevent this condition.

When taps for loading (Fig. 14A) or tuning (Fig. 14B) are used, additional circuits for parasitics are formed. If the parasitic is caused by the use of tapped coils for loading or excitation, detuning of the coupling circuits by the addition of reactance or a change to inductive coupling may be required. The use of a tuning capacitor across a part of an inductance, as shown in Fig. 14B, creates a complex circuit which is resonant at more than one frequency. In general, this method of obtaining vernier control of tuning is undesirable, especially if the capacitor is shunted across a relatively small portion of the tank inductance.

If "shunt feed" is used for both the grid bias and the plate-voltage supply, considerable trouble may result from the complex circuits thus formed. The choke coils tend to resonate at various frequencies with the tank elements, and cause parasitics of the tuned-plate-tuned-grid variety. For this reason, it is desirable to eliminate shunt-feed chokes wherever possible. If shunt feed is used in one circuit, it is preferable to use series feed in the other. In case two chokes are used, whether in shunt-feed or in series-feed circuits, parasitics thus caused can often be eliminated by using a plate choke having about 100 times the inductance of the grid choke, This arrangement prevents the parasitic oscillating circuit from receiving sufficient excitation to continue in oscillation.

When tubes are paralleled, intertube parasitics having a very high frequency may exist. They may be eliminated by means of small resistors (in the order of 10 to 50 ohms) connected in series with each grid lead at the socket; or, the grids may be connected together with as short leads as possible and small choke coils placed in series with each plate lead.

In the checking of a transmitter for parasitics, an all-wave receiver is quite useful. The receiver will respond not only to parasitics but also to normal harmonics at integral multiples of the operating frequency. The latter are to be expected and need cause no confusion. If the receiver is a superheterodyne and is located near the transmitter, it is also important that signals due to image-frequency response not be mistaken for parasitics. An oscillating detector or a beat oscillator is a valuable aid in this method of testing. A pure tone should result from an unmodulated carrier and from its various harmonics. A rough tone usually indicates the presence of a parasitic.

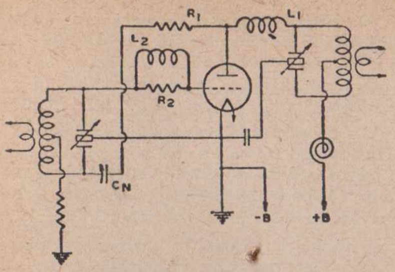


Fig. 15

Fig. 15 illustrates an r-f amplifier circuit with several circuit elements introduced to eliminate parasitic oscillations. R_1 and R_2 are non-inductive resistors having a small resistance. L_1 and L_2 are very small r-f chokes. One or more of these damping elements may be found necessary. In some cases, R_2 may be replaced by a variable capacitor having a very small maximum capacitance. Thus, a tuned circuit or "parasitic trap" is formed for the elimination of ultra-high-frequency parasitics.

PROTECTIVE DEVICES

Transmitting tubes are designed to give long reliable, and trouble-free service when they are operated within their maximum ratings in properly designed equipment. Even in a well-designed transmitter, however, a tube can be subjected to an overload which may be destructive if allowed to persist. Such an overload may be caused by the failure of a driver stage. In this event, the following amplifier tube will, if biased by means of a grid leak, lose its grid bias ; unless the tube has a fairly high mu, it will then draw excessive plate current. The tube must dissipate the entire d.c. plate input because, with no excitation present, the plate efficiency of the tube is zero. Unless the overload is promptly removed, the tube will be damaged.

Although fixed bias from a rectifier may be employed for an r-f amplifier tube, the bias can still be lost because of rectifier trouble. Even if the grid bias and the grid excitation do not fail, an overload may result from inadvertent detuning of the plate tank from resonance. Such detuning causes a large increase in plate current and a rapid decrease in efficiency.

In view of these considerations, it is evident that radio transmitters should be equipped with suitable protective devices. D.c. meters in the various circuits, while invaluable for tuning and testing purposes, as well as for power calculations, offer little assistance in preventing damage due to sudden overloads. A meter will show when the overload exists, but valuable apparatus may be destroyed before the operator can open the power-supply switch.

Protective devices, in order to be effective, must operate very rapidly when an overload occurs, so that the power input to the tube is either greatly reduced or entirely removed. Four commonly used protective devices are : (1) plate-supply series resistor ; (2) cathode resistor ; (3) high-voltage fuse ; and (4) d.c. overload relay.

A series resistor placed in the positive plate-supply lead is useful as a protective device when an amplifier stage is being adjusted initially, or when circuit changes and tests are being made. A sudden rise in plate current will increase the voltage drop across the resistor and automatically decrease the effective plate voltage. Data for calculating resistor values are given in TRANSMITTING-TUBE INSTALLATION. A series resistor in the plate circuit wastes power, and, therefore, is ordinarily not used in normal transmitter operation.

A cathode resistor, used to furnish part or all of the required d.c. grid bias, acts to protect a tube against heavy overloads. The method of calculating the correct value for a cathode-bias resistor is explained under GRID-BIAS CONSIDERATIONS. The proper value for normal operating conditions may not be adequate to prevent exceeding the maximum rate plate dissipation of a tube when the grid excitation fails; however, the severity of the overload will be greatly reduced.

High-voltage fuses of the proper rating, placed in the positive plate-supply lead, protect vacuum-tube circuits very effectively. In the case of a screen-grid tube where the screen voltage is obtained from the plate supply by means of series resistor, the fuse is placed in the common positive lead so that its opening will remove both the screen voltage and the plate voltage; otherwise, with voltage on the screen only, the screen may draw excessive current.

High-voltage fuses are generally designed to blow at a current about 50 per cent higher than their rated value. Fuses designed for small currents are usually intended to carry continuously somewhat less than their rated current. For example, a typical fuse rated at 0.25 ampere has a maximum d.c. load rating of 200 milliamperes for continuous operation.

The continuous-duty current rating of the high-voltage fuse employed in an amplifier stage should be about equal to the normal d.c. plate current of the tube being protected. Thus, when the d.c. plate current reaches a value about 50 per cent. greater than the rated value for the tube, the fuse should blow promptly.

Where a fuse is used as a protective device in a low-power stage which is followed by other stages employing grid-leak bias, it is not usually desirable to use fuses in these other stages. It is apparent that opening of the first fuse may cause fuses in the following stages to blow, due to the removal of grid excitation from all tubes following the low-power stage. If the tubes in the higher-power stages have a fairly high mu, or employ a fixed bias sufficient to reduce the plate current to a low value when grid excitation fails, fuses can be used satisfactorily. Otherwise, a d.c. overload relay is preferable.

A d.c. overload relay, although initially more costly than a fuse, is one of the most satisfactory protective devices. Operating on the magnetic principle, such a relay can usually be adjusted to function on a predetermined value of d.c. current. In addition, a relay can be used almost indefinitely, because it can be reset after each opening. The contactors are about the only parts subject to appreciable wear, and they can usually be replaced.

A relay is seldom used directly to open a high-voltage d.c. circuit. Instead, the holding coil of the relay is placed in the negative plate-supply lead and the contactors are used to open the primary circuit of the high-voltage transformer. In some cases, it may be desirable to place the holding coil in the filament-to-ground return lead, although the coil then carries both the d.c. grid current and the d.c. plate current. When the holding coil is placed in either of the two positions mentioned, the coil should be shunted by a resistor having about 20 times the resistance of the relay winding. This arrangement serves to maintain the ground connection in the event that the relay winding should develop an open circuit. The relay contactors must be heavy enough to carry the relatively large a.c. current flowing in the primary of the plate-supply transformer.

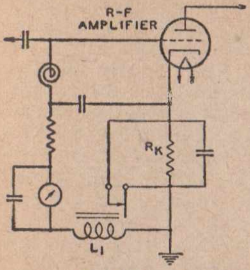


Fig. 16

Fig. 16 shows a very effective method of using a small d.c. relay in conjunction with a cathode resistor to protect a grid-leak-biased tube against grid-excitation failure.* The holding coil of the relay, inserted in the grid-return circuit, causes the relay contactors to short circuit the cathode resistor R_k as long as normal d.c. grid current flows ; thus, the development of bias voltage across R_k is prevented. When the grid excitation fails, however, the relay contactors open and R_k adds enough cathode bias to the circuit so that the plate current drops to a small value. The resistance value of R_k is not critical. It should be about five or more times that of the resistor which would normally be used for cathode bias. A resistance of 10,000 to 25,000 ohms is suitable for most tubes. The wattage rating of R_k depends on the d.c. plate current which will flow against the bias voltage developed across R_k. This type of protective device does not guard against d.c. plate-current overloads caused by plate-circuit detuning and is, therefore, not as universally effective as a d.c. overload relay.

Some radio amateurs may feel that the use of protective devices for vacuum-tube circuits is not necessary for home-built transmitters. It should be remembered, however, that a fuse or a d.c. overload relay will not only protect the amplifier tubes but may prevent the destruction of meters, power transformers, rectifier tubes, and other circuit elements. One heavy overload removed in time may represent a saving many times the cost of a good protective device.

RECTIFIERS AND FILTERS

RECTIFIER TUBES

Rectifier tubes are of the diode type. Their operation is discussed under the section GENERIC TUBE TYPES. The installation requirements of rectifier tubes are, in general, similar to those of other transmitting tubes and are covered under TRANSMITTING TUBE INSTALLATION. Special installation considerations peculiar to rectifier tubes follow.

During its **initial operation,** a mercury-vapor rectifier tube should be operated with normal filament voltage and no plate voltage in order to distribute the mercury properly. The time required for this slow-treating schedule is given under the CHARACTERISTICS for each mercury-vapor tube type. It is unnecessary to repeat this procedure unless during subsequent handling, the mercury is again spattered on the filament and plate.

The application of plate voltage should always be delayed until

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* D. A. Griffin, "Automatic Protection with Grid-Leak Bias," QST, October, 1935.

the filament has attained normal operating temperature. The **delay period** is determined by the length of time necessary to heat the filament and, in mercury-vapor tubes, the length of time necessary to raise the condensed-mercury temperature to the minimum value at which the tube will operate satisfactorily. Factors which increase the delay period are poor regulation of the filament-voltage supply and low ambient temperature. If the filament-voltage supply has good regulation and the ambient temperature is normal, the delay period will be that specified under CHARACTERISTICS for each rectifier tube type. If there is any evidence in the tube of improper operation, such as sputtering or arc-back, the delay period should be increased.

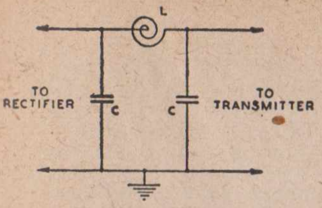
The **condensed-mercury** temperature of a mercury-vapor rectifier tube should be maintained within the ranges tabulated for each tube type. Low condensed-mercury temperature raises the potential at which the tube starts to conduct and is unfavorable for long filament life. High condensed-mercury temperature decreases the potential at which the tube starts to conduct and is favorable for long filament life but reduces the peak inverse voltage that the tube can stand. The temperature of the condensed mercury may be measured with a thermocouple or a small thermometer attached with a small amount of putty at a point near the base of the bulb.

The **bulbs** of mercury-vapor rectifier tubes eventually darken in service. This darkening is normal and is not an indication of the end of tube life.

Voltage and **current ratings** for rectifier tubes in this book are given on the basis of maximum peak inverse voltage, maximum peak plate current, and maximum average plate current.

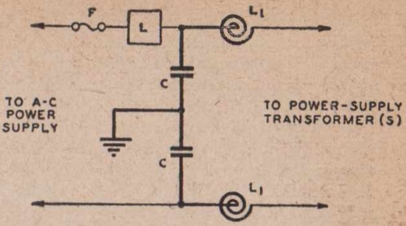
Maximum peak inverse voltage is the highest peak voltage that a rectifier tube can safely stand in the direction opposite to that in which it is designed to pass current. In a mercury-vapor rectifier tube, it is the safe arc-back limit with the tube operating within the recommended condensed-mercury temperature range. The relation between peak inverse voltage, d.c. output voltage, and RMS value of a.c. input voltage depends largely on the individual chracteristics of the rectifier circuit and the power supply. The presence of line surges, keying surges, any other transients, or waveform distortion may raise the actual peak voltage to a value higher than that calculated for sine-wave voltages. Therefore, the actual inverse voltage, not the calculated value, should be such as not to exceed the rated maximum peak inverse voltage for the rectifier tube. A cathode-ray oscillograph, or a spark gap connected across the tube, is useful in determining the actual peak inverse voltage. In single-phase, half-wave circuits with sine-wave input and with condenser input to the filter, the peak inverse voltage may be as high as 2.8 times the RMS value of the applied voltage. In single-phase, full-wave circuits with sine-wave input, the peak inverse voltage on a rectifier tube is approximately 1.4 times the RMS value of the transformer plate-to-plate voltage applied to the tubes. In polyphase circuits, the peak inverse voltage should be calculated for each circuit.

Maximum peak plate current is the highest instantaneous current that a rectifier tube can safely stand in the direction in which it is designed to pass current. The safe value of this peak current in hot-cathode types of rectifier tubes is a function of the electron emission available and the duration of the pulsating flow from the rectifier tube during each half-cycle. In a given circuit, the value of peak plate current is largely determined by the filter constants. If a large choke is used in the filter circuit next to the rectifier tubes, the peak plate



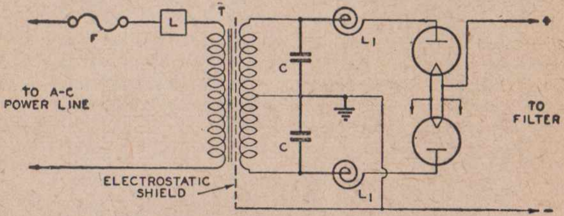
C = R-F BY-PASS CONDENSER, MICA
L = R-F CHOKE

Fig. 17



C = R-F BY-PASS CONDENSER, MICA
F = FUSE
L = OVERLOAD RELAY
L_1 = R-F CHOKE, LOW RESISTANCE

Fig. 18



C = R-F BY-PASS CONDENSER, MICA
F = FUSE
L = OVERLOAD RELAY
L_1 = R-F CHOKE
T = POWER-SUPPLY TRANSFORMER

Fig. 19

current is not much greater than the load current ; if a large condenser is used in the filter next to the rectifier tubes, the peak current is often many times the load current. In order to determine accurately the peak current in any circuit, the best procedure usually is to measure it with a peak-indicating meter or to use an oscillograph.

Maximum average plate current is the highest value of average current that should be allowed to flow through the tube. With a steady load, this current may be read directly on a d.c. meter. With a fluctuating load, the reading should be averaged over the period of time specified under CHARACTERISTICS for each rectifier tube.

A suitable **fuse** or an **overload relay** should be placed in the primary circuit of the power transformer for protection of the power supply against accidental overload.

Rectifier tubes, especially those of the mercury-vapor type, should be isolated from the transmitter as much as possible in order to avoid the detrimental effects of electromagnetic and electrostatic fields. These tend to produce breakdown effects in mercury vapor, are detrimental to tube life, and make filtering difficult. External shielding should be used when the tubes are in proximity to these external fields. R-f filtering should be used when the tubes are affected by r-f voltages. See Fig. 17. When shields are used, special attention must be given to adequate ventilation and to the maintenance of normal condensed-mercury temperature.

Mercury-vapor rectifier tubes occasionally produce a form of local interference in audio and modulator stages of transmitters and in radio receivers, through direct radiation or through the power line. This interference is generally identified in the receiver as a broadly tunable 120-cycle buzz (100 cycles for 50-cycle supply line, etc.). It is usually caused by the formation of a steep wave front when plate current within the tube begins to flow on the positive half of each cycle of the a.c. supply voltage. There are a number of effective methods for eliminating this type of interference. One is to introduce an r-f line filter in the primary circuit of the power-supply transformer. See Fig. 18. Another is to insert an r-f choke between each plate and transformer winding and to connect high-voltage, r-f by-pass condensers between the outside ends of the transformer winding and the center tap. See Fig. 19. These condensers should have a voltage rating high enough to withstand the peak voltage of each half of the secondary, which is approximately 1.4 times the RMS value. Transformers having electrostatic shielding between primary and secondary are not likely to transmit r-f disturbances to the line. Often the interference may be eliminated simply by making the plate leads of the rectifier extremely short. In general, the particular method of interference elimination must be selected by experiment for each installation.

RECTIFIER CIRCUITS

Rectifier circuits are shown in Figs. 20 to 24. Fig. 20 shows the widely used, single-phase, full-wave rectifier using two half-wave rectifier tubes. Fig. 21 shows a single-phase bridge circuit employing two half-wave rectifier tubes in series on each side of a single-phase transformer secondary. This circuit is capable of giving twice the d.c. output voltage for the same total transformer voltage and d.c. output current as Fig. 20. Since the total peak secondary voltage is also the same as that for Fig. 20, tubes of the same peak inverse voltage rating can be used. When the bridge circuit is used, it may be necessary to reduce the load current in order to avoid exceeding the power rating of the high-voltage transformer. Fig. 22 shows a three-phase, half-wave circuit using three half-wave rectifier tubes. In this circuit, each tube conducts for only one-third cycle and three-phase waveform is obtained. Fig. 23 shows a three-phase, double-Y parallel circuit employing six half-wave rectifier tubes. In this circuit, an interphase reactor is required but only one filament-voltage supply is necessary. Fig. 24 shows a three-phase, full-wave bridge circuit employing six half-wave rectifier tubes. Two tubes are connected in series with each transformer leg. Like the bridge circuit of Fig. 21, this circuit will give twice the d.c. output voltage of the half-wave circuit in Fig. 22. In the three-phrase full-wave and three-phase double-Y parallel circuits, six-phase waveform is obtained. This requires relatively little filtering. A summary of the approximate conditions which can be obtained with the use of any mercury-vapor rectifier tube in these circuits is shown in the tabulation. The table is based on sine-wave input and the use of a suitable choke preceding any condenser in the filter circuit (see FILTERS). The table does not take into account the voltage drop in the power transformer, the rectifier tubes, nor the filter-choke windings, under load conditions.

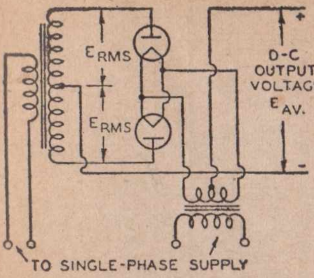


FIG. 20

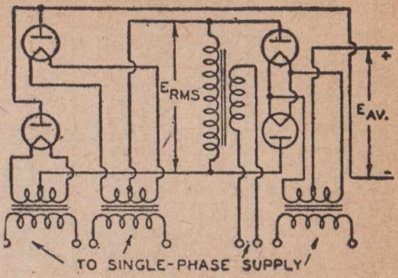


FIG. 21

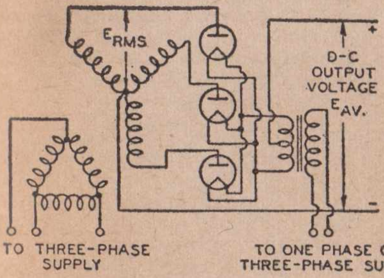


FIG.22

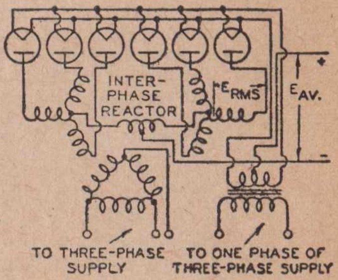


FIG. 23

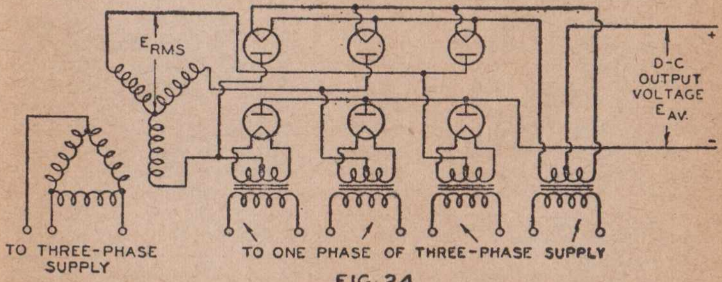


FIG. 24

CIRCUIT	SEE FIG.	TRANSFORMER SECONDARY VOLTAGE E_{RMS}	D-C OUTPUT VOLTAGE TO FILTER E_{AV}	PEAK INVERSE VOLTAGE E_{INV}	MAX. AVERAGE LOAD CURRENT PERMITTED
Single-Phase Full-Wave (2 Tubes)	20	(per tube) 0.353 x E_{INV}. or 1.11 x E_{AV}.	0.318 x E_{INV}.. or 0.9 x E_{RMS}	3.14 x E_{AV} or 2.83 x E_{RMS}	2 x Max. Average Plate-Current Rating per Rectifier Tube
Single-Phase Full-Wave Bridge (4 Tubes)	21	(total) 0.706 x E_{INV}. or 1.11 x E_{AV}.	0.636 x E_{INV}. or 0.9 x E_{RMS}	1.57 x E_{AV}. or 1.41 x E_{RMS}	2 x Max. Average Plate-Current Rating per Rectifier Tube
Three-Phase Half-Wave (3 Tubes)	22	(per leg) 0.408 x E_{INV}. or 0.855 x E_{AV}.	0.478 x E_{INV}. or 1.17 x E_{RMS}	2.09 x E_{AV}. or 2.45 x E_{RMS}	3 x Max. Average Plate-Current Rating per Rectifier Tube
Three-Phase Parallel Double Y	23	(per leg) 0.408 x E_{INV}. or 0.855 x E_{AV}.	0.478 x E_{INV}. or 1.17 x E_{RMS}	2.09 x E_{AV}. or 2.45 x E_{RMS}	6 x Max. Average Plate-Current Rating per Rectifier Tube
Three-Phase Full-Wave (6 Tubes)	24	(per leg) 0.408 x E_{INV}. or 0.428 x E_{AV}	0.956 x E_{INV}. or 2.34 x E_{RMS}	1.05 x E_{AV}. or 2.45 x E_{RMS}	3 x Max. Average Plate-Current Rating per Rectifier Tube

EXAMPLE OF USE OF TABLE

Problem : Choose a type of rectifier tube suitable for use in a single-phase, full-wave power supply to deliver a total average current of 500 milliamperes at a maximum d.c. voltage of 2385 volts. Also, for what maximum secondary voltage (E_{RMS}) should the transformer be designed in order to deliver 2385 volts to the filter at maximum load current.

Procedure : First, determine the maximum peak inverse voltage which each rectifier tube must withstand. By reference to the relations shown for the single-phase, full-wave circuit (Fig. 20 in the above table), it is found that the maximum peak inverse voltage corresponding to a d.c. voltage of 2385 volts is 3.14 x 2385, or 7489 volts. Since two half-wave rectifiers will be required in this service, each rectifier will only have to deliver 500/2, or 250 milliamperes. A rectifier tube meeting these voltage and current requirements is the 866, with a peak inverse voltage rating of 7500 volts and an average plate current rating of 250 milliamperes. In order to deliver 2385 volts to the filter at maximum load, the transformor should be designed so that each half of the secondary will produce an E_{RMS} of 1.11 x 2385, or 2647 volts.

The percentage change in output voltage of the power supply between no-load and full-load conditions is known as **voltage regulation.** For example, if the d.c. output voltage is 1000 volts at no load and is 900 volts at full load, the voltage regulation is (1000-900)/1000=0.1, or 10%. Well-designed power supplies have a regulation of 10 per cent or less. Good plate-supply regulation is essential in self-excited oscillators to maintain frequency stability ; it is essential for class B a-f amplifiers and modulators where the load current varies with the average signal voltage ; and it is equally essential in the keyed r-f amplifier stage where key thumps must be minimized and condenser breakdown avoided. The voltage output of a power supply is reduced by the voltage drop through the rectifier tubes (only 15 volts in mercury-vapor types), the transformer-windings, and the filter-choke windings. It is also influenced by the type of filter system. The power transformer should be of substantial size, of generous overload rating, and should have low-resistance windings. A filter choke should have the proper value of inductance for the operating conditions, and a low-resistance winding. The use of "swinging" chokes and choke-input filters helps to provide good regulation. Their use is discussed under FILTERS.

A heavy-duty bleeder resistor connected across the output terminals of the power supply assist in maintaining good voltage regulation. The resistor prevents the filter condensers from charging up to the peak value of the a.c. voltage and offers protection against accidental shock from contact with charged filter condensers after the power supply has been switched off. The value of current through the bleeder is frequently made about 10 per cent of the full-load current.

Two or more mercury-vapor rectifier tubes can be connected in parallel to give correspondingly increased output current over that obtainable with a single tube. A stabilizing resistor of 50 to 100 ohms should be connected in series with each plate lead in order that each tube will carry an equal share of the load. The value of the resistor to be used will depend on the amount of plate current that passes through the rectifier. Low plate current requires a high value; high plate current, a low value. When the plates of mercury-vapor rectifier tubes are connected in parallel, the corresponding filament leads should be similarly connected. Otherwise the tube drops will be considerably unbalanced and larger stabilizing resistors will be required. When it is desirable to minimize the small power loss caused by the voltage drop through the stabilizing resistor, an inductance of approximately one-third henry may be substituted. The use of the inductance has the added advantage of helping to limit the peak current to each tube. This is especially desirable if a condenser-input type of filter is used.

Two or more high-vacuum rectifier tubes can also be connected in parallel to give corresponding higher output current and, as a result of paralleling their internal resistances, give somewhat increased voltage output. The use of stabilizing resistors is generally unnecessary with parallel-connected high-vacuum rectifiers.

FILTERS

Filters of either the choke-input or the condenser-input type may be employed to minimize rectifier ripple voltage. With either type of filter, the maximum ratings shown under CHARACTERISTICS for each rectifier tube should not be exceeded.

A **choke-input filter** has the advantages of providing good voltage regulation, of limiting current surges during switching, and of limiting peak plate current during rectifier operation. This type of filter is preferable from the standpoint of obtaining the maximum continuous d.c. output from a rectifier tube under the most favorable conditions. It is specially recommended for use with mercury-vapor rectifier tubes and with high-vacuum rectifier tubes having closely-spaced electrodes. The performance of a good choke-input filter can be calculated accurately.

A **condenser-input filter** has the advantage of increasing the voltage output from a rectifier. It has the disadvantages of causing poor voltage regulation, of causing high switching surges, and of reducing the d.c. load current over that permissible when choke input is used. A large input capacitance causes a high surge current when the power switch is closed; a small input capacitance reduces the surge current but decreases the filtering action and the voltage output. When a condenser-input type of filter is used, a current-limiting resistor should be connected between the rectifier tubes and filter to reduce the tube current to a safe amount at the time of switching on the rectifier. The value of this resistance, which also includes the power transformer resistance, can be determined as follows :

$$\text{Current-limiting resistance in ohms} = \frac{\text{k x } E_{RMS}}{\text{rated peak plate tube current in amperes}}$$

where k is equal to 1.41 for circuits of Figs. 20 through 23, and 2.45 for Fig. 24. After the rectifier-filter system has been switched on, the resistor can be short-circuited to avoid reducing the d.c. output voltage. The resistor is employed at each switching operation. Because of the many variable factors involved in the functioning of a condenser-input filter, its performance is more difficult to determine than that of a choke-input system.

The general filter-design curves in Figs. 25A and 25B are useful in the selection of suitable combinations of chokes and condensers for choke-input filters. Values can be chosen from these curves to limit the peak plate current and the average plate current to the maximum rating of any rectifier tube for a given percentage of ripple voltage in single-phase, full-wave circuits operating from a 60-cycle supply. When the power supply is operated from a 50-cycle source, multiply the values of selected inductance and capacity by 60/50, or 1.2. When the power supply is operated from a 25-cycle source, multiply the selected filter values by 60/25, or 2.4.

The load resistance curves, identified by R_L, give the minimum or critical value of inductance that should be used with the indicated load resistance. Lower than the minimum inductance values may result in overloading of the rectifier tubes under steady operating conditions, and in poor regulation. The value of R_L for any specific design is obtained by dividing the required rectifier d.c. output voltage by the desired load current (in amperes). The d.c. output voltage used for this calculation is taken as 90% of the RMS voltage per rectifier tube plate. It does not take into consideration the regulation of the power transformer, filter choke(s), or rectifier tube(s). The percentage ripple curves, identified by E_{R_1}, represent the percentage ripple for any single-section filter combination. An E_{RMS} line is given for each rectifier tube type. It shows the various combinations of minimum filter inductance and maximum filter capacitance (C_1) that will limit the surge current to the maximum peak plate current rating of the particular tube it represents, at the maximum peak inverse voltage rating of the tube. Always select filter constants to the left of E_{RMS} When lower than the rated maximum peak inverse voltage is used for a tube type, lower inductance and high capacitance values may be used without exceeding the peak current rating of the tube. In this case, the filter combination is selected to the left of a new E_{RMS} line, the points of which are determined from the equation.

$$L_1 = \left(\frac{E_{RMS}}{I_{MAX.} \text{ x } 1110} \right)^2 C_1$$

where C_1 = First filter condenser capacitance in microfarads
L_1 = First filter choke inductance in henries
$I_{MAX.}$ = Peak plate current rating of tube in amperes
E_{RMS} = RMS transformer voltage per tube

When more filtering is required than can be obtained economically by means of a single filter section, a second filter section may be added to the first. The size of L_2 and C_2 for the second section may be easily determined from Fig. 25B. Since E_{R1} is known for the first section, the values of L_2 and C_2, as a product, may be read from the appropriate E_{R1} curve for any desired value of percentage ripple E_{R2}. Practically any values of L_2 and C_2 forming the product read from the curve can be used for the second section. However, in order to avoid serious circuit instability and impairment of filtering due to 120-cycle resonance, L_2 (in henries) must always be greater than $3 \ (C_1 + C_2) \div 2C_1 C_2$ where C_1 and C_2 are in microfarads.

When designing a single-section filter, use Fig. 25A and observe the following rules. Always select inductance values, (1) *above the proper R_L curve,* (2) *to the left of the proper ERMS curve, and* (3) *along the desired E_{R1} curve. Use the corresponding value of filter capacitance for each selected value of inductance. When designing the second section of a double-section filter, use Fig. 25B and observe the following rules.* (1) *Select desired percentage of output ripple voltage E_{R2} on appropriate curve of E_{R1}.* (2) *Read corresponding $L_2 C_2$ product.* (3) *To satisfy this product, choose convenient values of L_2 and C_2.* (4) *Check the chosen value of L_2 to insure that it is greater than $3 (C_1 + C_2) \div 2C_1 C_2$.*

When the load resistance varies over a wide range, good regulation may be obtained by (1) connecting a bleeder resistance across the filter output to restrict the range over which the effective load varies, (2) using an input choke with sufficient inductance to meet all values of load resistance up to the highest attained, or (3) using a swinging input choke. The last method is the more economical.

The inductance of a well-designed swinging choke rises from its normal value at rated load current to a high value at low load current. The required minimum and maximum values of swinging choke inductance can be determined from Fig. 25A at the intersection of the proper ERMS curve with the minimum and maximum R_L curves, respectively. It is generally more economical to select low values of swinging choke inductance and to depend on additional filter sections to provide the required smoothing.

EXAMPLE No. 1

Problem: Given a d.c. output of 3180 volts (corresponds to a peak inverse voltage of 10,000 volts) from a 60-cycle full-wave rectifier employing two 872-A's, design a single-section filter of the choke-input type which will limit the ripple voltage of 5% at a load current equal to the combined maximum d.c. load-current rating of the tubes (2.5 amperes), and prevent the peak plate current of either tube from rising higher than the maximum peak plate-current rating of the 872-A.

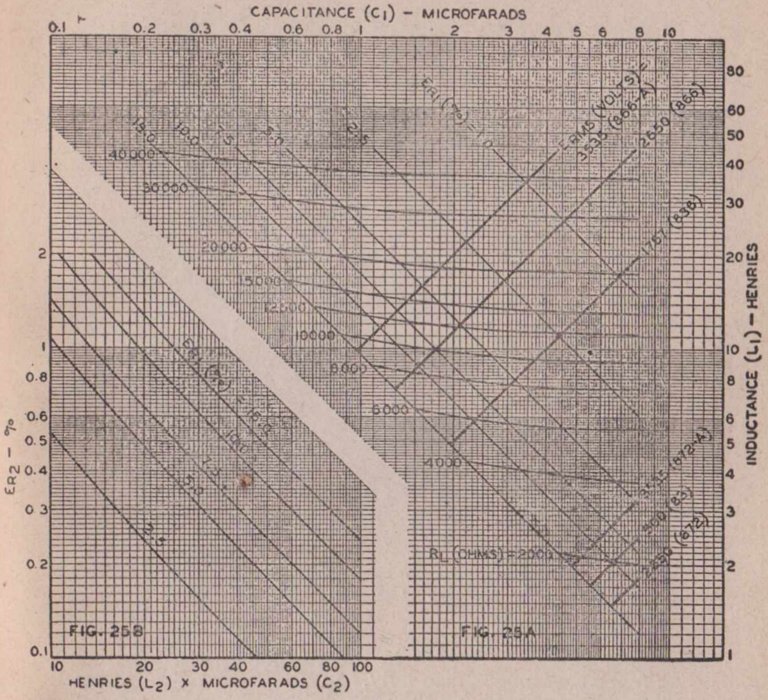
Procedure: ERMS is equal to 3180 x 1.11, or 3535 volts. R_L is equal to 3180/2.5 amperes, or 1272 ohms. From Fig. 25A, $R_L = 1272$ lies below curve ERMS$=3535$ (as shown for the 872-A) and, therefore, is not required for the selection of filter constants. Any combination of inductance and capacitance along the curve $E_{R1} = 5\%$ and to the left of the curve ERMS $= 3535$ will satisfy the requirements. A suitable combination is a filter section employing a 25-henry choke and a 1-microfarad condenser.

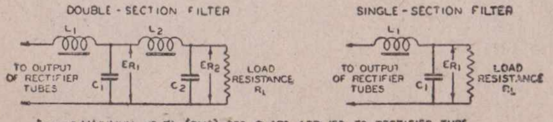
EXAMPLE No. 2

Problem: Given a d.c. output voltage of 2385 volts (corresponds to a peak inverse voltage of 7500 volts) from a 60-cycle full-wave rectifier employing two type 866's, design a double-section filter which will limit the output ripple voltage to 0.5% at a load current equal to the combined maximum d.c. load-current rating of the tubes (500 milliamperes) and prevent the peak plate current of either tube from rising higher than the maximum peak plate-current rating of the 866. The input choke is to be of the swinging type and the voltage regulation is to be good from no-load to full load.

Procedure: E_{RMS} is equal to 2385 x 1.11, or 2650 volts. At maximum load, $R_L = 2385/0.5$ ampere, or 4770 ohms. Since curve $R_L = 4770$ lies below curve $E_{RMS} = 2650$ volts (as shown for the 866), it is not needed in the selection of constants for the first filter section. A value of 10% ripple at the output of the first filter section will be assumed to be satisfactory. The minimum value of swinging-choke inductance and corresponding value of capacitance for the first-section filter condenser may, therefore, be selected along curve $E_{R1} = 10\%$ and to the left of curve $E_{RMS} = 2650$ volts (for 866). Suitable values are 13.5 henries and 1 microfarad. The maximum value of swinging choke inductance to be used with a condenser having a capacity of 1 microfarad should be as high as practical. Assume that this value is 40 henries. Then, with a capacitance value of 1 microfarad, the maximum value of R_L is 44,000 ohms. Therefore, a bleeder resistance of 44,000 ohms is required to keep the d.c. output from "soaring" at no-load conditions. With a load resistance of 44,000 ohms, the bleeder current is $2385/44000 = 0.054$ ampere, or 54 milliamperes. The total useful d.c. output current is then 500—54, or 446 milliamperes.

The design of the second filter section should now be considered. It must be capable of reducing the ripple voltage from 10% in the first section to 0.5% in its own output. From Fig. 25B, the value of the product L_2C_2 is 37 as read on the curve $E_{R_1} = 10\%$ when $E_{R_2} = 0.5\%$. If C_2 is chosen to be 2 microfarads, $L_2 = 37/2$, or 18.5 henries. This value of L_2 is greater than $3(C_1+C_2) \div 2C_1C_2 = 3(1 \times 2). \div 2(1 \times 2)$, or 2.25, and therefore is of ample size to avoid resonance effects.





ERMS = MAXIMUM VOLTS (RMS) PER PLATE APPLIED TO RECTIFIER TUBE
RL = LOAD RESISTANCE

ER_1 = Per cent ripple in D-C output voltage from (1) the first section of a double-section filter, or (2) a single section filter.
ER_2 = Per cent ripple in D-C output voltage from second section of a double-section filter.

GENERAL RULES FOR SELECTION OF FILTER CONSTANTS

SINGLE-SECTION FILTER (FIG. 25A)

Select Inductance Values (1) Above proper RL Curve
(2) To left of proper ERMS curve
(3) Along desired ER_1 curve

For each selected inductance value, use corresponding value of filter capacitance

DOUBLE-SECTION FILTER (FIG. 25B)

(1) Select desired percentage of output ripple voltage ER_2 on appropriate curve ER_1
(2) Read corresponding L_2C_2 product.
(3) To satisfy this product, choose convenient values of L_2 and C_2
(4) Check value of selected L_2 to make sure that it is greater than $3(C_1+C_2) \div 2C_1C_2$

* See text for applying these curves to other supply frequencies.

THYRATRONS

ESSENTIAL FEATURES OF THYRATRONS

A thyratron is an electronic tube in which the unidirectional flow of electron current through an inert gas or vapor from cathode to anode may be started by impressing an electro-static charge on one or more control electrodes.

The control electrode, or grid, controls only the starting of the discharge. After being started, the discharge cannot ordinarily be modified or stopped by controlling the charge on the grid because the positive ions generated in the gas or vapor neutralize the negative field of the grid charge, thus preventing any electrostatic action by the grid in controlling anode current. Control by positive grid potentials is not possible because the current through the tube in the forward direction is limited only by the external circuit and the high currents that would be drawn to the grid when made positive cannot be added to the current in the external circuit. The presence of positive space charge in the thyratron results in a reduction, during conduction, of the voltage drop from anode to cathode to a low value of the order of the ionization potential of the gas used. Thus, a gas-filled thyratron is capable of rectifying or controlling relatively large currents at high efficiency.

The positive space charge in the gas or metallic vapor which reduces the anode to cathode voltage drop prevents the modulation action obtained in vacuum tubes. In a vacuum type, the current is limited by the negative space charge which is not neutralized by positive gas ions, and therefore, the conductive properties of the tubes may be controlled by modifying the space charge with the electrostatic field set up by the grid potential. These differences are fundamental in the comparative actions of gas-filled and vacuum tubes. On direct current the thyratron grid can control only before conduction is started in the tube; thus the tube can be used as a starting mechanism only. In alternating current circuits, current flows through the tube intermittently, and at the end of each conduction period the grid can regain control. After the grid has regained control, the average current flowing through the tube can be changed by changing the instant in each cycle in which the grid starts the tube to conduct. By making the grid sufficiently negative, conduction through the tube can be entirely prevented, thus giving starting and stopping action as well as magnitude control.

A method often used to control the magnitude of the average output current in alternating current circuits is shown in Fig. 1. This method consists in applying to the grid alternating voltages of controllable phase with respect to the anode voltage. The characteristic voltage below which conduction will not occur is plotted as a function of time underneath the positive sine wave anode voltage. Whenever the grid voltage is more positive than this critical curve, conduction will occur. By changing the phase as shown in the diagram, start of conduction can be delayed, thus reducing average anode current. A better method is shown in Fig. 2, wherein a "peaker" type transformer or other method of obtaining steeply peaked waves is used in conjunction with a negative bias. The advantage of this method lies in the fact that the potential on the grid is negative during the entire inverse voltage half-cycle, thus no positive grid current can flow during the period when the anode is at a negative potential. This method has the further advantage that the grid voltage and characteristic control curve intersect at nearly right angles, thus insuring very precise control regardless of shift in characteristics due to change in ambient temperatures, line voltages, or variations due to unavoidable manufacturing variations.

Thyratrons are commonly made as three or four element types. The fourth element is known as the shield grid and has the following functions:

1. To reduce the capacity of the anode to the control grid, thus minimizing the coupling between anode and grid, with resultant reduction of loss of control due to anode voltage transients.

2. To shield the control grid from the anode, thus reducing grid currents, which might be caused by a deposit of cathode material on the grid, and by reducing the operating temperature of the control grid.

3. To modify the critical control grid characteristic by changes in the shield grid potential.

4. To effect dual control by the application of starting voltages to each grid. The starting of the tube thus is controlled by the combination of two signals. A blocking voltage could be applied to either grid which would prevent starting of the tube, and upon the removal of the blocking voltage, the tube could then be controlled by a phase-shifted voltage on the other. The higher impedance grid control circuit should be connected to the control grid.

5. To reduce the current to the control grid during the conduction period due to the smaller active grid area of the control grid.

TYPICAL APPLICATION OF THYRATRONS

Thyratrons can be used advantageously wherever currents of relatively large magnitudes are to be controlled, and where sufficient control can be obtained by the change in starting time. The broad general classifications of this type of application are:

1. **Control** Control can be effected in d.c. circuits as a sensitive starting relay. Thyratrons can also be used in conjunction with ignition tubes to control very large currents, such as are used in resistance welding.

2. **Rectification.** These tubes may be used to rectify alternating to direct currents. The control action of the grid may be used to control, or automatically regulate, the output d.c. voltages supplied by the tube. Rectification finds application in the control of the speed of direct current motors, and in the control of stored energy type welding circuits.

3. **Inversion.** The tubes may be used to change direct current to alternating current by use of the blocking action of the grids. Frequencies of the order of 1000 cycles per second or less can be generated.

4. **Frequency Changing.** By combination of the above rectification and inversion process, power can be converted from one frequency to another.

Circuit diagrams and information for effecting the above applications can be found in various standard textbooks.

ESSENTIAL FEATURES OF GRID GLOW TUBES

A grid glow tube is a cold cathode gas or vapor discharge tube provided with one or more electrodes which serve to start the discharge. The overall characteristics are similar to those of thyratrons but, in general, the anode current ratings are low compared to thyratrons. The major advantage of a grid glow tube results from the use of a cold cathode in eliminating filament power requirements which is important in applications requiring long standby service. The tubes may be employed in any of the applications which were previously outlined for thyratrons. The limitation is, of course, defined by the rating of the tube. One additional important application is the use of the grid glow tube as an intermittent light source for stroboscopic applications.

INSTALLATION OF THYRATRONS

Mechanical. Thyratrons of the mercury vapor type must be installed in a vertical position with the cathode base down. Gas type thyratrons may be mounted in any desired position. If the tubes are subjected to conditions of vibration or mechanical shock, some shock absorbing means must be provided. Bulbs should be prevented from direct contact with metal or cold liquids which may possibly cause the glass envelope to crack.

Cooling. At no time during operation of a mercury vapor tube should the temperature of the tube, measured at the top edge of the base, be outside the rated temperature range. In order to insure that the tube temperature is kept within the proper range, it may be found necessary to heat or cool the enclosure in which the tubes are operated. In either case, the air in the enclosure should be kept in motion by a suitable fan and the direction of air flow should be upward past the tube so that the point of lowest temperature is at the bottom of the tube in order to insure proper distribution of mercury within the tube.

Cathode and Heater Circuits. The life of a hot cathode tube is critically dependent on the temperature of the cathode. Therefore, it is advisable to measure the filament or heater voltages at the time of installation of equipment and adjust them to meet the specified voltage with proper regard for the variation from mean line voltage at the time of making the adjustment. Cathode voltage should be measured at the base pin terminals. For indirectly heated types of cathodes, the grid and anode returns should be made to the cathode. In the case of a directly heated type of cathode, it is generally preferable to make the returns to the centre tap of the cathode transformer. To obtain the maximum tube life with directly heated cathodes, it is desirable to operate the cathode approximately 90 deg. out of phase with the anode current. In the case of d.c. cathode heating, it is customary to make return connections to the negative side of the cathode supply.

Cathode Heating Time. The minimum time for heating a cathode before application of anode voltage is specified in the technical data sheets. For gas-filled tubes, this is the only heating time necessary to be observed in proper operation of the tube. However, in the case of mercury vapor tubes, the temperature of the tube, as previously described under cooling, also must be within the rated range before starting. When a new tube is installed it must be operated only with filament or heater voltage for a period of 15 to 30 minutes to insure proper distribution of the mercury before anode voltage is applied. It is advisable that time delay relays be used to protect the tubes from cold starting.

Grid Circuits. There are several methods of applying grid voltage for control purposes. Although most of these methods will give control, many of them definitely affect reliability of operation and tube life. There are certain fundamental precautions which must be observed in applying grid voltage to a thyratron.

1. It is undesirable to draw positive grid current at any time when the anode is negative. The reason for this is that the tube would thereby be ionized during the time that the grid is drawing positive current, thus causing an inverse electron current to flow from the anode, which will increase the probability of arc-back. In the case of a gas tube, even where arc back does not occur, the rate of gas cleanup is greatly accelerated by the presence of inverse anode current. Where it is necessary to allow the grid to become positive while the anode is on the negative half cycle, sufficient grid resistance should be inserted to limit the grid current to a relatively low value. This will minimize the objections to positive grid current previously mentioned but at the expense of reliability of control. It is definitely preferable to use a method of grid control which will not cause the tube to be ionized when blocking inverse voltage.

One of the most suitable method of achieving this result is to apply a grid signal of short duration superimposed on a negative grid-bias.

The high sensitivity of control grids in thyratrons makes it essential to shield the grid control circuits from the effect of external electric fields or transients by the use of suitable wave traps and grid to cathode by-pass condensers. The grid to cathode condenser should have the highest capacity consistent with the strength of the required grid signal.

DEFINITIONS

Anode Potential, Maximum Peak Forward—is the highest rated instantaneous voltage between anode and cathode in the direction in which the tube is designed to pass current. This is the maximum voltage which can be blocked by the action of the grid.

Anode Potential, Maximum Peak Inverse—is the highest rated instantaneous voltage between anode and cathode in the direction opposite to that in which the tube is designed to pass current. Allowance should be made for line fluctuations and voltage surges so that the actual voltage on the tube never exceeds the rated maximum. Voltages in excess of this limit may cause arc-backs resulting in glass or mechanical failure or loss of emission.

Anode Current, Maximum Average—is the highest average value of current that the tube is rated to carry continuously in the normal direction. In the case of a rapidly repeating duty cycle, this may be measured on a d.c. meter. Otherwise it is necessary to calculate the average current over a period not greater than the maximum averaging time.

Anode Current, Maximum Peak—is the highest instantaneous current that the tube is rated to carry recurrently in the direction of normal current flow. This value should be determined by means of an oscillograph or other reliable means since it depends on the wave-form and load conditions of the individual circuit. Excessive currents will result in deterioration of the cathode, overheating of the bulb and short life.

Anode Current, Maximum Surge—is the largest transient current that the tube is rated to carry in the direction of normal current flow without being rendered immediately inoperative. This rating is intended to form a basis for equipment design to limit abnormal currents that may flow during short-circuit conditions. It does not means that the tube can be subjected to repeated short-circuits without the probability of great reduction in life. The duration of the surge current must not be greater than one-tenth of a second.

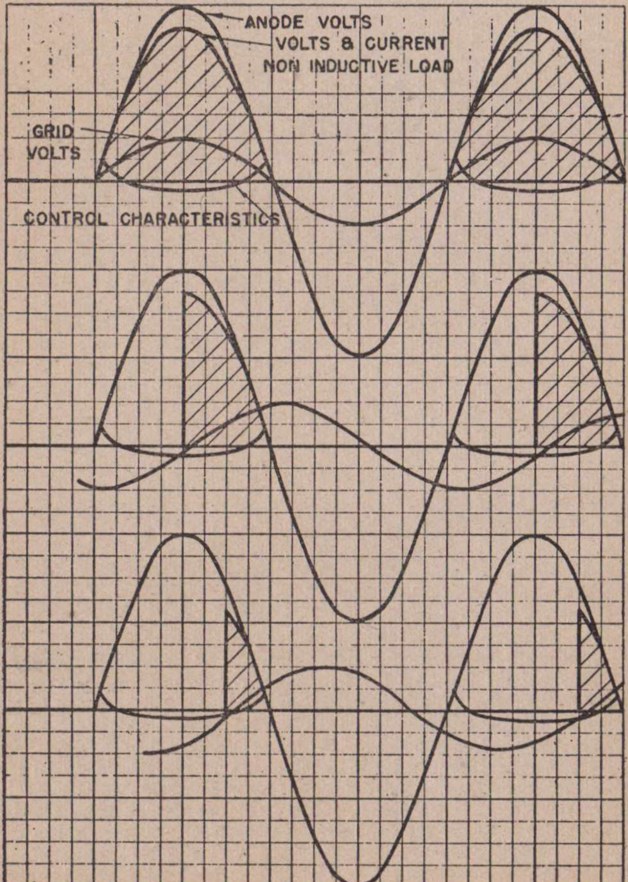


FIG. 1

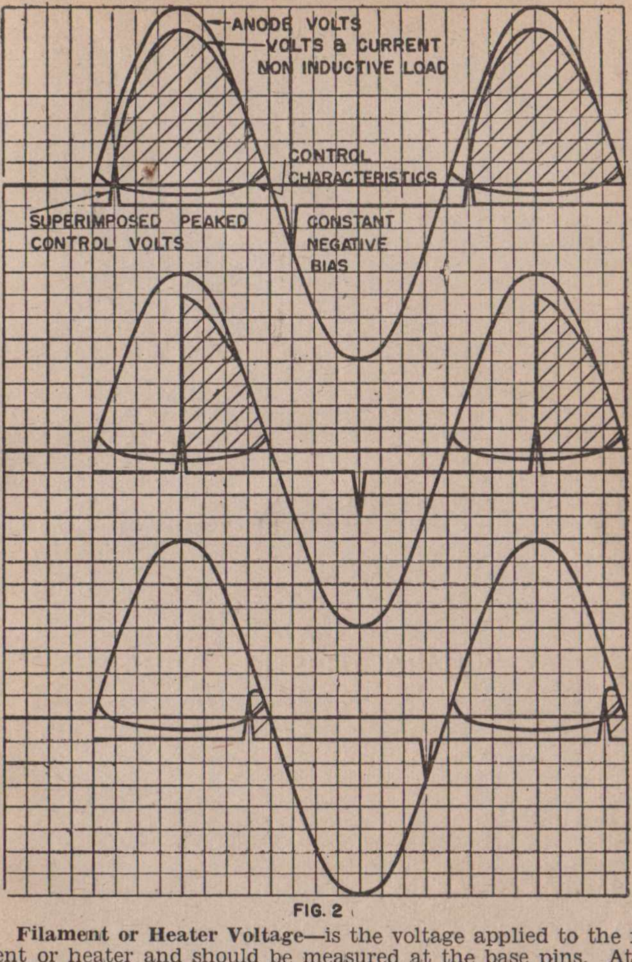


FIG. 2

Filament or Heater Voltage—is the voltage applied to the filament or heater and should be measured at the base pins. At all times the voltage must be maintained at the recommended value and the tube will operate most satisfactorily when the fluctuations of cathode voltage due to all causes are not greater than plus or minus 5%.

Filament or Heater Current—is an average value of current for the specified filament or heater voltage.

Filament or Heater Heating Time—is the minimum time required for the filament or heater to reach emitting temperature. A longer heating time should be provided whenever possible.

Grid Current, Average—just before breakdown is the grid current as measured with the grid voltage just sufficiently negative to prevent the tube from conducting. This current determines the voltage drop across the series grid resistor at the instant of breakdown.

Grid Current, Maximum Average—is the highest average current which the tube is rated to carry to the grid continuously in the normal direction.

Grid Current, Maximum Peak—is the largest instantaneous current which the tube is rated to carry to the grid recurrently in the normal direction of current flow.

Tube Voltage Drop—is the value of the anode to cathode voltage drop while the tube is passing current. The maximum and minimum values cover the range of voltages obtained with variations of load current and with life.

Ionization Time—is the time required for a sufficient number of positive ions to be formed around the cathode to allow the maximum peak current to pass without damaging the cathode.

Deionization Time—is the time required under normal conditions to clear the space inside the bulb of positive ions. This is necessary to regain grid control. The time given is based on a condition of maximum anode current.

Maximum Averaging Time—is the longest period over which the current should be averaged regardless of wave form.

Condensed Mercury Temperature Range, Optimum—is the range of temperature, measured at the junction of the cathode base and bulb at which the tube will operate most satisfactorily and give the utmost reliability and longest life.

Condensed Mercury Temperature, Maximum—is the highest temperature, measured as above, at which the tube can be operated without danger of arc-back or loss of grid control.

Condensed Mercury Temperature, Minimum—is the lowest temperature, measured as above, at which the tube can be operated without loss of emission due to a high voltage drop.

CHARACTERISTIC CURVES

Curves shown in the technical data give the relationship of the control grid voltage plotted as abscissa to the anode peak volts plotted as ordinates. The area between limiting curves indicates variations which may be expected in individual tubes initially and throughout life when operated within the specified temperature range. It will be apparent that any individual tube at a definite temperature will have a characteristic control curve of a very limited area. For any given anode voltage, the tube will fire with the grid more positive than the corresponding critical point. The control grid curve is the locus of the voltage points above which the tube will conduct after voltage application to produce ionization. In order to achieve short ionizing time when conduction is desired, the grid should be made considerably more positive than the values shown on the characteristic curve.

PHOTOTUBES

GENERAL INFORMATION

Phototubes are electronic devices which permit the passage of electrons from cathode to anode when the cathode surface is exposed to radiant energy. Varying the intensity of the light causes a corresponding variation of electron flow within the tube and resultant variation of the electric current in the external circuit.

The current change rapidly follows the change in light intensity so that variations in light through a sound track on a film may be made to reproduce the original sounds with great fidelity. The number of electrons emitted by the cathode depends upon both the wave length and the intensity of the radiant energy falling upon the sensitized surface of the cathode. Advantage is taken of the fact that different metals are sensitive to different wave lengths to provide a line of phototubes which cover not only the usual visible spectrum but also include tubes which are sensitive only to specific regions of ultraviolet radiation. A phototube suitable for almost any application is thus available.

Sensitivity of Phototubes

The sensitivity of a phototube may be defined as the number of microamperes per microwatt of radiant energy reaching the cathode. The radiant energy is comprised of visible light and invisble infra-red and ultraviolet radiation. The effect of the ultraviolet radiation is limited by the nature and thickness of the glass envelope as well as by the response of the sensitive cathode surface to short wave lengths. Phototubes designed to be affected by visible light are made up with glass envelopes which cut off the greater part of the ultraviolet radiation. The sensitivity of phototubes in this class is defined as the luminous sensitivity and is expressed by the number of microamperes per lumen of light flux on the cathode. As an illumination of one lumen on the cathode of a phototube would be excessive, the sensitivity values of phototubes are actually determined by using values in the order of 0.1 lumen. The dynamic sensitivity is determined by varying a light input of 0.1 mean lumen sinusoidally from 0 to 0.2 lumen and finding the ratio of the instantaneous values of anode current at 250 volts on the tube and 1 megohm load resistance, to the corresponding value of light flux. The light source used is a Mazda projection lamp operating at a filament colour temperature of 2870 deg. K. The dynamic sensitivity of a gas phototube is measured in a similar way except with 90 volts on the tube and a mean light input of .015 lumen.

Static and Dynamic Sensitivity

Static luminous sensitivity of a phototube is the sensitivity obtained when a constant or slowly varying light flux is applied. A phototube used for sound reproduction is subject to rapid variations in light flux especially in the upper register and, consequently, the dynamic sensitivity is important. This dynamic sensitivity may be defined as the ratio of the instantaneous amplitude of variation in the phototube circuit to the corresponding amplitude of variation in the luminous flux input. In a gas tube these rapid variations may result in reduced sensitivity because of the time lag caused by gas ionization which tends to smooth out the variations in current. This reduction in sensitivity is not great enough to affect seriously the fidelity of sound reproduction within the normal upper limit of sound frequency which is about 10,000 cycles.

Vacuum and Gas Phototubes

A phototube which is exhausted to a high degree of vacuum can deliver current to the external circuit in direct ratio to the number of electrons driven from the cathode by the action of the radiant energy. Any amplification of this current is obtained outside the tube by means of an amplifier. High vacuum tubes are more constant in sensitivity throughout life than gas tubes and are less liable to be damaged by accidental operation at voltage or current in excess of rated values. A vacuum type tube can be operated at a considerably higher voltage than a gas tube. This is important in certain applications.

In a gas type phototube the electrons liberated from the cathode by the radiant energy are increased in number by collisions with gas atoms which disrupt the atom and release additional electrons which move to the anode and free positive ions which are attracted to the cathode. These positive ions striking the cathode release electrons in addition to those released by the radiant energy. The current through a gas phototube is thus increased by the production of ions and consequent increased electron current. The current may thus be several times greater than that from a similar vacuum phototube. The gas ratio of a phototube is the ratio of its response with a given illumination at the operating voltage to its response at the voltage at which gas amplification begins. Ordinarily, this is taken as the ratio of the phototube response at 90 volts to its response at 25 volts. If this gas ratio is excessively high a phototube becomes unstable, so the ratio is usually made not greater than 10.

Ultraviolet Phototubes

The group of four phototubes makes possible the measurement of the radiant energy in different regions of the ultraviolet spectrum which produce characteristically different effects. As each pure metal has a photoelectric response to a definite band of wave lengths in the spectrum, it is possible to select a phototube which will measure the energy output of an ultraviolet source with the assurance that frequencies or wave lengths outside the sensitivity range of the phototube are not affecting the measurements. The data given for each tube outlines the principal or best known physical effects of the ultraviolet region, as well as the spectral range in angstrom units. These ultraviolet phototubes supply very minute currents, as the total amount of energy reaching the cathode is small.

The 789 phototube, which is sensitive to wave lengths below 2000 angstroms, is made up with a very thin indrawn window to permit as high a percentage as possible of the short wavelengths to reach the cathode surface. This window, which has a thickness of only a few microns, must be treated with special care. It should not be touched except with a very soft camel's hair brush, and even this may be avoided by gently pouring alcohol and later ether into the window opening and swirling it around to clean the glass.

These phototubes may be used to determine the integrated output or quantity of radiation from a source of ultraviolet or to indicate the intensity of radiation.

Phototube Applications

Phototubes are inherently suited to the control of artificial lighting for schools, offices, factories, public buildings, streets, and signs. They may be used for starting, stopping, or controlling mechanical operations and for counting such objects as cartons, sheets of paper, steel ingots, vehicles or pedestrians. Phototubes are used for matching colours, keeping printing presses in correct registry, rejecting packages which are not labeled or are incorrectly labeled. Doors in garages, restaurants, railway stations, department stores may be opened by phototubes as people approach, and closed after them. These versatile tubes can detect and record the density of smoke, control the temperature of furnaces, detect the difference between flame and solids heated in the flame. Materials can be graded as to size, thickness or colour. Since light is the controlling medium, no actual contact need be made to the object which actuates the control mechanism.

Installation

Phototubes which are sensitive to visible light may be mounted in any position with the base of the tube either up or down. However, the group of ultraviolet sensitive phototubes cannot be operated with the base above horizontal because the sliding shield within the tube, which is used during manufacture, may slide and cover the sensitive surface of the cathode. If this shield is not at the bottom of the tube when received, the tube should be held with the base down and gently tapped until the shield slides down. The sensitive surface of the cathode must always face the source of light on which operation depends and be shielded from other sources. If phototubes are mounted where there is vibration, the sockets should be cushioned. Temperature of the air surrounding the tube should not exceed 50 deg. C.

It is essential to minimize electrical leakage and capacitance between electrode connections as these may reduce or distort the small current generated by the action of the radiant energy on the cathode. High quality sockets and well insulated and shielded leads are vital to the successful application of phototubes. The operating source of illumination should cover as much of the surface of the cathode as possible, although the tube may operate with only a small portion of the cathode illuminated.

Operation

The rated voltage and current of a gas-filled tube should never be exceeded. These two factors govern the number and velocity of positive ions striking the cathode per second. If too many ions bombard the cathode with excessive velocity, the sensitive surface may be disintegrated and the sensitivity of the tube may be impaired. A gas discharge, evident as a faint blue glow, may occur if the rated current or voltage of a gas phototube is exceeded. If such a glow occurs, the anode voltage should be removed from the tube immediately in order to prevent permanent damage.

A phototube generally gives best results under constant use. The characteristics of a phototube which has not been used for a month or more may change somewhat, but will be restored to normal after one or two hours of operation with the usual voltage and illumination. Exposure to excessive amounts of light, such as direct sunlight, may temporarily decrease the sensitivity of a tube even though no voltage is applied. The magnitude and duration of this decrease depend upon the length of over-exposure.

Characteristic Curves

The curves showing the relative response of the cathode surfaces give an indication of the region in the spectrum where the phototubes have greatest sensitivity. On the short wave end, the sensitivity is limited by the low transmission of the glass envelope to the shorter wave lengths, while on the long wave end the limit is determined by the cathode surface material.

The curves showing the sensitivity have the current in micro-amperes plotted as ordinates, and anode volts as abscissae. Curves are shown for different values of illumination and the effect of different values of load resistance. The performance of the tube under almost any normal condition is thus indicated on the curve sheet.

IGNITRONS

GENERAL INFORMATION

Description

The Ignitron is a heavy duty mercury pool tube which controls large unidirectional currents at high efficiency. The control is obtained by an ignitor electrode which projects into the mercury pool and which, if supplied with a relatively small electric current, starts the conduction each cycle as desired. The Ignitron is formed chiefly of metal except for the glass insulation which supports the graphite anode in the upper part and the ignitor in the lower end of the tube. The conduction is chiefly by electrons moving from the arc spot on the pool to the anode. The negative electron space charge is neutralized by the formation of positive ions in the mercury vapor, thus allowing the passage of large currents with small potential drop. The use of a metal envelope and water cooling, on most types, allows high current rating of relatively small size tubes.

Most Ignitrons have a water jacket made of stainless steel and provided with spiral baffles built in as a part of the tube. The smallest size is designed to be installed in a clamp which also cools the tube by air or water cooling.

Ignitrons for welding service are made up with a single ignitor and anode. The tubes are designed to supply large currents and very accurate and reliable ignitor action over a wide range of per cent. duty operation. Sizes are standardized and designated by letters as an aid in determining the size required for a given job or replacement.

Ignitrons designed for rectifier service are required to operate once each cycle continuously under more severe conditions than occur in welding; hence are constructed with deionization baffles within the envelope to shorten the deionization time and thereby minimize the possibility of arc back. They are provided with two ignitors either of which is suitable for continuous operation on the various circuits used in rectification service, as well as for services where the ignitor is operated by connection to the main anode through a thyratron. The No. 2 or reserve ignitor should be used in case of unsatisfactory performance of No. 1 ignitor.

An auxiliary anode, to which the ignitor current is transferred when the tube is fired, is provided to make it possible to prolong the excitation period in circuits where separate ignitor excitation is used. This extension of ignition time is necessary where interphase circuits are used with separate excitation, as stable operation requires that the tubes start conduction at the proper phase whether or not the interphase transformer has started to function.

It is not advisable to operate the separate ignitor excitation circuits for more than one minute before starting conduction on the main anode as this may cause mercury to condense on the main anode, thus increasing the danger of arc-back.

Installation

These tubes must be mounted vertically with the cathode pool down. Operation will be most stable if they are protected from shock and vibration which disturb the surface of the mercury pool and tend to change the operation characteristics. After shipping or handling an ignitron, and before it is installed, it must be tested to be certain that mercury has not lodged in a position which will cause the anode to be short-circuited to the metal envelope. This can be checked by applying a source of voltage in series with a test lamp across the anode and cathode terminals. If a short circuit is indicated by lighting of the lamp, it can be relieved by holding the tube with anode about 45 deg. above horizontal position and tapping it with the bare hand. Ignitrons should be installed so that the leads and supports cannot introduce stresses on the metal to glass seals. The types having heavy cathode lugs should be supported from a bus bar by bolting to the cathode lug.

The ignitor should be connected to its control circuit by leads which are not unduly exposed to electromagnetic or electrostatic fields from the high welding currents or other transients or to radio frequency current.

The rated flow of cooling water for each water-cooled ignitron should be upward through the water jacket. As the temperature of the inner wall of the tube is closely dependent on the velocity of the cooling water, the water flow should be maintained at or above the specified minimum even if the temperature at the outlet is well below the maximum.

Since the tubes in welding service normally operate with the envelope at line potential, insulating hose lengths conducting the cooling water to and from the water jackets of each tube are necessary, otherwise excessive currents will flow in the contained water column and cause increased power losses as well as tend to corrode the water jacket hose fittings. The outlet hose connections should be unrestricted and preferably made to an open drain.

The most reliable source of clean cooling water should be selected. If scale or colloidal materials are present in the water main, install a strainer or conditioner to free the water from sediment or scale-forming compounds. The cooling water must not contain enough solids or dissolved constituents to form a coating in the water jacket during service. Such a coating greatly reduces the cooling efficiency and will cause unsatisfactory tube performance. Suitable cooling water should contain less than 250 parts of solids by weight per million parts of water.

Water connections and the cooling jackets of ignitrons should be flushed out periodically with water at 20 to 50 lbs. pressure. To maintain proper cooling efficiency, flushing is advisable at three-month intervals. Water should never be allowed to drop on top of the tube. Electrical interlocks should be provided so that the tube can not be operated when there is no water flow.

The stainless steel used in ignitrons is resistant to corrosion, but some chemicals, such as acids and chlorine, have a corrosive effect and their presence in the cooling water or use as cleaning agents must be limited in the interest of long tube life. The chlorine content of cooling water should be less than 20 parts by weight per million parts of water. Where only corrosive water is available, it should not be used in the water jacket but distilled water, with the addition of alkaline chromates, and cooled by means of a heat exchanger, should be provided.

The temperature of the anode structure must always be higher than that of the cooling water to prevent condensation of mercury on the anode and possible arc back when voltage is applied initially or during operation.

Operation

When the anode of the ignitron is at a positive potential of 50 volts or more with respect to the cathode, and a relatively small current is passed through the ignitor into the mercury pool (the ignitor positive with respect to the pool), an arc spot will form on the pool close to the ignitor-mercury junction and conduction to the anode is immediately established.

When ionization occurs in the tube, it will remain conducting until the anode current drops to zero. It is thus necessary to ignite or fire the ignitron in each cycle that operation is desired. Voltage can be applied to the anode simultaneously with its application to the control electrode or ignitor.

After the ignitor has functioned to produce the initial arc, no further current need flow through it and if allowed to flow, will produce overheating of the ignitor. For this reason, circuits should be used which will either furnish current to the ignitor in impulses, such as a condenser discharge, or which will reduce the ignitor current to zero immediately after the ignitor begins to conduct.

The frequency at which the ignitron operates is limited by the speed of deionization during the half-cycle when the tube is not conducting and depends very greatly on the water temperature and anode current. Consult the manufacturer whenever it is desired to operate the tube at frequencies outside the range of 25-60 cycles, where unusual operating conditions are encountered and before equipment is finally designed since the ratings given are for normal operation only.

Ignitrons are used extensively in electric resistance welding control due to their ability to carry extremely high currents for short periods of time. Two tubes connected in reverse parallel act as an accurately time single-pole, single-throw switch to supply alternating current. Accurate control localizes the heat during the welding operation and thus makes it possible to weld even thin metals of practically all kinds without warping or burning. A minimum amount of indentation at the weld also is obtained. When other than "energy storage" methods of welding are used, welding timers are essential for the controlled welding of aluminium, heat-treated alloys, and other materials where timing and current requirements are critical.

The firing or ignition of the ignitrons can be accomplished at any point in the a.c. cycle by a timing circuit using a thyratron connected between the anode and ignitor of each ignitron. By this means it is possible to control both the number of cycles during which the ignitron operates and the effective current per cycle.

When conduction to the anode of the ignitron is started, the voltage in the ignitor circuit will be less than the voltage required to operate the thyratron, and current ceases to flow to the ignitor. The voltage in the anode circuits of the ignitrons must be sufficiently high and the load impedance sufficiently low to insure prompt ignition. If the transformer should be energized with the welding electrodes out of contact, or very low current be required, additional load should be provided to increase the tube current to at least 50 amperes to cause sufficiently speedy ignition.

A modification of this control is to connect a condenser in series with the thyratron and ignitor and control the condenser discharge by means of the thyratron.

The kVA demand during welding operations may be several times the readings taken by conventional instruments. If the current demand of the welder is too high to permit continuous conduction for a time long enough to read the ammeter, good results may be obtained by following the meter indicator with a stop until no movement can be observed; the meter will then indicate quite closely the RMS current demand of the welder. Any application should be made on the basis of test data or other definite information relative to maximum voltage and current demands on the tubes.

Ignitrons for rectifier service may be used in any of the conventional rectifier circuits. In the circuits where the ignitron cathodes are at the same potential, a single independent ignitor firing circuit or control may be used. Where the cathodes are at different voltages, a separate firing or control circuit is required for each ignitron. It is not advisable to operate the ignitor control circuits for more than one minute before starting conduction on the main anode as this may cause mercury to condense on the anode and thus increase the possibility of arc-back.

As rectifier service is much more severe than welding service, the current rating for a tube of a given size is less when used as a rectifier than when used for welding.

Definitions

Anode Voltage, Peak Forward is the highest rated peak voltage to be applied between anode and cathode in the direction in which the tube is designed to pass current. Voltage in excess of this amount may cause the tube to pass current without ignitor excitation, resulting in loss of control.

Anode Voltage, Peak Inverse is the highest peak voltage to be applied between anode and cathode in the direction opposite to that in which the tube is designed to pass current.

Anode Current, Peak is the highest peak current that the tube is rated to carry recurrently at the peak anode voltage.

Anode Current Maximum Average is the highest average current, averaged over a time interval not greater than the maximum averaging time, that a tube is rated to conduct.

Anode Current, Maximum Average at Maximum Demand is the highest average current which a tube is rated to conduct at the maximum demand kVA.

Anode Current, Maximum Average at Maximum kVA is the highest demand kVA rating of a tube when conducting the maximum average anode current.

Anode Current Surge is the maximum peak current not exceeding one-tenth of one second in duration, that the tube can conduct without becoming immediately inoperative.

Ignitor Voltage, Maximum Peak Allowed is the highest ignitor to cathode potential difference for which the ignitor lead insulation is designed.

Ignitor Voltage, Maximum Peak Required is the highest ignitor to cathode potential difference (ignitor positive) necessary to insure ignition in a time of the order of 100 micro-seconds.

Ignitor Current, Maximum Peak Allowed is the highest current that the ignitor and lead are designed to conduct to the mercury pool.

Ignitor Current, Maximum Peak Required is the highest current necessary through the ignitor to insure ignition in a time of the order of 100 micro-seconds.

Ignitor Current, Maximum Average Allowed is the highest average current averaged over not more than 5 seconds that the ignitor is designed to conduct to the mercury pool.

Tube Voltage Drop is the anode-cathode difference of potential when the tube is carrying normal current, averaged over the conducting period. Voltage drop is a function of the tube temperature and anode current for a particular tube, and varies slightly from tube to tube.

Maximum Averaging Time is the longest time over which current shall be averaged in calculating the average anode current regardless of wave form or duty cycle.

Size Classification. Ignitrons for welding service are mechanically interchangeable with those of other manufacturers of the same size classification.

Maximum Demand kVA is the product of the highest RMS current through a pair of tubes on full cycle operation of the welder and the RMS line voltage applied to the tubes.

KVA at Maximum Average Current is the highest demand kVA rating of an ignitron when conducting the maximum average anode current.

Per Cent. Duty is the highest percentage of time the tubes are conducting during any time interval not greater than the maximum averaging time.

Demand Current denotes the RMS current measured in the line between the pair of tubes and the welding machine during the welding operation. Not to be calculated from kVA rating on the transformer nameplate.

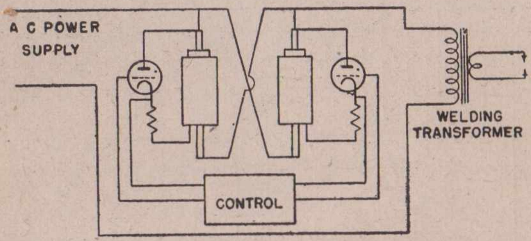
Maximum Current Duration is the maximum time which a tube can conduct a given demand current without overheating. It cannot be repeated at a period less than the maximum averaging time.

The maximum time of conduction can be calculated by multiplying the maximum averaging time by the per cent. duty corresponding to the demand current.

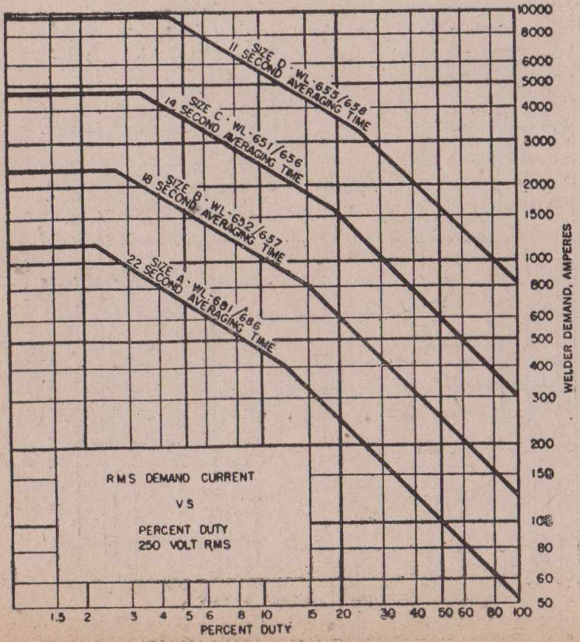
Example:

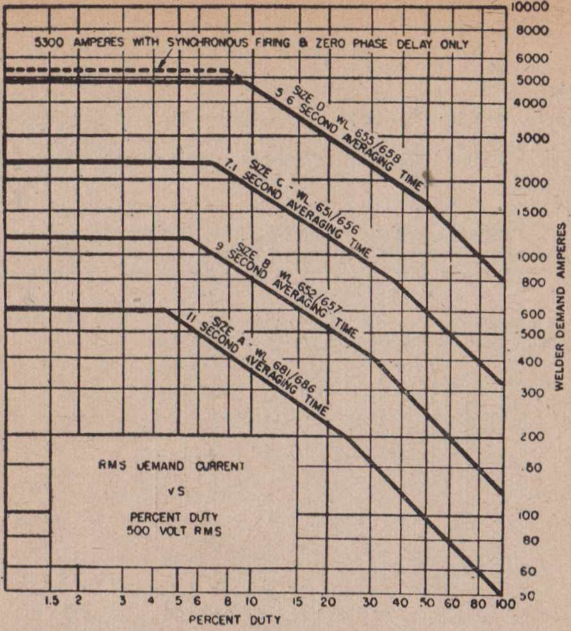
Question: What is the longest permissible time of continuous conduction allowed for the WL-651/656 Ignitron at 500 volts at a current of 1000 amperes to the welding transformer?

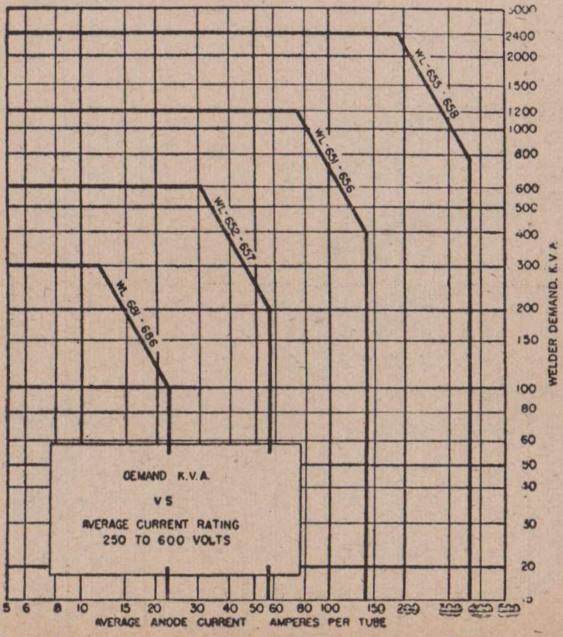
Answer: From the curve for WL-651/656 Ignitron at 1000 amperes, a duty cycle of 27.5% is allowable. The maximum averaging time is 7.1 seconds. Therefore, the time required is 27.5% of 7.1 seconds, or 1.95 seconds.



CIRCUIT DIAGRAM OF WELDER USING IGNITRONS AND THYRATRONS







Rating for two Ignitions connected back to back in standard welding circuit. Welder Demand Amperes are measured in circuit between tubes and welder.

CATHODE-RAY TUBES

Introduction

In recent years the cathode-ray tube—providing, as it does, a two dimensional indicating device free from inertia effects and capable of plotting one quantity as a function of another—has become one of the most important instruments available for electrical observations, measurements, and indications. As used in the cathode-ray oscillograph it provides the engineer and technician with an instrument whose usefulness is immeasurable. Its use makes possible instantaneous observations of the variations of related phenomena with respect to one another, and hours, days, even weeks of painstaking point by point investigation are often eliminated. Used at first almost entirely for oscillographic work, the cathode-ray tube later became the medium for reproduction of television pictures, and even more recently it has been applied to a myriad of special indicating applications.

The cathode-ray tube is not as new a device as might be supposed from the rapid increase in its use in recent years. In fact, the first device in which an electron stream in a sealed tube was focused on a fluorescent screen to produce a movable fluorescent spot was built by Braun in 1897. The introduction of the hot cathode in 1905, the application of gas focusing (now generally abandoned), improvements in cathode design, the use of a negative grid, general improvement in the "electron gun," improvements in the fluorescent screen, and the development of suitable auxiliary circuits gradually brought the cathode-ray tube to its present usefulness as a multi-purpose device.

The Modern Cathode-ray Tube

An outline drawing of a modern high-vacuum cathode-ray tube is shown in Figure 1. A heater element (7) mounted within a cathode sleeve (8) operates to heat the oxide coating on the end of this sleeve and cause electron emission. The electric field produced by the control electrode or grid (10), and the focusing electrode (11) acts to draw the electrons emitted from the cathode into a narrow beam having a small minimum cross-section in the vicinity of the grid.

From this point the electron beam diverges until it passes through the region between the focusing electrode (11) and the accelerating electrode (13) where the electric field set up by these electrodes causes the beam to converge so that it reaches the fluorescent screen (24) in a small spot. This action is analogous to the action of optical lenses on light, and it may be said that the minimum beam cross-section in the vicinity of the grid is focused onto the screen by the electron lens formed by the field between the focusing electrode and the accelerating electrode.

The control electrode is ordinarily operated at a negative potential with respect to the cathode and the beam current (and therefore the brightness of the spot) is varied by varying this bias potential. This potential difference is in the order of 100 volts maximum. The focusing electrode usually operates at a lower voltage than the accelerating electrode, and it is by variation of this focusing electrode voltage, in the vicinity of 500 volts for 2000 volts accelerating potential, that the spot is properly focused on the screen. The entire beam forming structure is known as the "electron gun."

After leaving the gun the electron beam passes between the plates of the deflection-plate pair (16) and then between the plates of the pair (17). A potential difference applied between the plates of the pair (16) produces an electric field which deflects the electron beam in a direction perpendicular to the plane of those plates. Similarly a potential applied between the plates of pair (17) results in deflection of the beam in a direction perpendicular to the direction of deflection produced by plate pair (16). Thus it is possible to control the position of the spot on the screen by two potentials applied to the two sets of deflection plates.

It will be noted that in this cathode-ray tube, focusing and deflection of the

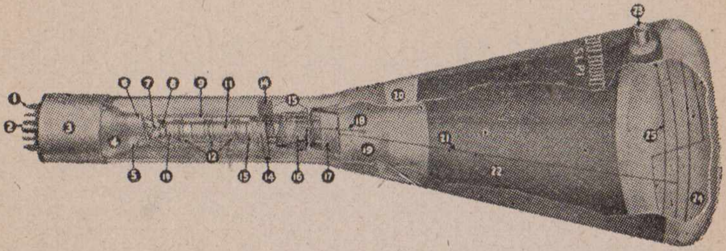


Fig. 1—A typical high-vacuum, hot-cathode, low-voltage, electron-lens focus, cathode-ray tube. The parts shown are as follows:

1—Base Pins
2—Alignment Key
3—Base Collar
4—Stem
5—Getter
6—Press
7—Heater Leads (Heater inserted inside the cathode tubing)
8—Cathode Support Collar (Cathode inserted inside the grid tubing)
9—Ceramic Supports (two supports diametrically opposed)
10—Control Electrode
11—Focusing Electrode
12—Support Collar
13—Accelerating Electrode
14—Mount Suppports
15—Mica Deflection Plate Support Rings
16—Deflection Plate Pair D_3-D_4
17—Deflection Plate Pair D_1-D_2
18—Spring Contact (Makes contact with static shield)
19—Static Shield
20—Glass Envelope
21—Electron Beam
22—Intensifier Electrode
23—Intensifier Terminal
24—Fluorescent Screen Material
25—Pattern traced by beam

beam are both accomplished by electrostatic fields. It is also possible to use electromagnetic fields for either focusing or deflection or both. However, the convenience of electrostatic focusing and deflection, and the advantages of electrostatic deflection, especially for operation over wide frequency ranges, have made it almost universal except in a few special applications.

The intensifier electrode (22), a Du Mont development, is operated at a higher voltage than the accelerating electrode. This intensifier electrode serves to further accelerate the beam subsequent to deflection. The sensitivity of the beam to electrostatic deflection varies inversely with the potential applied to the accelerating electrode, which potential, measured from cathode, determines the velocity of electrons in the deflection-plate region. However, the brilliance of the trace caused by the electron beam increases with increase in accelerating potential. A compromise must therefore be made between brilliance and deflection sensitivity. With the intensifier-type cathode-ray tube, the necessity for compromise is greatly reduced, since the beam may be deflected at a low accelerating electrode potential and then further accelerated after deflection by a higher potential applied to the intensifier electrode.

Considerations Involved in the Choice and Use of Cathode-ray Tubes

In choosing a cathode-ray tube for any particular application, points which should be considered are the type of screen to be used, the operating potentials which can be supplied conveniently or economically, the spot size and intensity required, the deflection sensitivity required, and the importance of deflection-plate or grid capacitances.

Some of these factors are interdependent, and compromises must usually be made

Screens

Standard Du Mont cathode-ray tubes are available with four types of screens, referred to as type P1, P2, P4, and P5, which satisfy the requirements of most applications. The type P1 screen produces a green trace of medium persistence and is well suited for general-purpose visual oscillographic work. It is quite efficient, and bright traces can be obtained with comparatively low accelerating voltages. The spectral distribution of the light produced is in the region of high sensitivity of the human eye, resulting in good contrast when the tube is illuminated by external daylight or incandescent lighting.

The type P2 screen produces a green trace with a long persistence characteristic and is useful for visual observations of transient signals and of very low frequency recurrent signals. With this type of screen a pattern can be observed for a period ranging from a fraction of a second to 50 or 100 seconds after it has been produced, depending upon the writing rate of the spot, the accelerating potential, and the level of the surrounding light. Because of the many factors affecting the useful persistence time, it is difficult to give quantitative data. However, it has been found empirically that, at a writing rate of 150 inches per second, a persistence time of approximately 5 seconds may be obtained from a cathode-ray tube operating at an accelerating potential of 2500 volts. It is essential that a high accelerating potential be used with long-persistence screens, and it is for this reason that tubes having a maximum overall accelerating potential rating of less than 2500 volts are not manufactured with the type P2 screen.

The type P4 screen is generally used for television applications in which a white trace is desired. It has been found that where a screen must be observed for long periods of time, this type of screen will cause less eye fatigue than the other screen types.

The type P5 short persistence blue screen is particularly suited for applications involving photographic film recording. The high actinic value of its radiation is desirable for best film exposure density and the short persistence characteristic is essential to prevent fogging of a moving film recorder and time base. Photographic recording methods are discussed in a section which follows.

Operating Potentials, Spot Size, Intensity, Deflection Sensitivity

In most applications high deflection sensitivity, high intensity, small spot size, and minimum operating potentials are desirable. Since there are several conflicting factors involved, compromise is usually necessary. In general, intensity and spot size must be considered together. With a given tube the spot size and brilliance improve with increasing accelerating voltage, but the deflection sensitivity decreases. Furthermore, high accelerating voltages are in themselves undesirable from the standpoint of economy and simplicity in equipment. The particular application will, therefore, determine the tube to be used and the conditions of its operation. Where maximum intensity and minimum spot size are most important, high accelerating voltages are indicated. Where maximum deflection sensitivity is the most important requirement, lower accelerating potentials should be used. For applications where a maximum deflection sensitivity and a maximum brilliance are required, intensifier-type cathode-ray tubes should be used, since a high final accelerating potential can be used with a minimum of effect on the deflection sensitivity. The intensifier-type cathode-ray tube also simplifies the power supply problem for a given overall accelerating potential by reducing the maximum voltage for which the power supply must be insulated from ground.

Deflection-Plate Capacitances

For applications where high frequencies must be supplied to the deflection plates, minimum deflection-plate lead lengths and capacitances are essential. For such applications, special high-frequency cathode-ray tubes are made in which the leads are brought from the deflection plates directly to terminal caps on the neck of the cathode-ray tube opposite the plates. In this way the total effective capacitance between two plates of a deflection-plate pair can be lowered to two or three micro-microfarads.

Special Considerations Involved In Photographic Work

Photography of cathode-ray tube patterns has been mentioned briefly in connection with fluorescent screens, but there are further special considerations involved when cathode-ray tube patterns are to be photographed.

Photography of the stationary patterns produced on the cathode-ray tube screen by recurrent signals may be effected very easily since the camera shutter may be left open as long as is necessary to obtain the required negative density. In such cases the brilliance of the trace is comparatively unimportant, since the camera shutter need only be left open for a comparatively long period when the brilliance is low. With some types of signals (such as square waves) where the writing rate over various portions of the cycle changes greatly with resultant large variations in brightness over different parts of the pattern, it may become necessary to overexpose the brighter parts of the pattern in order to obtain satisfactory recording of the less intense portions.

It is in the photography of transient patterns, however, that the most careful attention must be paid to writing rates and film requirements. There are two methods applicable to photographic recording of non-recurrent transient signals; a moving film method and a stationary film method. In the moving film method the spot on the cathode-ray tube is deflected by the signal along one axis only, and the time axis is provided by the motion of the film in a direction perpendicular to the deflection of the spot. In the stationary film method, the time-base is provided by a single linear sweep of the spot by one set of deflection plates, the signal being applied to the other set. The single sweep must be initiated simultaneously with or just prior to the start of the transient to be studied. The camera shutter must be opened before the occurrence of the transient and closed after the transient has occurred.

The moving film method may put restrictions upon the allowable persistence time of the fluorescent screen, depending upon the speed of movement of the film, which in turn is determined by the signal to be recorded. It has the advantage of being capable of providing a time base of practically unlimited length, however, and in some cases simplifies the electrical arrangements. Regardless of which method is used, the writing speed of the spot will have a fundamental bearing upon the negative density produced with a given set of electrical and optical conditions; and, in fact, there will be a limit to the writing speed which can be recorded satisfactorily under such conditions.

It has been determined empirically that writing rates of 1500 inches per second can be photographed satisfactorily using a type P1 screen, an accelerating potential of 1000 volts, a lens opening of f4.5, a magnification of 0.50, and an emulsion having a Weston speed rating of approximately 24. The practicability of photographing transient traces of higher writing rates may be determined from the above data and the following facts. The writing rate can be increased in approximately inverse proportion to the square of the f rating of the lens. It can be further increased approximately in proportion to the square of the accelerating potential. Further increase can be effected by the use of faster film and by the use of the type P5 fluorescent screen. In fact, this screen is recommended for equipment which is to be used primarily for photographic purposes. Satisfactory photographic recording of writing rates of 20,000 inches per second is not at all uncommon, and rates as high as 100,000 inches per second have been recorded with excellent results.

Circuits especially devised for transient studies have been incorporated into existing commercial oscillographic equipment.

A table of films recommended for use with the various types of fluorescent screens follows:

SCREEN	TYPE P1 (medium-persistence green radiation)	TYPE P2 (long-persistence blue-green radiation)	TYPE P5 (short-persistence blue radiation)
ROLL FILM	1. Verichrome 2. Super-XX 3. Panatomic-X	1. Verichrome 2. Regular N.C. 3. Panatomic-X	1. Verichrome 2. Regular N.C. 3. Panatomic-X
PLATES	1. Eastman Super Panchro Press 2. Eastman Ortho-Press 3. Eastman 50	1. Eastman Super Panchro Press 2. Eastman Ortho-Press 3. Eastman 50	1. Eastman 40 2. Eastman Ortho-Press 3. Eastman Universal
FILM PACKS	1. Verichrome 2. Super-XX 3. Panatomic-X	1. Verichrome 2. Panatomic-X	1. Verichrome 2. Panatomic-X
35-mm. ROLL FILM	1. Super-XX Pan. 2. Plus-X 3. Panatomic-X	1. Super-XX Pan. 2. Plus-X 3. Safety Positive Film	1. Ortho Negative Film 2. Super-XX Pan. 3. Safety Positive Film

The following materials are suggested for photography of black-and-white screens:

TYPE P4

Tri-X Pan.
Super Panchro Press
Super Ortho Press
Super-XX
Ortho-X

Operating Notes

Cathode-ray tube power supplies must usually provide between 1000 and 5000 volts d.c. at from one to three miliamperes. In oscillographic applications, usual practice is to operate the accelerating electrode (second anode) at ground potential, in order that the deflection plates may be substantially at ground potential and thus facilitate their coupling to deflecting signal circuits and reduce the hazard in making connections directly to the deflection plates. When this method of operation is used, it is necessary to insulate the transformer winding supplying heater power to the cathode-ray tube for the full accelerating voltage, since the heater and cathode are operated at a negative potential with respect to ground equal to this voltage.

A voltage divider is ordinarily used to provide the required voltages for the control electrode (grid) and focusing electrode (first anode). The negative grid voltage is provided by a rheostat or potentiometer at the negative end of the voltage divider, and sufficient range should be provided to permit variation of grid bias from zero to a value at least equal to the maximum cut-off voltage for the tube at the accelerating voltage at which it is to be operated. The focusing voltage potentiometer should be capable of providing a range of voltage to the focusing electrode corresponding to the range over which the voltage required for focus is permitted to vary by the specification for the particular tube type involved.

In order to reduce defocusing of the spot to a minimum, positioning and signal voltages should be balanced whenever possible; that is, equal positive and negative voltages should be applied to the two plates of a deflection-plate pair.

The intensifier should ordinarily be operated at a potential 30% to 100% above the accelerating electrode potential. When lower values of intensifier voltage are to be used, the intensifier can be connected to a 300 or 400 volt plate supply if such a supply is readily available. If not, or if a higher intensifier potential is desired, a separate rectifier with a simple resistance-capacitance filter, operating from the same transformer winding as the accelerating voltage supply, is easily provided.

A typical power supply, with positioning circuits and deflection-plate input circuits, is shown in Figure 2. Such a supply will provide adequate voltages for operating intensifier-type cathode-ray tubes, such as the Type 5LP series. A supply for cathode-ray tubes not provided with an intensifier electrode is shown in Figure 3.

In a transformer designed for operating cathode-ray tube circuits, both the cathode-ray tube heater winding and the primary winding should be completely surrounded with grounded electrostatic shields. These shields are necessary to prevent electrostatic coupling to the heater winding which might cause intensity modulation and to prevent electrostatic coupling from the high voltage winding to the other windings. It is advisable to ground the chassis of cathode-ray equipment to prevent any possibility of the chassis attaining a high potential with respect to ground. The potentials at which cathode-ray tubes operate are dangerous, and precaution should be taken to prevent contact with them.

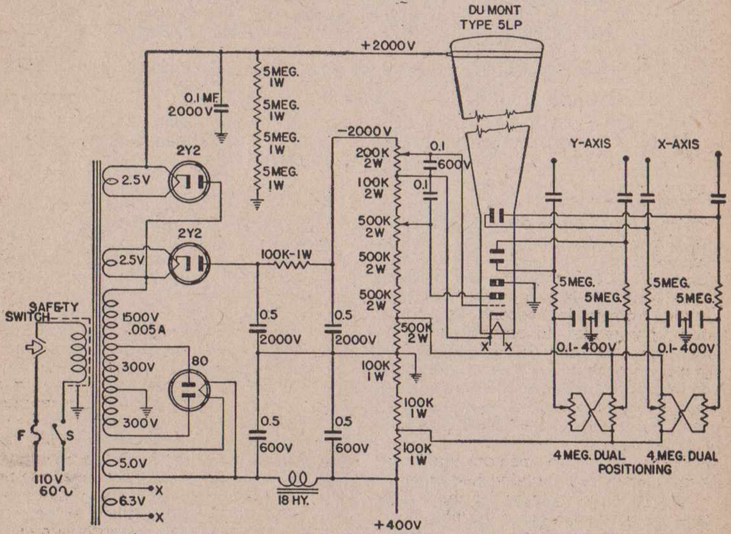


Fig. 2—Typical power supply for intensifier type cathode-ray tube.

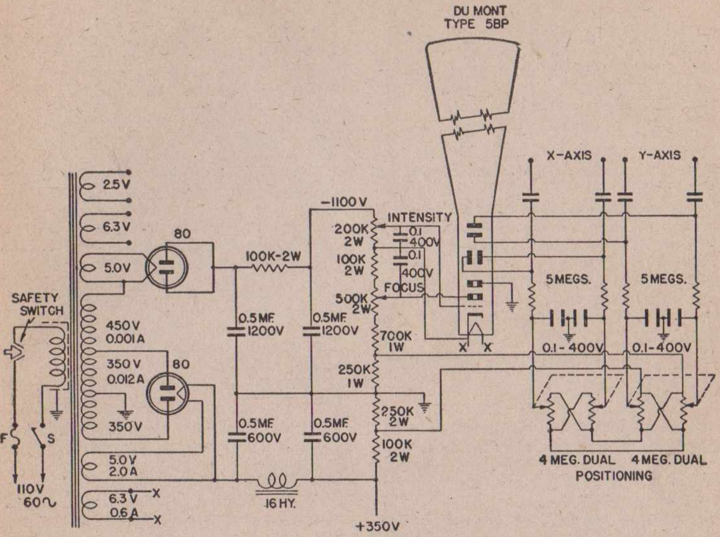


Fig. 3—Typical power supply for cathode-ray tube (no intensifier).

Discussion of Tube Characteristic Sheets

On the following pages will be found descriptions and characteristics of the various Du Mont cathode-ray tubes. These bulletins are arranged to give the essential data on each type in the manner which the industry has found most useful and complete.

Values of capacitance are average values, and are given for the modulating electrode and the deflection plate electrodes in various combinations which are deemed sufficient for design purposes. The tolerances given the various ratings under typical operation are those adopted by the Radio Manufacturers Association as standard throughout the industry. Particular notice of these tolerances should be given in designing the associated operating equipment with which the cathode-ray tube is to be used.

The units of deflection factor and deflection sensitivity have been chosen so that all types of tubes, regardless of accelerating potentials used, are referred to a common level for comparison. That level is one kilovolt. If the tube is to be operated at an accelerating potential other than one kilovolt, as it usually is, the deflection factor value should be multiplied by the value in kilovolts of the operating potential to obtain the actual operating deflection factor. The sensitivity value should be divided by the same ratio. In intensifier-type tubes this value is given for the condition of the intensifier operating at the same potential as the second anode. In addition, the effect of the intensifier is indicated by the values of deflection factor and sensitivity under typical operating conditions.

In the event that the exact accelerating potential actually used is not given under typical operating conditions, the correct values of cut-off bias, focusing voltage and deflection factors can be readily computed, since these values are all directly proportional to the accelerating potential.

These proportions also hold for intensifier-type cathode-ray tubes providing the ratio of intensifier potential to second anode potential is kept constant. It will be found that the effect of the intensifier potential on cut-off bias and focusing voltage is negligible. Increasing the intensifier potential does not decrease the life of the cathode; in fact, it will tend to increase its useful life since for a given trace intensity a lesser value of beam current is required.

Definition and Terms

Cathode-ray Tube: An essentially inertialess indicating electronic device in which a stream of electrons produced by a cathode is directed toward a fluorescent or phosphorescent screen, deflected by either an electric or magnetic field in accordance with the strength and direction of that field, and then impinged on the screen to produce a visible spot of light. The deflection may be static or dynamic.

Gun Structure: A metal assembly within the tube in which the electron stream is produced, controlled, focused, and accelerated. This assembly usually consists of:

1. Heater: A spiral coil of resistance wire which is heated by the current flow through it. The heat produced serves to raise the temperature of the cathode.

2. Cathode: A metal sleeve, surrounding the heater, the end of which is coated with a material which copiously emits electrons when heated to a high temperature.

3. Control Electrode: A metal structure adjacent to the cathode which controls the potential relationship between this electrode, sometimes called the grid, and the cathode. This electrode controls the light intensity of the image on the screen of the tube by controlling the magnitude of the beam current.

4. Focusing Electrode: A metal cylinder, otherwise known as Anode No. 1. The electrostatic field produced by this electrode in combination with the control electrode, and the accelerating electrode (see below) acts similarly to an optical lens in focusing the electron stream to a small spot on the screen (see below).

5. Accelerating electrode: Otherwise known as Anode No. 2. This electrode serves to increase the kinetic energy of the electron stream by increasing its velocity so that upon impact on the screen a visible radiation will be emitted.

Deflection Plates: Usually consist of two pairs of parallel plates, the pairs being perpendicular to each other. The electrostatic field existing between each plate pair causes angular displacement of the electron beam.

Intensifier Electrode: Otherwise known as Anode No. 3. Imparts additional kinetic energy to the electron stream after deflection. This post-acceleration results in an increase in light intensity without a large decrease in deflection sensitivity (see text).

Screen: A fluorescent-phosphorescent chemical coating on the face of the glass blank which converts kinetic energy of the electron stream into visible radiation.

Trace: The line or combination of lines produced by the rapid movement of the spot. Such effect is due to the persistence characteristic of the human eye and of the screen.

Astigmatism: Focus condition in which the spot is not round thus causing different trace widths depending upon the direction of the trace.

Symmetrical Deflection: Deflection by an electric field produced by a pair of deflection plates to which equal and opposite deflection signal potentials are applied.

Non-Linear Deflection: Phenomenon in which the increment of deflection per unit increment of applied deflection voltage is not constant along the direction of deflection.

Halo: A ring or circular band of visible radiation surrounding the spot on the screen.

Yoke: A coil of wire placed near or around the neck of the tube to produce either deflection, focusing, or both. Used with electromagnetic types. This system is not ordinarily used for oscillographic applications, but is found in television and in special equipment.

Symbols:

E_{c1}—Control Electrode Voltage
E_{b1}—Focusing Electrode Voltage
E_{b2}—Accelerating Electrode Voltage
E_{b3}—Intensifier Electrode Voltage
D_3D_4—Deflection plate pair adjacent to accelerating electrode.
D_1D_2—Deflection plate pair adjacent to screen
Volts/kv.in.—term for deflection factor with $E_{b2}=1000$ volts
mm. kv./d.c. volt—term for deflection sensitivity with $E_{b2}=1000$ volts

Installation Notes

Du Mont cathode-ray tubes may be operated in any position. It is sometimes necessary that they be inclosed in a grounded metal shield to protect them from stray electric fields, and they should be located as far as possible from transformers and chokes, the magnetic field of which can cause spurious magnetic deflection. In some cases magnetic shielding is necessary to prefent such magnetic deflection of the beam. Care should be taken to insure that any shields used are not magnetized.

It is possible that the nickel assembly composing the gun structure will become magnetized due to the existence of a strong magnetic field. The effect of such magnetization may be to defocus the spot, or otherwise change its shape, to reduce its intensity, to distort the deflecting fields thus producing nonlinear deflection, or to deposition the spot or trace permanently. This disturbance may be remedied by placing the tube axially within a solenoid which produces a strong alternating field and then gradually removing the tube from the influence of that alternating field.

Du Mont cathode-ray tubes are sufficiently strong mechanically to withstand the shocks of ordinary handling and temperature changes. Especially in the case of the larger tubes, however, the glass bulb is under considerable stress from atmospheric pressure. Consequently, hard bumps and extreme temperature changes should be avoided. Care should be taken to avoid scratching the bulb since such scratches will greatly weaken the glass.

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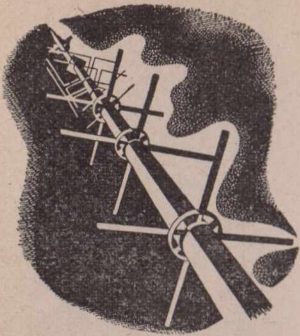

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