Cyclopedia
of
Applied Electricity

A General Reference Work on

DIRECT-CURRENT GENERATORS AND MOTORS, STORAGE BATTERIES, ELECTRIC WIRING, ELECTRICAL MEASUREMENTS, ELECTRIC LIGHTING, ELECTRIC RAILWAYS, POWER STATIONS, POWER TRANSMISSION, ALTERNATING-CURRENT MACHINERY, TELEPHONY, TELEGRAPHY, ETC.

Prepared by a Corps of

ELECTRICAL EXPERTS, ENGINEERS, AND DESIGNERS OF THE HIGHEST PROFESSIONAL STANDING

Illustrated with over Two Thousand Engravings

SEVEN VOLUMES

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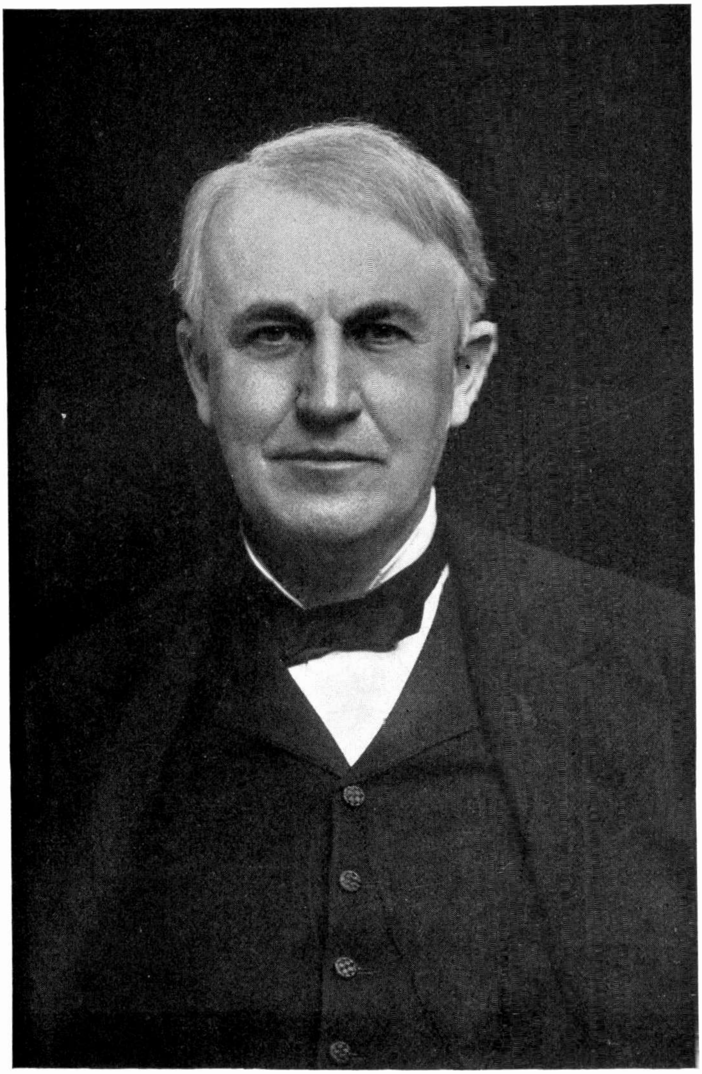

THOMAS A. EDISON

Pioneer Electrical Investigator and Inventor of Numerous Telegraph, Telephone, Lighting, and Other Electrical Devices.

Authors and Collaborators

FRANCIS B. CROCKER, E. M., Ph. D.
Professor of Electrical Engineering, Columbia University, New York
Past-President, American Institute of Electrical Engineers

WILLIAM ESTY, S. B., M. A.
Head, Department of Electrical Engineering, Lehigh University
Joint Author of "The Elements of Electrical Engineering"

HENRY H. NORRIS, M. E.
Professor in Charge, Department of Electrical Engineering, Cornell University

JAMES R. CRAVATH
Consulting Electrical Engineer
Formerly Associate Editor, *Electrical World*

GEORGE C. SHAAD, E. E.
Professor of Electrical Engineering, University of Kansas

ROBERT ANDREWS MILLIKAN, Ph. D.
Professor of Physics, University of Chicago

KEMPSTER B. MILLER, M. E.
Consulting Engineer and Telephone Expert
Of the firm of McMeen & Miller, Electrical Engineers and Patent Experts, Chicago

LOUIS DERR, S. B., A. M.
Professor of Physics, Massachusetts Institute of Technology

DAVID P. MORETON, B. S., E. E.
Associate Professor of Electrical Engineering, Armour Institute of Technology
American Institute of Electrical Engineers

MORTON ARENDT, E. E.
Assistant Professor of Electrical Engineering, Columbia University, New York
American Institute of Electrical Engineers

Authors and Collaborators—Continued

GEORGE W. PATTERSON, S. B., Ph. D.
Head, Department of Electrical Engineering, University of Michigan

WILLIAM H. FREEDMAN, C. E., E. E., M. S.
Head, Department of Applied Electricity, Pratt Institute. Brooklyn, N. Y.
Formerly Head, Department of Electrical Engineering, University of Vermont

CHARLES THOM
Chief of Quadruplex Department, Western Union Main Office, New York City

CHARLES G. ASHLEY
Electrical Engineer, and Expert in Wireless Telephony and Telegraphy

A. FREDERICK COLLINS
Editor, *Collins Wireless Bulletin*
Author of "Wireless Telegraphy, Its History, Theory, and Practice"

CHARLES E. KNOX, E. E.
Consulting Electrical Engineer
American Institute of Electrical Engineers

JOHN LORD BACON
Engineer and Superintendent of Construction with R. P. Shields & Son, General Contractors and Builders
American Society of Mechanical Engineers

JESSIE M. SHEPHERD, A. B.
Associate Editor, Textbook Department, American School of Correspondence

GEORGE R METCALFE, M. E.
Editor, American Institute of Electrical Engineers
Formerly Head, Technical Publication Department, Westinghouse Electric & Manufacturing Co.

R. F. SCHUCHARDT, B. S.
Testing Engineer, Commonwealth Edison Co. Chicago

LEIGH S. KEITH, B S.
Managing Engineer with McMeen & Miller, Electrical Engineers and Patent Experts, Chicago
American Institute of Electrical Engineers

Authors and Collaborators—Continued

SAMUEL G. McMEEN
Consulting Engineer and Telephone Expert
Of the Firm of McMeen & Miller, Electrical Engineers and Patent Experts, Chicago
American Institute of Electrical Engineers

LAWRENCE K. SAGER, S. B., M. P. L.
Patent Attorney and Electrical Expert, New York City

ERNEST L. WALLACE, B. S.
Assistant Examiner, United States Patent Office, Washington, D. C.
Formerly Instructor in Electrical Engineering, American School of Correspondence

PERCY H. THOMAS, S. B.
Of Thomas & Neall, Electrical Engineers, New York City
Formerly Chief Electrician, Cooper Hewitt Electric Co.

JAMES DIXON, E. E.
American Institute of Electrical Engineers

GLENN M. HOBBS, Ph. D.
Secretary, American School of Correspondence
Formerly Instructor in Physics, University of Chicago
American Physical Society

H. C. CUSHING, Jr.
Consulting Electrical Engineer
Author of "Standard Wiring for Electric Lighting Power"

J. P SCHROETER
Graduate, Munich Technical School
Instructor in Electrical Engineering, American School of Correspondence

ALTON D. ADAMS
Consulting Engineer, and Expert on Hydro-Electric Power Development

CHARLES DAY
With Dodge & Day, Engineers, Philadelphia
American Institute of Electrical Engineers

HARRIS C. TROW, S. B., *Managing Editor*
Editor-in-Chief, Textbook Department, American School of Correspondence

Authorities Consulted

THE editors have freely consulted the standard technical literature of America and Europe in the preparation of these volumes. They desire to express their indebtedness, particularly to the following eminent authorities, whose well-known works should be in the library of every electrician and engineer.

Grateful acknowledgment is here made also for the invaluable co-operation of the foremost engineering firms and manufacturers in making these volumes thoroughly representative of the very best and latest practice in the design, construction, and operation of electrical machinery and instruments; also for the valuable drawings, data, suggestions, criticisms, and other courtesies.

FRANCIS B. CROCKER, M. E., Ph. D.

Head of Department of Electrical Engineering, Columbia University; Past-President, American Institute of Electrical Engineers

Author of "Electric Lighting"; Joint Author of "Management of Electrical Machinery," "Electric Motors"

SCHUYLER S. WHEELER, D. Sc.

President, Crocker-Wheeler Co.; Past-President, American Institute of Electrical Engineers

Joint Author of "Management of Electrical Machinery"

ALFRED E. WIENER, E. E., M. E.

Member, American Institute of Electrical Engineers

Author of "Practical Calculation of Dynamo-Electric Machines"

WILLIAM S. FRANKLIN, M. S., D. Sc.

Professor of Physics, Lehigh University

Joint Author of "The Elements of Electrical Engineering," "The Elements of Alternating Currents"

WILLIAM ESTY, S. B., M. A.

Head of Department of Electrical Engineering, Lehigh University

Joint Author of "The Elements of Electrical Engineering"

R. B. WILLIAMSON

Joint Author of "The Elements of Alternating Currents"

HORATIO A. FOSTER

Consulting Engineer; Member of American Institute of Electrical Engineers; Member of American Society of Mechanical Engineers

Author of "Electrical Engineer's Pocket-Book"

Authorities Consulted—Continued

DUGALD C. JACKSON, C. E.

Head of Department of Electrical Engineering, Massachusetts Institute of Technology; Member, American Society of Mechanical Engineers, American Institute of Electrical Engineers, etc.

Author of "A Textbook on Electromagnetism and the Construction of Dynamos"; Joint Author of "Alternating Currents and Alternating-Current Machinery"

J. FISHER-HINNEN

Late Chief of the Drawing Department at the Oerlikon Works

Author of "Continuous-Current Dynamos"

WILLIAM L. HOOPER, Ph. D.

Head of Department of Electrical Engineering, Tufts College

Joint Author of "Electrical Problems for Engineering Students"

ROBERT ANDREWS MILLIKAN, Ph. D.

Professor of Physics, University of Chicago

Joint Author of "A First Course in Physics," "Electricity, Sound and Light," etc.

JOHN PRICE JACKSON, M. E.

Professor of Electrical Engineering, Pennsylvania State College; Member, American Institute of Electrical Engineers, etc.

Joint Author of "Alternating Currents and Alternating-Current Machinery"

MICHAEL IDVORSKY PUPIN, A. B., Sc. D., Ph. D.

Professor of Electro-Mechanics, Columbia University, New York

Author of "Propagation of Long Electric Waves," and Wave-Transmission over Non-Uniform Cables and Long-Distance Air Lines"

LAMAR LYNDON, B. E., M. E.

Consulting Electrical Engineer; Associate Member of American Institute of Electrical Engineers; Member, American Electro-Chemical Society

Author of "Storage Battery Engineering"

EDWIN J. HOUSTON, Ph. D.

Professor of Physics, Franklin Institute, Pennsylvania; Joint Inventor of Thomson-Houston System of Arc Lighting; Electrical Expert and Consulting Engineer

Joint Author of "Alternating Currents," "Arc Lighting," "Electric Heating," "Electric Motors," "Electric Railways," "Incandescent Lighting," etc.

ARTHUR E. KENNELY, D. Sc.

Professor of Electrical Engineering, Harvard University

Joint Author of "Alternating Currents," "Arc Lighting," "Electric Heating," "Electric Motors," "Electric Railways," "Incandescent Lighting," etc.

Authorities Consulted—Continued

SILVANUS P. THOMPSON, D. Sc., B. A., F. R. S., F. R. A. S.

Principal and Professor of Physics in the City and Guilds of London Technical College; Past-President, Institution of Electrical Engineers

Author of "Electricity and Magnetism," "Dynamo-Electric Machinery," "Polyphase Electric Currents and Alternate-Current Motors," "The Electromagnet," etc.

KEMPSTER B. MILLER, M. E.

Consulting Engineer and Telephone Expert; of the Firm of McMeen and Miller, Electrical Engineers and Patent Experts, Chicago

Author of "American Telephone Practice"

MAURICE A. OUDIN, M. S.

Member, American Institute of Electrical Engineers

Author of "Standard Polyphase Apparatus and Systems"

FREDERICK BEDELL, Ph. D.

Professor of Applied Electricity, Cornell University

Author of "The Principles of the Transformer"; Joint Author of "Alternating Currents"

H. F. PARSHALL

Member of American Institute of Electrical Engineers, Institution of Electrical Engineers, American Society of Mechanical Engineers, etc.

Joint Author of "Armature Windings of Electric Machines"

J. A. FLEMING, M. A., D. Sc. (Lond.), F. R. S.

Professor of Electrical Engineering in University College, London; Late Fellow and Scholar of St. John's College, Cambridge; Fellow of University College, London; Member, Institution of Electrical Engineers; Member of the Physical Society of London; Member of the Royal Institution of Great Britain, etc., etc.

Author of "The Alternate-Current Transformer," etc.

LOUIS BELL, Ph. D.

Consulting Electrical Engineer; Lecturer on Power Transmission, Massachusetts Institute of Technology

Author of "Electric Power Transmission," "Power Distribution for Electric Railways," "The Art of Illumination," "Wireless Telephony," etc.

CHARLES PROTEUS STEINMETZ

Consulting Engineer, with the General Electric Co.; Professor of Electrical Engineering, Union College

Author of "The Theory and Calculation of Alternating-Current Phenomena," "Theoretical Elements of Electrical Engineering," etc.

MORTON ARENDT, E. E

Assistant Professor of Electrical Engineering, Columbia University, New York

Joint Author of "Electric Motors"

Authorities Consulted—Continued

J. J. THOMSON, D. Sc., LL. D., Ph. D., F. R. S.

Fellow of Trinity College, Cambridge University; Cavendish Professor of Experimental Physics, Cambridge University

Author of "The Conduction of Electricity through Gases," "Electricity and Matter," etc.

HENRY SMITH CARHART, A. M., LL. D.

Professor of Physics and Director of the Physical Laboratory, University of Michigan

Author of "Primary Batteries," "Elements of Physics," "University Physics," "Electrical Measurements," "High School Physics," etc.

F. A. C. PERRINE, A. M., D. Sc.

Consulting Engineer; Formerly President, Stanley Electric Manufacturing Company; Formerly Manager, Insulated Wire Department, John A. Roebling's Sons Company

Author of "Conductors for Electrical Distribution"

WILLIAM MAVER, Jr.

Ex-Electrician, Baltimore and Ohio Telegraph Company

Author of "Wireless Telegraphy," "American Telegraphy and Encyclopedia of the Telegraph"

E. B. RAYMOND

Testing Department, General Electric Co.

Author of "Alternating-Current Engineering"

AUGUSTUS TREADWELL, Jr., E. E.

Associate Member, American Institute of Electrical Engineers

Author of "The Storage Battery: A Practical Treatise on the Construction, Theory, and Use of Secondary Batteries"

SAMUEL SHELDON, A. M., Ph. D.

Professor of Physics and Electrical Engineering, Polytechnic Institute of Brooklyn

Joint Author of "Dynamo-Electric Machinery," "Alternating-Current Machines"

HOBART MASON, B. S., E. E.

Assistant in Electrical Engineering, Polytechnic Institute of Brooklyn; Associate Member, American Institute of Electrical Engineers

Joint Author of "Dynamo-Electric Machinery," "Alternating-Current Machines"

H. M. HOBART, B. Sc.

Member, Institution of Civil Engineers, American Institute of Electrical Engineers

Joint Author of "Armature Construction"

ALBERT CUSHING CREHORE, A. B., Ph. D.

Electrical Engineer; Assistant Professor of Physics, Dartmouth College

Author of "Synchronous and Other Multiple Telegraphs"; Joint Author of "Alternating Currents"

AN EXAMPLE OF JOINT CONSTRUCTION. AËRIAL TELEPHONE AND POWER WIRES

Foreword

ONE of the simplest acts in modern life is switching on the electric current that gives light or power, or that makes possible communication between distant points. A child can perform that act as effectively as a man, so thoroughly has electricity been broken to the harness of the world's work; but behind that simple act stand a hundred years of struggle and achievement, and the untiring labors of thousands of the century's greatest scientists. To compact the results of these labors into the compass of a practical reference work is the achievement that has been attempted—and it is believed accomplished—in this latest edition of the Cyclopedia of Applied Electricity.

¶ Books on electrical topics are almost as many as the subjects of which they treat and many of them are worthy of a place in the first rank. But many, also, worthy in themselves, are too scientific in their treatment to be available for the mass of electrical workers; and all of them, if gathered into a great common library, would contain so many duplicate pages that their use would entail an appalling waste of time upon the man who is trying to keep up with electrical progress. To overcome these difficulties the publishers of this Cyclopedia went direct to the original sources, and secured as writers of the various sections, men of wide practical experience and thorough technical training, each an acknowledged authority in his work; and these contributions have been correlated by our Board of Editors so as to make the work a unified whole, logical in arrangement and at the same time devoid of duplication.

¶ The Cyclopedia is, therefore, a complete and practical working treatise on the generation and application of electric power. It covers the known principles and laws of Electricity, its generation by dynamos operated by steam, gas, and water power; its transmission and storage; and its commercial application for purposes of power, light, transportation, and communication. It includes the construction as well as the operation of all plants and instruments involved in its use; and it is exhaustive in its treatment of operating "troubles" and their remedies.

¶ It accomplishes these things both by the simplicity of its text and the graphicness of its supplementary diagrams and illustrations. The Cyclopedia is as thoroughly scientific as any work could be; but its treatment is as free as possible from abstruse mathematics and unnecessary technical phrasing, while it gives particular attention to the careful explanation of involved but necessary formulas. Diagrams, curves, and practical examples are used without stint, where they can help to explain the subject under discussion; and they are kept simple, practical, and easy to understand.

¶ The Cyclopedia is a compilation of many of the most valuable Instruction Books of the American School of Correspondence, and the method adopted in its preparation is that which this School has developed and employed so successfully for many years. This method is not an experiment, but has stood the severest of all tests—that of practical use—which has demonstrated it to be the best devised for the education of the busy, practical man.

¶ In conclusion, grateful acknowledgment is due to the staff of authors and collaborators, without whose hearty co-operation this work would have been impossible.

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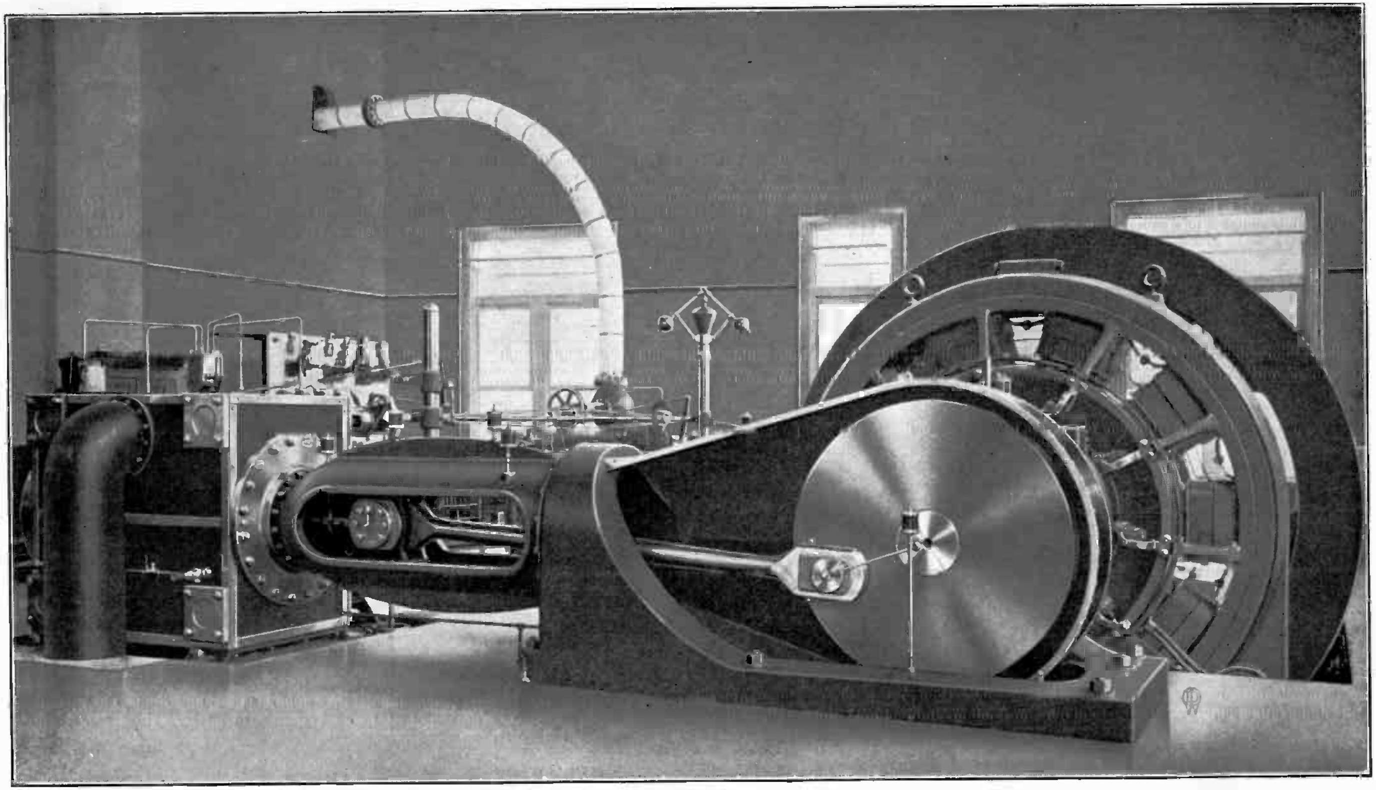


DIRECT-CURRENT VERTICALLY SPLIT GENERATOR DIRECT CONNECTED TO CROSS-COMPOUND HAMILTON-CORLISS ENGINE

Fort Wayne Electric Works

ELEMENTS OF ELECTRICITY AND MAGNETISM*

MAGNETISM

1. Natural and Artificial Magnets. It has been known for many centuries that some specimens of the ore known as magnetite (Fe_3O_4) have the property of attracting small bits of iron and steel. This ore probably received its name from the fact that it is abundant in the province of Magnesia in Thessaly, although the Latin writer Pliny says that the word magnet is derived from the name of the Greek shepherd Magnes, who, on the top of Mount Ida, observed the attraction of a large stone for his iron crook. Pieces of ore which exhibit this attractive property for iron or steel are known as *natural magnets.*

It was also known to the ancients that artificial magnets may be made by stroking pieces of steel with natural magnets, but it was not until the twelfth century that the discovery was made that a suspended magnet would assume a north-and-south position. Because of this property natural magnets came to be known as lodestones (leading stones), and magnets, either artificial or natural, began to be used for determining directions. The first mention of the use of a compass in Europe is in 1190. It is thought to have been introduced from China.

Artificial magnets are now made either by repeatedly stroking a bar of steel, first from the middle to one end on one of the ends, or *poles,* of a magnet, and then from the middle to the other end on the other pole, or else by passing electric currents about the bar in a manner to be described later. The form shown in Fig. 1 is called a *bar* magnet, that shown in Fig. 2 a *horseshoe* magnet.

*This paper is a modification and abridgment of the treatment of *Magnetism and Electricity* found in Millikan and Gale's *First Course in Physics* (Ginn & Co., Boston), to which the student is referred for a more complete presentation of the subject.

2. The Poles of a Magnet. If a magnet is dipped into iron filings, the filings are observed to cling in tufts near the ends, but scarcely at all near the middle (Fig. 3). These places near the ends of the magnet, in which its strength seems to be concentrated, are called the *poles* of the magnet. It has been decided to call the end of a freely suspended magnet which points to the north, the *north-seeking* or *north pole*, and it is commonly designated by the letter N. The other end is called the *south-seeking* or *south pole*, and is designated by the letter S. The direction in which the compass needle points is called the *magnetic meridian.*

Fig. 1. Bar Magnet.

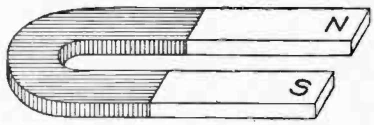


Fig. 2. Horseshoe Magnet.

3. The Laws of Magnetic Attraction and Repulsion. In the experiment with the iron filings, no particular difference was observed between the action of the two poles. That there is a difference, however, may be shown by experimenting with two magnets, either of which may be suspended (see Fig. 4). If two N poles are brought near one another, they are found to repel each other. The S poles likewise are found to repel each other. But the N pole of one magnet is found to be attracted by the S pole of another. The results of these experiments may be summarized in a general law: *Magnet poles of like kind repel each other, while poles of unlike kind attract.*

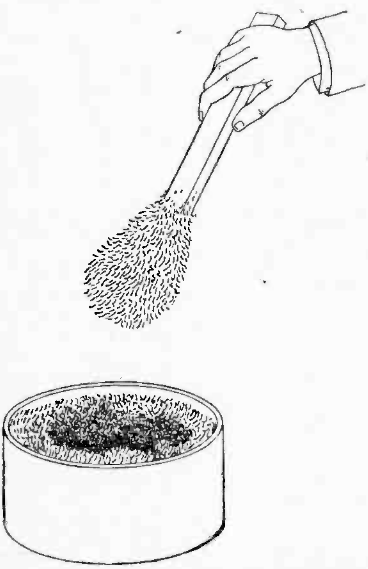


Fig. 3. Experiment Showing Existence of Magnet Poles.

The force of attraction is found, like gravitation, to vary inversely as the square of the distance between the poles; that is, separating two poles to twice their original distance reduces the force acting between them to one-fourth its original value, separating them to three times their original distance, reduces the force to one-ninth its original value, etc.

4. Magnetic Substances. Iron and steel are the only common substances which exhibit magnetic properties to a marked degree. Nickel and cobalt, however, are also attracted appreciably by strong magnets. Bismuth, antimony, and a number of other substances are actually repelled instead of attracted, but the effect is very small. Until quite recently iron and steel were the only substances whose magnetic properties were sufficiently strong to make them of any value as magnets. Within the last five years, however, it has been discovered that it is possible to make certain alloys out of non-magnetic materials such as copper, magnesium, and aluminum which are almost as strongly magnetic as iron. These are known as the *Heussler alloys*.

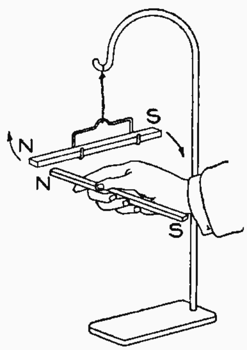


Fig. 4. Showing Variation in Action of Magnet Poles.

5. Magnetic Induction. If a small unmagnetized nail is suspended from one end of a bar magnet, it is found that a second nail may be suspended from this first nail, which itself acts like a magnet,

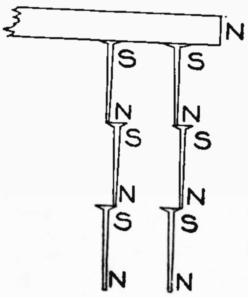


Fig. 5.

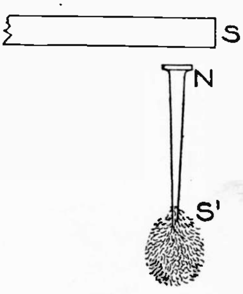


Fig. 6.

Experiments Showing Magnetic Induction.

a third from the second, etc., as shown in Fig. 5. But if the bar magnet is carefully pulled away from the first nail, the others will instantly fall away from each other, thus showing that the nails were strong magnets only so long as they were in contact with the bar magnet. Any piece of soft iron may be thus magnetized *temporarily* by holding it in contact with a permanent magnet. Indeed, it is not necessary that there be actual contact, for if a nail is simply brought near to the permanent magnet it is found to become a magnet. This may be proved by presenting some iron filings to one end of a nail held near a magnet in the manner shown in Fig. 6. Even inserting a plate of glass, or of copper, or of any other material except iron between S and N will not change appreciably the number of filings which cling to the end of S'. But as soon at the permanent magnet is removed, most of the filings will fall. *Magnetism produced in this way by the mere presence of adjacent magnets, with or without contact, is called induced magnetism.* If the induced magnetism of the nail in Fig. 6 is tested with a compass needle, it is found that the *remote* induced pole S' is of the same kind as the inducing pole S, while the *near* pole N is of unlike kind. This is the general law of magnetic induction.

Magnetic induction explains the fact that a magnet attracts an unmagnetized piece of iron, for it first magnetizes it by induction, so that the near pole is unlike the inducing pole, and the remote pole like the inducing pole, and then, since the two unlike poles are closer together than the like poles, the attraction overbalances the repulsion and the iron is drawn toward the magnet. Magnetic induction also explains the formation of the tufts of iron filings shown in Fig. 3, each little filing becoming a temporary magnet such that the end which points toward the inducing pole is unlike this pole, and the end which points away from it is like this pole. The bush-like appearance is due to the repulsive action which the outside free poles exert upon each other.

6. Retentivity and Permeability. A piece of soft iron will very easily become a strong temporary magnet, but when removed from the influence of the magnet it loses practically all of its magnetism. On the other hand, a piece of steel will not be so strongly magnetized as the soft iron, but it will retain a much larger fraction of its magnetism after it is removed from the influence of the permanent magnet. This power of resisting either magnetization or demagnetization is called *retentivity*. Thus, steel has a much greater retentivity than wrought iron, and, in general, the harder the steel the greater its retentivity.

A substance which has the property of becoming strongly magnetic under the influence of a permanent magnet, whether it has a high retentivity or not, is said to possess *permeability* in large degree. Thus, iron is much more permeable than nickel. Permeability is measured by the amount of magnetization which a substance is able to receive; while retentivity is measured by the tenacity with which it holds it.

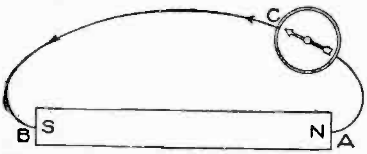


Fig. 7. Direction of Magnetic Lines of Force.

7. Magnetic Lines of Force. If we could separate the N and S poles of a small magnet so as to obtain an independent N pole, and were to place this N pole near the N pole of a bar magnet, it would move over to the S pole of the bar magnet, along some curved path similar to that shown in Fig. 7. The reason that the motion is along a curved rather than along a straight path is that the free pole is at one and the same time repelled by the N pole of the bar magnet and attracted by its S pole, and the relative strengths of these two forces are continually changing as the relative distances of the moving pole from these two poles are changed.

It is not difficult to test this conclusion experimentally. Thus, if a bar or horseshoe magnet is placed just beneath a flat dish containing water (see Fig. 8), and a cork carrying a magnetized needle placed near the N pole in the manner shown in the figure, the cork will actually be found to move in a curved path from N around to S. In this case the cork and the needle actually move as would an independent pole, since the upper pole of the needle is so much farther from the magnet than the lower pole that the influence of the former on the motion is very small.

Any path which an independent N pole would take in going from N to S is called a *line of magnetic force.* The simplest way of finding the direction of this path at any point near a magnet is to hold a compass needle at the point considered, for the needle must obviously set itself along the line in which its poles would move if independent, that is, along the line of force which passes through the given point (see C, Fig. 7).

Fig. 8. Direct Proof that Magnetic Lines of Force are Curved.

8. Magnetic Fields of Force. The region about a magnet in which its magnetic forces can be detected is called its *field of force.* The simplest way of gaining an idea of the way in which the lines of force are arranged in the magnetic field about any magnet is to sift iron filings upon a piece of paper placed immediately over the magnet. Each little filing becomes a temporary magnet by induction, and therefore, like the compass needle, sets itself in the direction of the line of force at the point where it is. Fig. 9 shows the shape of the *magnetic field* about a bar magnet. Fig. 10 shows the direction of the *lines of force* about a horseshoe magnet. Fig. 11 is the ideal diagram corresponding to Fig. 9 and showing the lines of force emerging from the N pole and passing around in curved lines to the S pole. This way of imagining the lines of force to be closed curves passing on the outside of the magnet from N around to S, and on the inside of the magnet from S back to N, was introduced by Faraday about 1830, and has been found of great assistance in correlating the facts of magnetism.

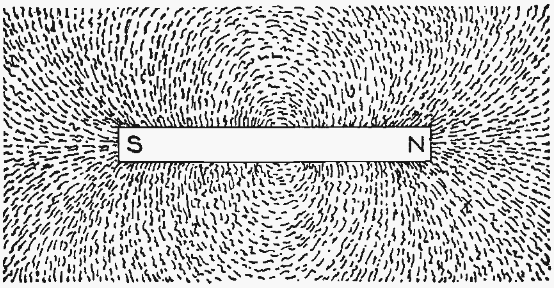


Fig. 9. Shape of Magnetic Field about a Bar Magnet.

9. Molecular Nature of Magnetism. If a small test-tube full of iron filings be stroked from one end to the other with a magnet, it will be found to behave toward a compass needle as if it were itself a magnet, but it will lose its magnetism as soon as the filings are shaken up. If a magnetized needle is heated red-hot, it is found to lose its

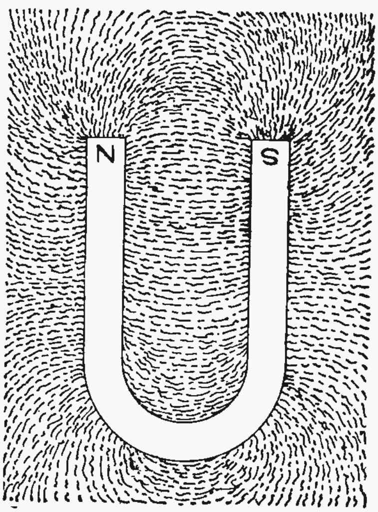


Fig. 10. Direction of Lines of Force about a Horseshoe Magnet.

magnetism completely. Again, if any magnet is jarred or hammered or twisted, the strength of its poles as measured by their ability to pick up tacks or iron filings, is found to be greatly diminished.

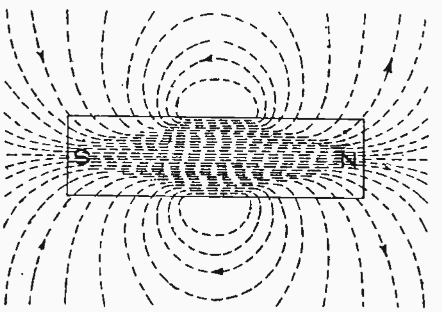


Fig. 11. Ideal Diagram of Lines of Force about a Bar Magnet.

These facts point to the conclusion that magnetism has something to do with the arrangement of the molecules, since causes which violently disturb the molecules of the magnet weaken its magnetism. Again, if a magnetized needle is broken, each part will be found to be a complete magnet. That is, two new poles will appear at the point of breaking, a new *N* pole on the part which has the original *S* pole, and a new *S* pole on the part which has the original *N* pole. The subdivision may be continued indefinitely, but always with the same result, as indicated in Fig. 12. This points to the conclusion that the molecules of a magnetized bar are themselves little magnets arranged in rows with their opposite poles in contact.

If an unmagnetized piece of hard steel is pounded vigorously while it lies between the poles of a magnet, or if it is heated to redness and then allowed to cool in this position, it will be found to have become magnetized. This points to the conclusion that the molecules of the steel are magnets even when the bar as a whole is not magnetized, and that magnetization consists in causing these molecular magnets to arrange themselves in rows, end to end.

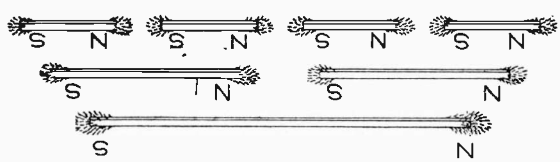


Fig. 12. A Magnet Broken into Smaller Magnets, Showing Connection between Magnetism and Molecular Arrangement.

In an unmagnetized bar of iron or steel, then, it is probable that the molecules themselves are tiny magnets which are arranged either haphazard or in little closed groups or chains, as in Fig. 13, so that, on the whole, opposite poles neutralize each other throughout the bar. But when the bar is brought near a magnet, the molecules are swung around by the outside magnetic force into some such arrangement as that shown by Fig. 14, in which the opposite poles completely neutralize one another only in the middle of the bar. Accord-

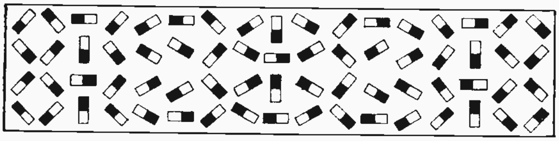


Fig. 13. Theoretical Arrangement of Molecules in a Bar of Ordinary Iron or Steel.

ing to this view, the reason that heating and jarring weaken a magnet is that disturbances of this sort tend to shake the molecules out of alignment. On the other hand heating and jarring facilitate magnetization when an unmagnetized bar is between the poles of a magnet, because they assist the magnetizing force in breaking up the molecular groups or chains and getting the molecules into alignment. Soft iron, then, has higher permeability than hard steel, merely because the molecules of the former substance do not offer so much resistance to a force tending to swing them into line as do those of the latter substance. Steel has on the other hand a much greater retentivity than soft iron, merely because its molecules are not so easily moved out of position when once they have been aligned.

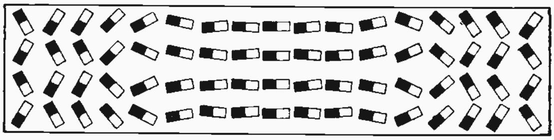


Fig. 14. Theoretical Arrangement Assumed by Molecules when Bar is Magnetized.

10. Saturated Magnets. Strong evidence for the correctness of the above view is found in the fact that a piece of iron or steel cannot be magnetized beyond a certain limit, no matter how strong the magnetizing force. This limit probably corresponds to the condition in which the axes of all the molecules are brought into parallelism, as in Fig. 14. The magnet is then said to be *saturated*, since it is as strong as it is possible to make it.

11. The Earth's Magnetism. The fact that a compass needle always points north and south, or approximately so, indicates that the earth itself is a great magnet, having an S pole near the geographical north pole and an N pole near the geographical south pole; for the magnetic pole of the earth which is near the geographical north pole must of course be unlike the pole of a suspended magnet which points toward it, and the pole of the suspended magnet which points toward the north is the one which by convention it has been decided to call the north pole. The magnetic pole of the earth which is near the north geographical pole was found in 1831 by Sir James Ross in Boothia Felix, Canada, latitude 70° 30′ N., longitude 95° W. It was located again in 1905 by Captain Amundsen at a point a little farther west. Its approximate location is 70° 5′ N., and 96° 46′ W. It is probable that it slowly shifts its position.

12. Declination. It is, of course, on account of the fact that the earth's magnetic and geographical poles do not altogether coincide, that the magnetic needle does not point exactly north, and also that the direction in which it does point changes as the needle is moved about over the earth's surface. This last fact was first discovered by Columbus on his voyage to America, and caused great alarm among his sailors. There are other local causes, however, such as large deposits of iron ore, which cause local deviations of the needle from the true north. The number of degrees by which the needle varies from the north and south line at a given point, is called the *declination* at that point.

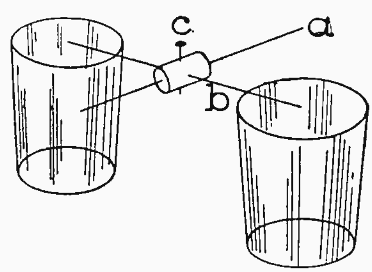


Fig. 15. Dip of the Magnetic Needle.

13. Inclination or Dip. Let an unmagnetized knitting needle *a* (Fig. 15) be thrust through a cork, and let a second needle *b* be passed through the cork at right angles to *a*. Let the system be adjusted by means of wax or a pin *c*, until it is in neutral equilibrium about *b* as an axis, when *a* is pointing east and west. Then let *a* be strongly magnetized by stroking one end of it from the middle out with the N pole of a strong magnet, and the other end from the middle out with the S pole of the same magnet. When now the needle is replaced on its supports and turned into a north-and-south line with its N pole toward the north, it will be found, in the north temperate zone, to dip so as to make an angle of from 60° to 75° with the horizontal. This shows that in the latitudes mentioned the earth's magnetic lines are not at all parallel to the earth's surface. The angle between these lines and the earth's surface is called the *dip*, or *inclination*, of the needle. At Washington it is 71° 5′; at Chicago, 72° 50′; at the magnetic poles it is of course 90°; and at the so-called *magnetic equator*—an irregular curved line passing through the tropics —the dip is 0°.

14. The Earth's Inductive Action. A very instructive way of showing that the earth acts like a great magnet is to hold any ordinary iron or steel rod parallel to the earth's magnetic lines, that is, about in the geographical meridian, but with the north end slanting down at an angle of say 70°, and then to strike one end a few blows with the hammer. The rod will be found to have become a magnet with its upper end an *S* pole, like the north pole of the earth, and its lower end an *N* pole. If the rod is reversed and tapped again with the hammer, its magnetism will be reversed. If held in an east-and-west position and tapped, it will become demagnetized, as is shown by the fact that both ends of it will attract either end of a compass needle.

STATIC ELECTRICITY

15. Electrification by Friction. If a piece of hard rubber or a stick of sealing wax is rubbed with flannel or cat's fur and then brought near some dry pith balls, bits of paper, or other light bodies, these bodies are found to jump toward the rod. After coming into contact with it, however, they become repelled. These experiments may be very satisfactorily performed in winter with the aid of a pith ball suspended by a fine silk thread, as shown in Fig. 16.

This sort of attraction was observed by the Greeks as early as 600 B. C., when it was found that amber which had been rubbed with silk attracted various sorts of light bodies. It was not, however, until 1600 A. D. that Dr. William Gilbert, physician to Queen Elizabeth, and sometimes called the father of the modern science of electricity and magnetism, discovered that the effect could be produced by rubbing together a great variety of other substances besides amber and silk, such, for example, as glass and silk, sealing wax and flannel, hard rubber and cat's fur, etc.

Gilbert named the effect which was produced upon these various substances by friction, *electrification,* after the Greek name for amber, *electron.* Thus, a body which, like rubbed amber, has been endowed with the property of attracting light bodies is said to have been *electrified,* or to have been given a charge of *electricity.* In this statement nothing whatever is said about the nature of electricity. We simply define an electrically charged body as one which has been put into the condition in which it acts toward light bodies like the rubbed amber or the rubbed sealing wax. To this day we do not know with certainty what the nature of electricity is, but we are fairly familiar with the laws which govern its action. It is these laws to which attention will be mainly devoted in the following sections.

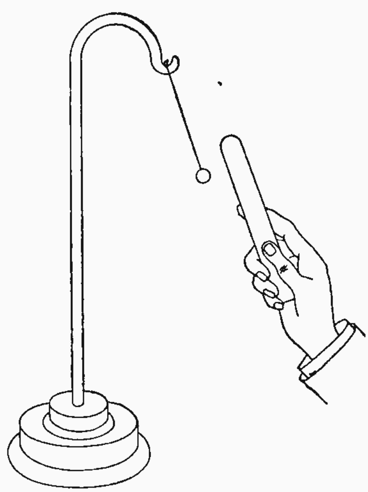


Fig. 16. Electrification by Friction.

16. Positive and Negative Electricity. If a pith ball has touched a glass rod which has been rubbed with silk and thus been put into the condition in which it is strongly repelled by this rod, it is found not to be repelled, but on the contrary to be very strongly attracted by a stick of sealing wax which has been rubbed with cat's fur or flannel. Similarly, if the pith ball has touched the sealing wax so that it is repelled by it, it is found to be strongly attracted by the glass rod. Again, two pith balls both of which have been in contact with the glass rod are found to repel one another, while pith balls one of which has been in contact with the glass rod and the other with the sealing wax attract one another.

Evidently, then, the electrifications which are imparted to glass by rubbing it with silk, and to sealing wax by rubbing it with flannel are opposite in the sense that an electrified body that is attracted by one is repelled by the other. We say, therefore, that there are two kinds of electrification, and we arbitrarily call one *positive* and the other *negative.* Thus, a *positively electrified body* is one which acts with respect to other electrified bodies like a *glass rod which has been* *rubbed with silk*, and a *negatively electrified body* is one which acts like a piece *of sealing wax which has been rubbed with flannel.* These facts and definitions may then be stated in the following general law: *Electrical charges of like sign repel each other, while charges of unlike sign attract each other.* The forces of attraction or repulsion are found, like those of gravitation and magnetism, *to decrease as the square of the distance increases.*

17. Conductors and Insulators. If a pith ball is in contact with a metal body A (Fig. 17), and if this body is connected to another metal body B by a wire, then, when B is rubbed with an electrified glass rod, A will be found immediately to repel the pith ball from itself. That is, a portion of the charge communicated to B evidently passes instantly over the wire to A. If the experiment is repeated when A and B are connected with a thread of silk, or with a rod of wood instead of metal, no effect will be observed at all upon the pith ball. If a moistened thread connects A and B, the pith ball will be affected, but not so soon as when A and B are connected with a wire.

Fig. 17. Experiment Showing the Conducting or Insulating Property of Various Materials.

These experiments make it clear that while electric charges pass with perfect readiness through a wire, they are quite unable to pass along dry silk or wool, while they pass with considerable difficulty along moist silk. We are therefore accustomed to divide substances into two classes, *conductors* and *non-conductors* or *insulators*, according to their ability to transmit electrical charges from point to point. Thus metals and solutions of salts and acids in water are all conductors of electricity, while glass, porcelain, rubber, mica, shellac, wood, silk, vaseline, turpentine, paraffin, and oils generally are insulators. No hard and fast line, however, can be drawn between conductors and non-conductors, since all so-called insulators conduct to some extent, while the so-called conductors differ greatly among themselves in the facility with which they transmit charges.

The fact of conduction brings out sharply one of the most essential distinctions between electricity and magnetism. Magnetic poles exist only in iron and steel, while electrical charges can be communicated to any body whatsoever, provided they are insulated.

These charges pass from point to point over conductors, and can be transferred by contact from one body to any other, while magnetic poles remain fixed in position, and are wholly uninfluenced by contact with other bodies, unless these bodies themselves are magnets.

18. Electrostatic Induction. If a metal ball *A*, Fig. 18, is strongly charged by rubbing it with a charged rod, and then brought near an insulated metal body *B* which is provided with pith balls or strips of paper, *a*, *b*, *c*, as shown, the divergence of *a* and *c*, will show that the ends of *B* have received electrical charges because of the presence of *A*, while the failure of *b* to diverge will show that the middle of *B* is uncharged. Further, the rod which charged *A* will be found to repel *c* but to attract *a*. When *A* is removed all evidences of electrification in *B* will disappear.

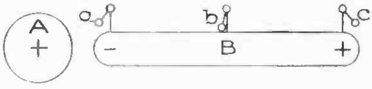


Fig. 18. Electrostatic Induction.

From experiments of this sort we conclude that when a conductor is brought near a charged body the end away from the charged body becomes electrified with the same kind of electricity as that on the charged body, while the end near the charged body receives a charge of opposite sign. *This method of producing electrification by the mere influence which an electric charge has upon a conductor placed in its neighborhood, is called electrostatic induction.* The fact that as soon as *A* is removed, *a* and *c* collapse, shows that this form of electrification is only a temporary phenomenon.

19. The Two-Fluid Theory of Electricity. We can describe the facts of induction conveniently by assuming that in every conductor there exists an equal number of positively and negatively charged corpuscles, which are very much smaller than atoms and which are able to move about freely among the molecules of the conductor. According to this view, when no electrified body is near the conductor *B*, it appears to have no charge at all, because all of the little positive charges within it counteract the effects upon outside bodies of all the little negative charges. But as soon as an electrical charge is brought near *B*, it drives as far away as possible the little corpuscles which carry charges of sign like its own, while it attracts the corpuscles of unlike sign. *B*, therefore, becomes electrified like *A* at its remote end, and unlike *A* at its near end. As soon as the inducing charge s removed, B immediately becomes neutral again because the little positive and negative corpuscles come together under the influence of their mutual attraction. This picture of the mechanism of electrification by induction is a modern modification of the so-called *two-fluid theory* of electricity, which conceived of all conductors as containing equal amounts of two weightless electrical fluids, called positive electricity and negative electricity. Although it is extremely doubtful whether this theory represents the actual conditions within a conductor, yet we are able to say with perfect positiveness that *the electrical behavior of a conductor is exactly what it would be if it did contain equal amounts of positive and negative electrical fluids,* or equal numbers of minute positive and negative corpuscles which are free to move about among the molecules of the conductor under the influence of outside electrical forces. Furthermore, since the real nature of electricity is as yet unknown, it has gradually become a universally recognized convention to speak of the positive electricity within a conductor as being repelled to the remote end, and the negative electricity as being attracted to the near end by an outside positive charge, and *vice versa*. This does not imply the acceptance of the two-fluid theory. It is merely a way of describing the fact that the remote end does acquire a charge like that of the inducing body, and the near end a charge unlike that of the inducing body.

20. The Electron Theory. A slightly different theory has recently been put forward by physicists of high standing both in England and in Germany. According to this theory a certain amount of positive electricity is supposed to constitute the nucleus of the atom of every substance. About this positive charge are grouped a number of very minute negatively charged corpuscles or electrons, the mass of each of which is approximately $\frac{1}{2000}$ of that of the hydrogen atom. The sum of the negative charges of these electrons is supposed to be just equal to the positive charge of the atom, so that in its normal condition, the whole atom is neutral and uncharged. But in the jostlings of the molecules of the conductor, electrons are continually getting loose from the atoms, moving about freely among the molecules, and re-entering other atoms which have lost their electrons. Therefore, at a given instant, there are always in every conductor a large number of free negative electrons and an exactly equal number of atoms which have lost electrons and which are therefore positively charged. Such a conductor would, as a whole, show no charge of either positive or negative electricity. But if a body charged, for example, negatively, were brought near such a body, the negatively charged electrons would stream away to the remote end, leaving behind them the positively charged atoms which are not supposed to be free to move from their positions. On the other hand, if a positively charged body is brought near the conductor, the negative electrons are attracted and the remote end is left with the immovable positive atoms.

The only advantage of this theory over that suggested in the preceding section, in which the existence of both positive and negative corpuscles is assumed, is that there is much direct experimental evidence for the existence of free negatively charged corpuscles of about $\frac{1}{2000}$ the mass of the hydrogen atom, but no direct evidence as yet for the existence of positively charged electrons.

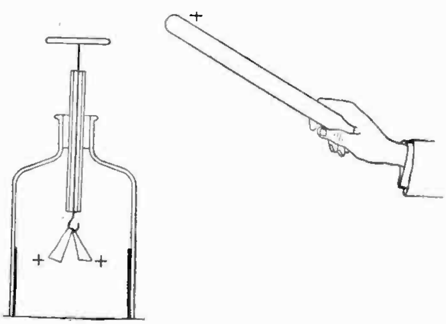


Fig. 19. Electroscope, for Detecting Presence of Electric Charge.

21. The Gold-Leaf Electroscope. One of the most sensitive and convenient instruments for detecting the presence of an electrical charge upon a body and for determining the sign of that charge, is the *gold-leaf electroscope* (Fig. 19). It consists of a glass jar, through the neck of which passes a metal rod supported by a rubber stopper or some other insulated material, and carrying at its lower end two gold leaves or strips of aluminum foil. To detect with this instrument the *presence* of an electrical charge, it is only necessary to bring near the upper end of the electroscope the body which is to be tested. If it is charged, it will repel electricity of the kind which it possesses to the leaves and draw the unlike kind to the upper end. The leaves under the influence of the like charges which they possess will stand apart or diverge. If the body is not charged the gold leaves will not be affected at all.

To determine the *sign* of an unknown charge with an electroscope, we first impart a charge of known sign to the electroscope by touching it with a piece of sealing wax, for example, which has been rubbed with cat's fur. This charges the leaves negatively and causes them to diverge. The unknown charge is then slowly brought near the upper end of the electroscope; and if the divergence of the leaves is *increased,* the sign of the unknown charge is negative, for the increased divergence means that more negative electricity has been repelled to the leaves. If the divergence is *decreased* instead of increased, the sign of the unknown charge is *positive,* for, the decreased divergence of the leaves means that a part of the negative electricity already on the leaves has been drawn to the upper end.

22. Charging by Induction. If a positively charged body C (Fig. 20) is brought near two conductors A and B in contact, we have seen that a positive charge will appear upon A and a negative charge upon B. If C were removed these charges would recombine and A and B both become neutral. But if, before C has been removed, A and B are separated, and if then C is removed, there is no opportunity for this recombination. Hence A is left permanently charged positively, and B negatively. These charges can be easily detected by bringing A and B into the neighborhood of a charged electroscope. One will cause the divergence of the leaves to increase, the other will cause it to decrease.

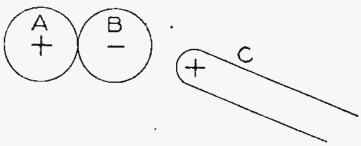
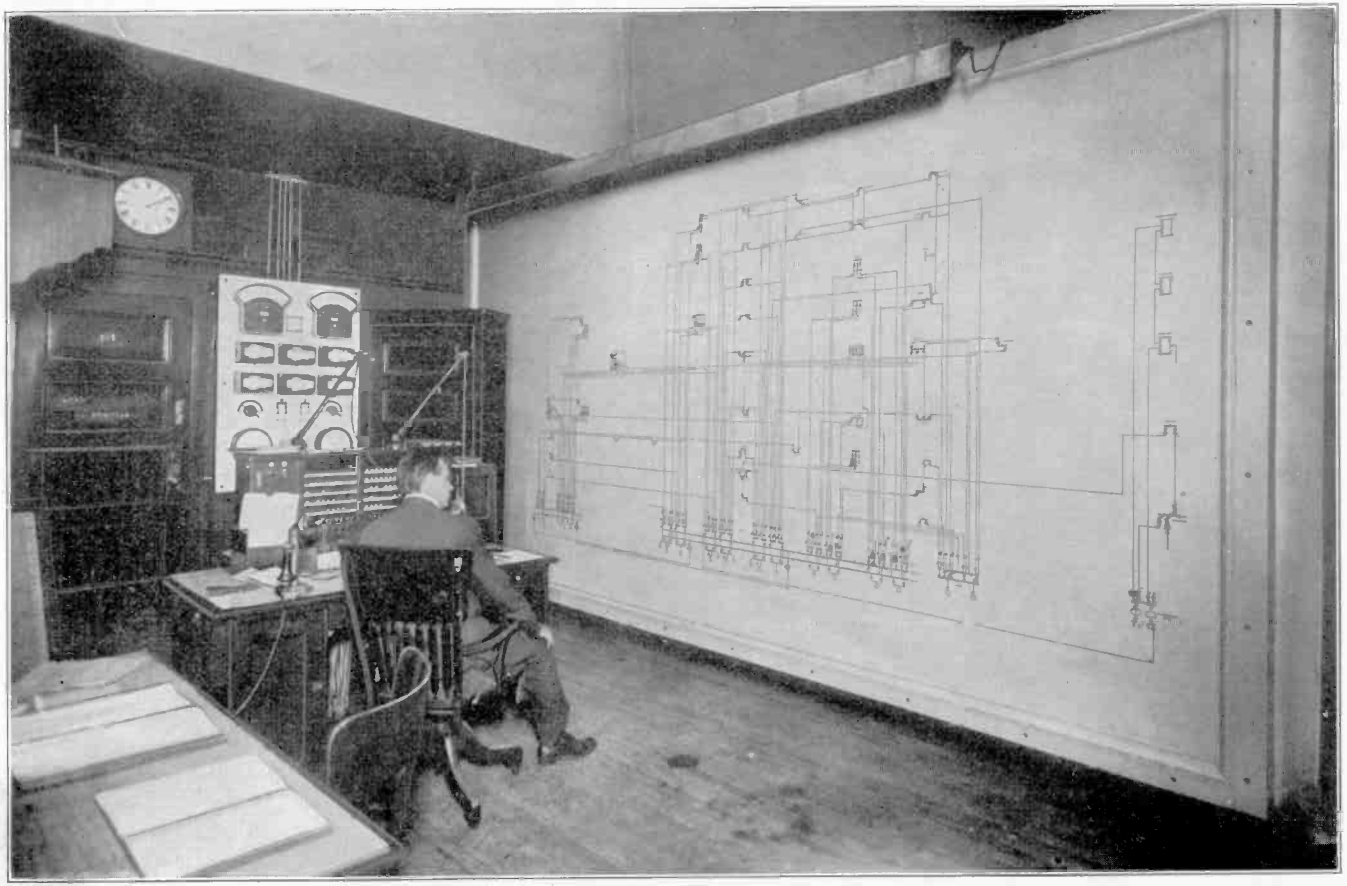


Fig. 20. Two Conductors in Contact, Charged by Induction.

Again, if a positively charged body C (Fig. 21) is brought near a conductor B, and if, while C is still in position, the finger is touched anywhere to the conductor B and then removed, then, when C is removed, B is found to be negatively charged. In this case the body of the experimenter corresponds to the conductor A of the preceding experiment, and removing the finger from B corresponds therefore to separating the two conductors A and B. In the use of this method of charging a single body by induction, it makes no difference with the sign of the charge left upon B where the finger touches the body B, whether at a or at b or at any other point, for it is always the kind of electricity which is like that on the charging body C that is repelled off to earth through the finger; while the charge which is unlike that upon C is drawn to the part of B which is next to C, and as soon as C is removed this spreads over the whole body B. Whenever, then,



A TELEPHONE SYSTEM AS AN ADJUNCT TO AN ELECTRIC LIGHT AND POWER SYSTEM
Note the Diagram of Power Feeder System to Large City.

a single body is charged by induction in this manner, *the sign of the charge left upon it is always opposite to that of the inducing charge.*

Thus, if we wished to charge an electroscope negatively by induction from a positively charged glass rod, we should first bring the rod near the knob of the electroscope, thus causing the leaves to diverge because of the positive electricity which is repelled to them. Then while the rod was still in position near the electroscope, we should touch the knob of the latter with the finger. The leaves would at once collapse. This is because the positive electricity on the electroscope passes off to earth through the finger, while the negative is held attracted to the knob of the electroscope by the positive charge on the rod. In this condition the negative is sometimes said to be *bound* by the attraction of the positive charge on *C*. We should then remove the finger and finally the rod. The negative would then be free to pass to the leaves and cause them to diverge. The electroscope would thus be charged negatively. This is often one of the most convenient methods of charging an electroscope. It should always be used where it is desired to obtain a charge of opposite sign to that of the charging body. If it is desired to obtain a charge on the electroscope of like sign to that of the charging body we simply touch the body directly to the knob of the electroscope, and thus charge it by conduction rather than by induction.

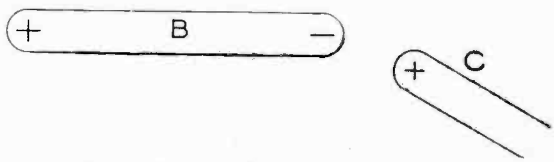


Fig. 21. Single Body Charged by Induction.

One advantage of charging by induction lies in the fact that the charging body loses none of its own charge, whereas, in charging by conduction the charging body must of course part with a portion of its charge.

23. Positive and Negative Electricities Always Appear Simultaneously and in Equal Amounts. If a strip of flannel is stuck fast to one side of a rod of sealing wax and rubbed back and forth over a a second rod of sealing wax, and if then the two bodies are brought near the knob of a charged electroscope before they are separated, it is found that they give no evidence at all of electrification. But if they are separated and brought in succession to the knob of the electroscope, they will exhibit positive and negative charges of equal strength, the flannel being positive and the bare sealing wax negative. Similarly, when a glass rod is charged positively by rubbing it with silk, the silk when tested is always found to possess a negative charge. These experiments show that in producing electrification by friction, positive and negative charges appear simultaneously and in equal amount. This confirms the view, already brought forward in connection with induction, that the process of electrification always consists in a separation of positive and negative charges which already exist in equal amounts within the bodies in which the electrification is developed. Certain it is that it is never possible to produce in any way whatever one kind of electricity without producing at the same time an equal amount of the opposite kind.

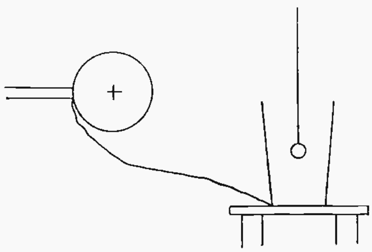


Fig. 22. Showing that an Electric Charge Lies on Outer Surface of Conductor.

24. An Electrical Charge Resides upon the Outside Surface of a Conductor. If a deep metal cup is placed upon an insulating stand and charged as strongly as possible, either from a charged rod or from an electrical machine (see Fig. 22), and a metal ball suspended by a silk thread is touched to the inside of the cup, the ball is found upon removal to show no evidence of charge when brought near the knob of the electroscope. If, on the other hand, the ball is touched to the outside of the cup, it exhibits a strong charge. Or, again, if the metal ball is first charged and then touched to the inside of the cup, it loses completely its charge, even though the cup itself may be very strongly charged. These experiments show that an electric charge resides entirely on the outside surface of a conductor. This is a result which might have been inferred from the fact that all the little electrical charges of which the total charge is made up repel each other and therefore move through the conductor until they are on the average as far apart as possible, that is, until they are all upon the surface.

25. Density of Charge Greatest where Curvature of Surface is Greatest. Since all of the parts of an electrical charge tend, because of their mutual repulsions, to get as far apart as possible, we might infer that if a charge of either sign is placed upon an oblong conductor, like that of Fig. 23 (1), it would distribute itself so that the electrification at the ends will be stronger than that in the middle. The correctness of this inference is easy to verify experimentally, for it is only necessary to attach a penny to the end of a piece of sealing wax and touch it first to the middle of a long charged conductor, and then bring it over the knob of the electroscope, then to repeat the operation when the penny is touched to the end of the conductor. The electroscope will be affected much more strongly in the latter case than in the former. If we should test in this way the distribution on a pear-shaped body, Fig. 23 (2), we should find the density of electrification considerably greater on the small end than on the large end. By density of electrification is meant the quantity of electricity on unit-area of the surface.

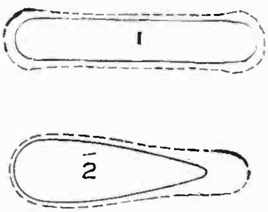


Fig. 23. Variation of Electric Charge with Curvature of Surface.

26. The Discharging Effect of Points. It might be inferred from the above that if one end of a pear-shaped body is made more and more pointed, then, when a charge is imparted to the body, the electric density on the small end will become greater and greater as the curvature of this end is made less and less. That this is in fact the case is indicated by the effect which experiment shows that points have upon electrical charges; for if a very sharp needle is attached to any insulated conductor which is provided with paper or pith-ball indicators (as shown in Fig. 18), it is found impossible to impart to the body a permanent charge; that is, if one attempts to charge it by rubbing over it a charged glass rod or other charged body, the indicators will be found to collapse as soon as the rod is removed. That this is due to an effect of the point can be proved either by removing the needle, or by covering up the point with wax, when the charge will be retained, as in the case of any insulated body. The probable explanation of the phenomenon is as follows:

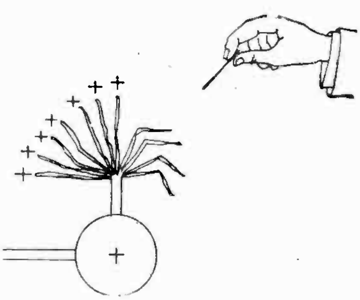


Fig. 24. Influence of Pointed Conductor upon Electric Charge.

The density of the charge becomes so intense upon the point that the molecules of air immediately adjoining the point are broken apart into positive and negative parts, and portions which are of unlike sign to the charge on the point are attracted to it, thus neutralizing the charge upon the body, while portions of like sign are repelled away.

The effect of points upon an electrical charge may be shown very strikingly by holding a very sharp needle in the hand and bringing it toward the knob of a charged electroscope. The leaves will fall together rapidly. Or, if the needle is brought near a tassel of tissue paper which is attached to an electrified conductor (see Fig. 24), the electrified streamers, which stand out in all directions because of their mutual repulsions, will at once fall together. In both of these cases the needle becomes electrified by *induction* and discharges to the knob of the electroscope, or to the tassel, electricity of opposite sign to that which it contains, thus neutralizing its charge.

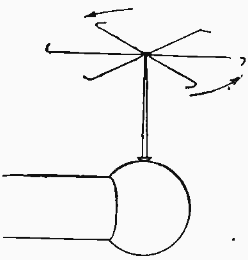


Fig. 25. Electric Whirl on Knob of Electrical Machine.

An interesting variation of the last experiment is to mount an electric whirl (see Fig. 25) upon one knob of an electrical machine. As soon as the machine is started, the whirl will rotate rapidly in the direction of the arrow. The explanation is as follows: On account of the great magnitude of the electric force near the points, the molecules of the gas just in front of them are broken into positive and negative parts. The part of sign unlike that of the charge on the points is drawn to them, while the other part is repelled. But since this repulsion is mutual, the point is pushed back with the same force with which the particles are pushed forward; hence the rotation. The repelled particles in their turn drag the air with them in their forward motion, and thus produce the *electric wind*, which may be detected easily by the hand or by a candle held in front of the point.

27. The Lightning Rod. The discharging effect of a sharp point is utilized in the lightning rod, invented by Franklin in 1752. The way in which the rod discharges the cloud and protects the building is as follows: As an electrically charged cloud approaches a building provided with a lightning rod, it induces an opposite charge in the earth and in the rod which is connected to the earth. As soon as the charge on the point becomes strong enough to break apart the molecules of the air in front of it, a stream of electrified particles, of sign opposite to that of the charge on the cloud, passes from the neighborhood of the rod to the cloud and thus neutralizes the charge of the cloud. We are accustomed to say merely that the point discharges the cloud.

28. Electrical Potential. There is a very instructive analogy between the use of the word *potential* in electricity and *pressure* in hydrostatics. For example, if water will flow from tank A (Fig. 26) to tank B through the connecting pipe R, we infer that the hydrostatic pressure at a must be greater than that at b, and we attribute the flow directly to this difference in pressure. In precisely the same way, if, when two bodies A and B (Fig. 27) are connected by a conducting wire r, a charge of positive electricity is found to pass from A to B, or of negative from B to A, we are accustomed to say that the electrical potential is higher at A than at B, and we assign this *difference of potential* as the cause of the flow. Thus, just as water tends to flow from points of higher hydrostatic pressure to points of lower hydrostatic pressure, so electricity is conceived of as tending to flow from points of higher electrical pressure or potential to points of lower electrical pressure or potential.

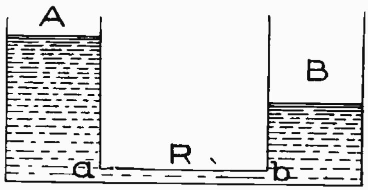


Fig. 26.

Fig. 27.

Figs. 26 and 27. Illustrating Analogy between Electric Potential and Hydrostatic Pressure.

Again, if water is not continuously supplied to one of the tanks of Fig. 26, we know that the pressures at a and b must soon become the same. Similarly, if no electricity is supplied to the bodies A and B of Fig. 27, their potentials very quickly become the same. In other words, *all points on a system of connected conductors in which the electricity is in a stationary, or static, condition are necessarily at the same potential*; for if this were not the case, then the electricity which we imagine all conductors to contain would move through the conductor until the potentials of all points were equalized. In other words, equality in the potentials of all points on a conductor in the static condition follows at once from the fact of mobility of electrical charges through or over a conductor.

But if water is continually poured into *A* (Fig. 26) and removed from *B*, the pressure at *a* will remain permanently above the pressure at *b*, and a continuous flow of water will take place through *R*. Similarly if *A* (Fig. 27) is connected with an electrical machine and *B* to earth, a permanent potential difference will exist between *A* and *B* and a continuous current of electricity will flow through *r*. Difference in potential is commonly denoted simply by the letters P. D. (potential difference).

When we speak simply of the *potential* of a body we mean the *difference of potential* which exists between the body and the earth, for the electrical condition of the earth is always taken as the zero to which the electrical conditions of all other bodies are referred. Thus a body which is positively charged is regarded as one which has a potential higher than that of the earth, while a body which is negatively charged is looked upon as one which has a potential lower than that of the earth. Fig. 28 represents the hydrostatic analogy of positively and negatively charged bodies. Since it has been decided to regard the flow of electricity as taking place from a point of higher to that of lower potential, it will be seen that when a discharge takes place between a negatively charged body and the earth we must regard the positive electricity as passing from the earth to the body, rather than the negative as passing from the body to the earth. This is, indeed, a mere convention, but it is one which it is very important to remember in connection with the study of current electricity. From the point of view of the electron theory (§ 20), it would be natural to invert this convention exactly, since this theory regards the negative electricity alone as moving through conductors. But since the opposite convention has become established, it will not be wise to attempt to change it until the electron theory has become more thoroughly established than is at present the case.

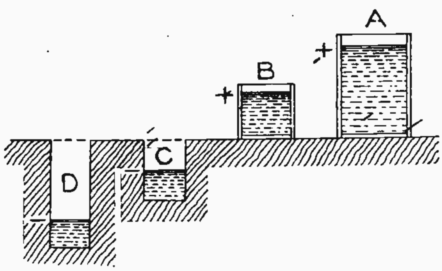


Fig. 28. Hydrostatic Analogy of Positively and Negatively Charged Bodies.

29. Some Methods of Measuring Potentials. One of the simplest methods of comparing the potential difference which exists between any two charged bodies and the earth, is to connect the charged bodies successively to the knob of an electroscope, the conducting case of which is in electrical connection with the earth. The amount of separation of the gold leaves is then a measure of the P. D. between the earth and the charged body.

Another very convenient way of measuring approximately a very large P. D. is to measure the length of the spark which will pass between the two bodies whose P. D. is sought. This P. D. is approximately proportional to the spark length, provided the dimensions of the bodies are large in comparison with the distance between them, each centimeter of spark length representing a P. D. of about 30,000 volts.

30. Condensers. If a metal plate *A* is mounted on an insulating plate and connected with an electroscope, as in Fig. 29, and if a

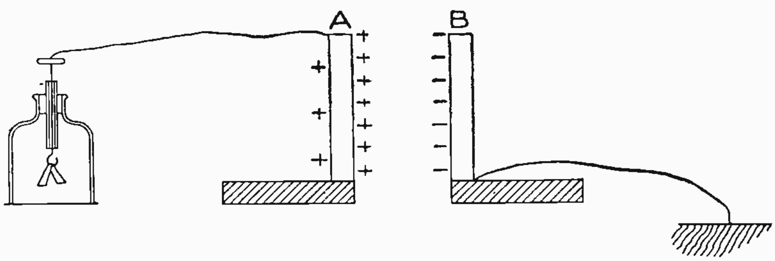


Fig. 29. Illustrating the Principle of the Condenser.

second plate *B* is similarly mounted and connected to earth, then, when a charge is placed on *A*, it will be found that the gold leaves fall together as *B* approaches *A* and diverge farther as *B* recedes from *A*. This shows that the potential of *A* is diminished by bringing *B* close to it, in spite of the fact that the quantity of electricity on *A* has remained unchanged. If we convey additional plus charges to *A*, we find that many times the original amount of electricity may be placed on *A* when *B* is close to it, before the leaves return to their original divergence, that is, before the body regains its original potential.

We say, therefore, that the *capacity* of *A* for holding electricity has been very greatly increased by bringing near it another conductor which is connected to earth. It is evident from this statement that *we measure the capacity of a body by the amount of electricity which must be put upon it in order to raise its potential to a given point.* The explanation of the increase of capacity in this case is obvious. As soon as B was brought near to A, it became charged, by induction, with electricity of sign opposite to that of A, the electricity of sign like that of A being driven off to earth through the connecting wire. The attraction between these opposite charges on A and B drew the electricity on A to the face nearest to B, and removed it from the more remote parts of A, so that it became possible to put a very much larger charge on A before the tendency of the electricity on A to pass over to the electroscope became as great as at first, that is, before the potential of A rose to its original value. Under circumstances of this sort the electricity on A is said to be *bound* by the opposite electricity on B.

An arrangement of this sort consisting of two conductors separated by a nonconductor is called a *condenser*. If the conducting points are very close together and one of them is joined to earth, the capacity of the system may be thousands of times as great as that of one of the plates alone.

31. The Leyden Jar. The most common form of condenser is a glass jar coated part way to the top inside and outside with tinfoil (Fig. 30). The inside coating is connected by a chain to the knob, while the outside coating is connected to earth. Condensers of this sort first came into use in Leyden, Holland, in 1745. Hence they are now called *Leyden jars*.

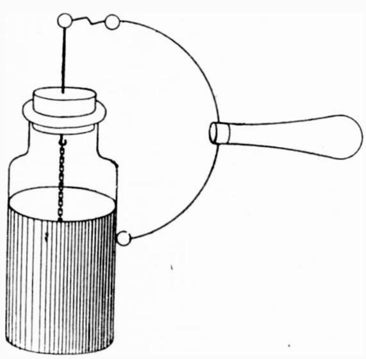


Fig. 30. Leyden Jar.

Such a jar is charged by holding the knob in contact with one terminal of an electrical machine and connecting the outer coat to earth either by a wire or simply by holding it with the hand. As fast as electricity passes to the knob, it spreads to the inner coat of the jar where it attracts electricity of the opposite kind from the earth to the outer coat, repelling electricity of the same kind. If the inner and outer coatings are now connected by a discharging rod (as in Fig. 30), a very powerful spark will be produced. If a charged jar is placed on a glass plate so as to insulate the outer coat, the knob may be touched with the finger and no appreciable discharge noticed. Similarly the outer coat may be touched with the finger with the same result. But if the inner and outer coats are connected with the discharger, a powerful spark passes.

The experiment shows that it is impossible to discharge one side of the jar alone, for practically all of the charge is *bound* by the opposite charge on the other coat. Therefore, the full discharge can occur only when the inner and outer coats are connected.

32. Electrical Screens. We have seen that if a positively charged body *A* (Fig. 31) is brought near an uncharged conductor *B*, negative electricity is attracted to the near end of the conductor and positive electricity appears on the remote end. This appearance of the two opposite charges on the two opposite ends of the conductor evidently tends to create a field of force at any point *p*, inside the conductor, which is opposite in direction to the field due to the charge on *A*. Since the electricity within the conductor is free to move under the influence of any electrical force which is acting upon it, it is clear that the accumulation of negative electricity at one end and of positive at the other will cease only when all electrical forces inside the conductor are reduced to zero, that is, when the charges on *A* and *B*, acting jointly, neutralize one another completely at any point *p* within the conductor. It appears, therefore, that the distribution of the induced charge on the surface of a conductor in the electrical field of a charged body must always be such that there is no force whatever inside the body. This theoretical conclusion was first experimentally verified by Faraday, who coated a large box with tinfoil and went inside the box with delicate electroscopes. He found that these electroscopes showed no effects whatever, even when powerfully charged bodies were brought near the outside of the box. The experiment is often repeated in a small way by placing an electroscope under a wire cage of rather small mesh. A charged rod brought near the cage will produce no effect whatever upon the electroscope. We thus learn that electrical influences can be completely cut off from a body by surrounding it on all sides with a conductor.

Fig. 31. Illustrating Principle of the Electrical Screen.

ELECTRICAL GENERATORS.

33. The Electrophorus. The electrophorus is a simple electrical generator which illustrates well the principle underlying the action of all electrostatic machines. All such machines generate electricity primarily by induction, not by friction. *B* (Fig. 32) is a hard rubber plate which is first charged by rubbing it with fur or flannel. *A* is a metal plate provided with an insulating handle. When the plate *A* is placed upon *B*, touched with the finger, and then removed, it is found possible to draw a spark from it, which in dry weather may be a quarter of an inch or more in length. The process may be repeated an indefinite number of times without producing any diminution in the size of the spark which may be drawn from *A*.

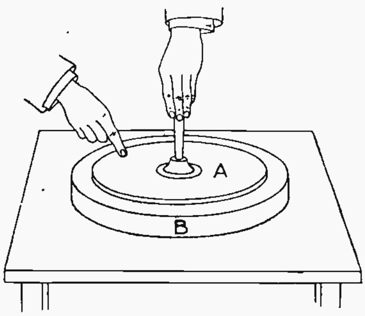


Fig. 32. The Electrophorus.

If the sign of the charge on *A* is tested by means of an electroscope, it will be found to be positive. This proves that *A* has been charged by induction, not by contact with *B*, for it is to be remembered

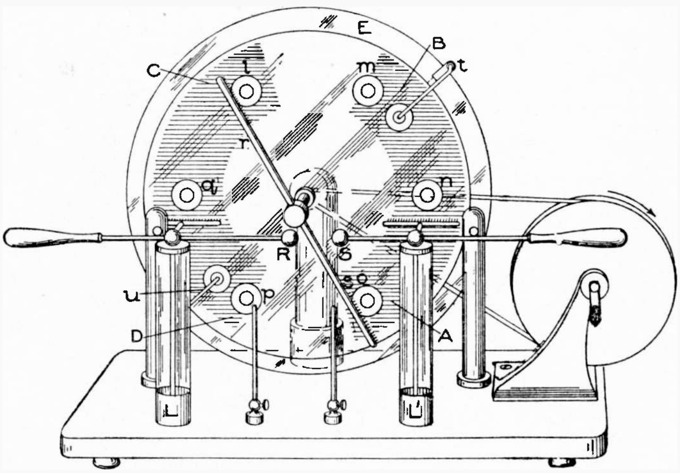


Fig. 33. Toepler-Holtz Static Machine.

that the latter is charged negatively. The reason for this is that even when *A* rests upon *B* it is in reality separated from it, at all but a very few points, by an insulating layer of air; and, since *B* is a non-conductor, its charge cannot pass off appreciably through these few points of contact. It simply repels negative electricity to the top side of the metal plate *A*, and draws positive to the lower side of this plate. The negative passes off to earth when the plate is touched with the finger. Hence, when the finger is removed and *A* lifted, is possesses a strong positive charge.

34. The Toepler-Holtz Static Machine. The ordinary static machine is nothing but a continuously acting electrophorus. Fig. 33 represents one type of such machine. Upon the back of the stationary glass plate *E* are pasted paper sectors, beneath which are strips of tinfoil *A B* and *C D*, called *inductors*. In front of *E* is a revolving glass plate carrying disks *l*, *m*, *n*, *o*, *p*, and *q*, called *carriers*. To the inductors *A B* and *C D* are fastened metal arms *t* and *u*, which bring *C* and *D* into electrical contact with the disks *l*, *m*, *n*, *o*, *p*, and *q*, when these disks pass beneath the tinsel brushes carried by *t* and *u*. A stationary metallic rod *r s* carries at its ends stationary brushes as well as sharp-pointed metallic combs. The two knobs *R* and *S* have their capacity increased by the Leyden jars *L* and *L'*.

The action of the machine is best understood from the diagram (Fig. 34). Suppose that a small + charge is originally placed on the inductor *C D*. Induction takes place in the metallic system consisting of the disks *l* and *o* and the rod *r s*, *l* becoming negatively charged, and *o* positively charged. As the plate carrying *l*, *m*, *n*, *o*, *p*, *q* rotates in the direction of the arrows, the negative charge on *l* is carried over to the position *m*, where a part of it passes over to the inductor *A B*, thus charging it negatively. When *l* reaches the position *n*, the remainder

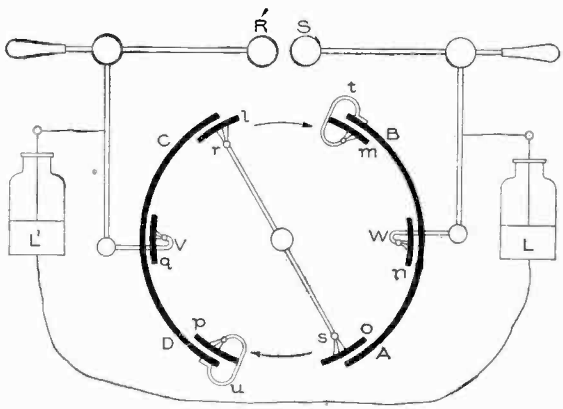


Fig. 34. Illustrating Action of Static Machine.

of its charge, being repelled by the negative which is now on *A B*, passes over into the Leyden jar *L*. When *l* reaches the position *o*, it again becomes charged by induction, this time positively, and more strongly than at first, since now the negative on *A B*, as well as the positive on *C D*, is acting inductively upon the rod *r s*. When *l* reaches the position *u*, a part of its now strong positive charge passes to *C D*, thus increasing the positive charge upon this inductor. In the position *v*, the remainder of the positive charge on *l* passes over to *L'*. This completes the cycle for *l*. Thus, as the rotation continues, *A B* and *C D* acquire stronger and stronger charges, the inductive action upon *r s* becomes more and more intense, and positive and negative charges are continuously imparted to *L* and *L'* until a discharge takes place between the knobs *R* and *S*.

There is usually sufficient charge on one of the inductors to start the machine, but in damp weather it is often found necessary to apply a charge to one of them by means of a piece of sealing wax or a glass rod before the machine will work.

ELECTRICITY IN MOTION—ELECTRICAL CURRENTS

35. The Magnetic Effect Due to a Charge in Motion. An electrical charge at rest produces no magnetic effect whatever. This can be proved by bringing a charged body near a compass needle or suspended magnet. It will attract both ends equally well by virtue of the principle of electrostatic induction. If the effect were magnetic, one end should be repelled and the other attracted. Again, if a sheet of zinc, aluminum, or copper is inserted between the deflected needle and the charge, all effect which was produced upon the needle by the charge will be cut off, for the metallic sheet will act as an electric screen (cf. § 32). But if such a metal screen is inserted between a compass needle and magnet, its insertion has no effect at all on the magnetic forces (cf. § 5).

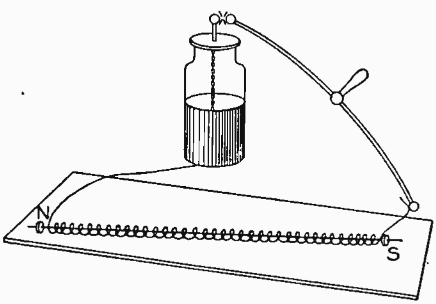


Fig. 35. Demonstrating Magnetic Effect of Electric Current.

If, however, a charged Leyden jar is discharged through a coil which surrounds an unmagnetized knitting needle in the manner shown in Fig. 35, the needle will be found after the discharge to have become distinctly magnetized. If the sign of the charge on the jar is reversed, the poles will, in general, be reversed also.

This experiment demonstrates the existence of some connection between electricity and magnetism. Just what this connection is, is not yet known with certainty; but it is known that *magnetic effects are always observable near the path of a moving electrical charge,* while no such effects can ever be observed near a charge at rest.

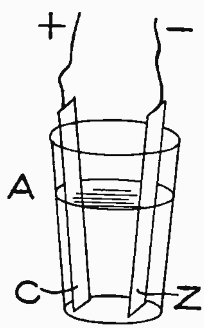


Fig. 36. Simplest Form of Galvanic Cell.

An electrical charge in motion is called an electrical current, and the presence of such current in a conductor is most commonly detected by the magnetic effect which it produces.

36. The Galvanic Cell. When a Leyden jar is discharged, but a very small quantity of electricity passes through the connecting wires, since the current lasts but a small fraction of a second. If we could keep the current flowing continuously through the wire, we should expect the magnetic effect to be more pronounced. This might be done by discharging Leyden jars in rapid succession through the wire. In 1786, however, Galvani, an Italian anatomist at the University of Bologna, accidentally discovered that there is a chemical method for producing such a continuous current. His discovery was not understood, however, until Volta, professor of physics at Como, devised an arrangement which is now known sometimes as the *voltaic,* sometimes as the *galvanic* cell.

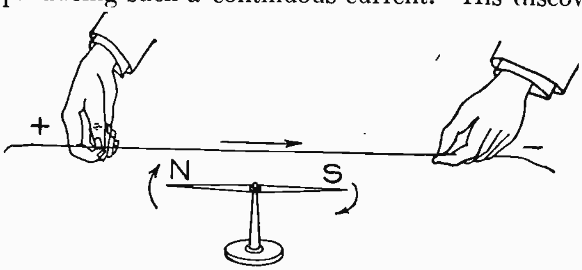


Fig. 37. Demonstrating Flow and Magnetic Effects of Current from Galvanic Cell.

Such a cell consists in its simplest form of a strip of copper and a strip of zinc immersed in dilute sulphuric acid (Fig. 36). If the wires leading from the copper and the zinc are connected for a few seconds to the end of the coil of Fig. 35, when an unmagnetized needle lies within this coil, the needle will be found to be much more strongly magnetized than it was when the Leyden jar was discharged through the coil. Or, if the wire connecting the copper and zinc is simply held above the needle in the manner shown in Fig. 37, the latter will be found to be strongly deflected. It is evident from these experiments that the wire which connects the terminals of a galvanic cell carries a current of electricity. Historically the second of these experiments, performed by the Danish physicist Oersted in 1819, preceded the discovery of the magnetizing effect of currents upon needles. It created a great deal of excitement at the time because it was the first clew which had been found to a relationship between electricity and magnetism.

It might be inferred from the above experiments that the two plates of a galvanic cell when not connected by a wire carry static positive and negative charges just as do the two coats of a Leyden jar before it is discharged through the wire. This inference can be easily verified with an electroscope.

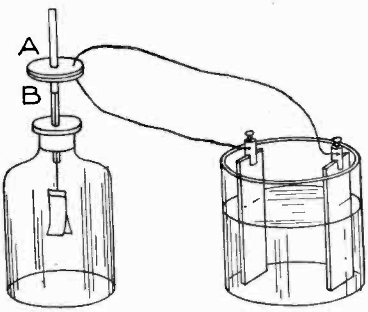


Fig. 38. Showing Existence of Static Charges on Plates of Galvanic Cell.

Thus, if a metal plate *A* (Fig. 38) covered with shellac on its lower side and provided with an insulating handle, is placed upon a similar plate *B* which is in contact with the knob on an electroscope; and if the copper plate, for example, of a galvanic cell is connected to *A* and the zinc to *B*; then, when the connecting wires are removed and the plate *A* lifted away from *B*, the leaves of the electroscope will diverge and when tested will be found to be negatively charged. If the deflection observed in the leaves of the electroscope is too small for purposes of demonstration, the conditions can be bettered by using a battery of from five to ten cells instead of the single cell. If, however, the plates *A* and *B* are sufficiently large—say, three or four inches in diameter—and if their surfaces are very flat, a single cell will be found to be sufficient. If, on the other hand, the copper plate is connected to *B* and the zinc to A in the above experiment, the electroscope will be found to be positively charged. This shows clearly that the copper plate possesses a positive electrical charge, while the zinc plate possesses a negative charge, these charges originating in the chemical action within the galvanic cell.

In this experiment the two metal plates separated by shellac constitute an electrical condenser which is charged positively on one side and negatively on the other by connecting it with the two plates of the galvanic cell, in precisely the same way in which a Leyden jar is charged by connecting its two coats one to one terminal and the other to the other terminal of a static machine. The potential of plate B is increased by moving A away from it, just as in the arrangement shown in Fig. 29 the potential of A was increased by moving B away from it. This device makes it possible to detect very small potential differences.

37. Comparison of a Galvanic Cell and Static Machine. If one of the terminals of a galvanic cell is touched directly to the knob of the gold-leaf electroscope without the use of the condenser plates A and B of Fig. 38, no divergence of the leaves can be detected; but if one knob of a static machine in operation were so touched, the leaves would be thrown apart very violently. Since we have seen that the divergence of the leaves is a measure of the potential of the body to which they are connected, we learn from this experiment that the chemical actions going on in a galvanic cell are able to produce between its terminals but very small potential differences in comparison with that produced by the static machine between its terminals. As a matter of fact, the potential difference between the terminals of the cell is but one volt (cf. § 40), while that between the terminals of an electrical machine may be several hundred thousand volts.

On the other hand, if the knobs of the static machine are connected to the ends of the wire shown in Fig. 37, and the machine operated, the current will not be large enough to produce any appreciable effect upon the needle. Since, under these same circumstances the galvanic cell produced a very large effect upon the needle, we learn that although the cell develops a much smaller P. D. than does the static machine, it nevertheless sends through the wire a very much larger amount of electricity per second. This means merely that the chemical actions which are going on within the cell are able to recharge the plates when they become discharged through the electric wire, far more rapidly than is the static machine able to recharge its terminals after they have once been discharged.

38. Shape of the Magnetic Field about a Current. If we place the wire which connects the plates of a galvanic cell in a vertical position (see Fig. 39), and explore with a compass needle the shape of the magnetic field about the current, we find that the magnetic lines are concentric circles lying in a plane perpendicular to the wire and having the wire as their common center. If we reverse the direction of the current, we find that the direction in which the compass needle points reverses also. If the current is very strong (say 40 amperes), this shape of the field can be shown by scattering iron filings on a plate through which the current passes, in the manner shown in Fig. 39. The relation between the direction in which the current flows and the direction in which the positive end of the needle points (this is, by definition, the direction of the magnetic field) is given in the following convenient rule: *If the right hand grasps the wire as in Fig. 40, so that the thumb points in the direction in which the positive electricity is moving, that is, in the direction from the copper toward the zinc, then the magnetic lines encircle the wire in the same direction as do the fingers of the hand.* Another way of stating this rule is as follows: *The relation between the direction of the current in a wire and the direction of the magnetic lines about it, is the same as the relation between the direction of the forward motion of a right-handed screw and the direction of rotation when it is being driven in.* In this form the rule is known as the *right-hand screw rule.*

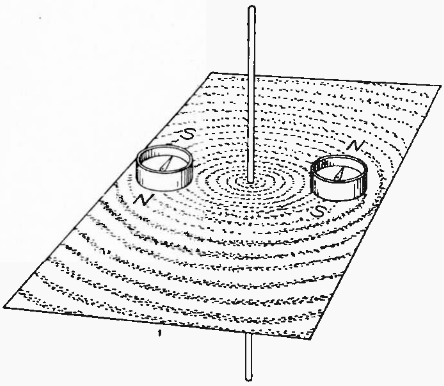
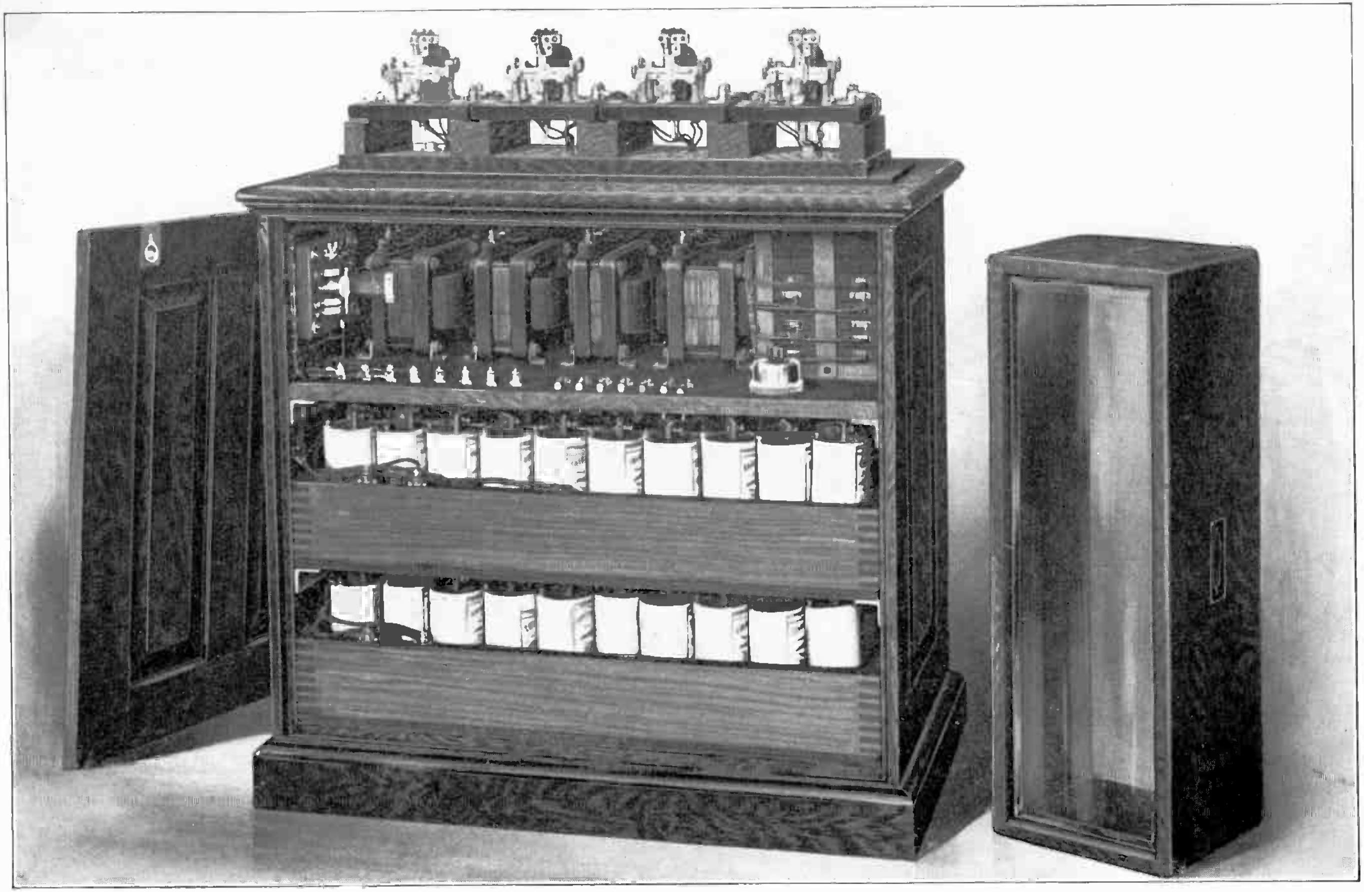


Fig. 39. Exploring Magnetic Field around a Conductor by means of Compass and Iron Filings.

39. The Measurement of Electrical Currents. Electrical cur-



DEAN HARMONIC CONVERTER
Dry Cell Type for Magneto Exchange.
The Dean Electric Co.

rents are, in general, measured by the strength of the magnetic effect which they are able to produce under specific conditions. Thus, if the wire carrying a current is wound into circular form as in Fig. 41, the right-hand screw rule shows us that the shape of the magnetic field at the center of the coil is similar to that shown in the figure. If, then, the coil is placed in a north-and-south plane and a compass needle is placed at the center, the passage of the current through the coil tends to deflect the needle so as to make it point east and west. The amount of deflection under these conditions is taken as the measure of current strength. The unit of current is called the ampere and is in fact approximately the same as the current which, flowing through a circular coil of three turns and 10 cm. radius, set in a north-and-south plane, will produce a deflection of 45 degrees at Washington in a small compass needle placed in its center (as in Fig. 41). Nearly all current-measuring instruments, commonly called *ammeters*, consist essentially either of a small magnet suspended at the center of a fixed coil as in Fig. 41, or of a movable coil suspended between the poles of a fixed magnet. The passage of the current through the coil produces a deflection, in the first case, of the magnetic needle with reference to the fixed coil, and in the second case, of the coil with reference to the fixed magnet. If the instrument has been suitably calibrated, the amount of the deflection gives at once the strength of the current in amperes.

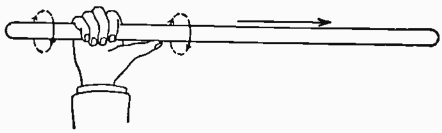


Fig. 40. Illustrating Right-Hand Screw Rule for Determining Direction of Magnetic Field.

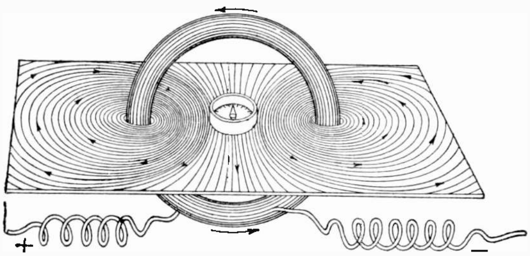


Fig. 41. Arrangement of Circular Conductor and Compass for Measuring Current Strength.

40. Electromotive Force and its Measurements. The potential difference which a galvanic cell or any other generator of electricity is able to maintain between its terminals when these terminals are not connected by a wire, *i. e.*, the total electrical pressure which the generator is capable of exerting, is commonly called its *electromotive force,* usually abbreviated to E. M. F. *The E. M. F. of an electrical generator may then be defined as its capacity for producing electrical pressure, or P. D.* This P. D. might be measured, as in §§ 29 and 36, by the deflection produced in an electroscope, or other similar instrument, when one terminal was connected to the case of the electroscope and the other terminal to the knob. Potential differences are in fact measured in this way in all so-called electrostatic voltmeters, which are now coming more and more into use.

The more common type of potential difference measurers, so-called *voltmeters,* consists, however, of an instrument made like an ammeter, save that the coil of wire is made of an enormous number of turns of extremely fine wire, so that it carries a very small current. The amount of current which it does carry, however, and therefore the amount of deflection of its needle is taken as proportional to the difference in electrical pressure existing between its ends when these are touched to the two points whose P.D. is sought. The principle underlying this type of voltmeter will be better understood from a consideration of the following water analogy. If the stop-cock K (Fig. 42) in the pipe connecting the water tanks C and D is closed, and if the water wheel A is set in motion by applying a weight W, the wheel will turn until it creates such a difference in the water levels between C and D that the back pressure against the left face of the wheel stops it and brings the weight W to rest. In precisely the same way, the chemical action within the galvanic cell whose terminals are not joined (Fig. 43) develops positive and negative charges upon these terminals, that is, creates a P. D. between them, until the back electrical pressure through the cell due to this P. D. is sufficient to put a stop to further chemical action.

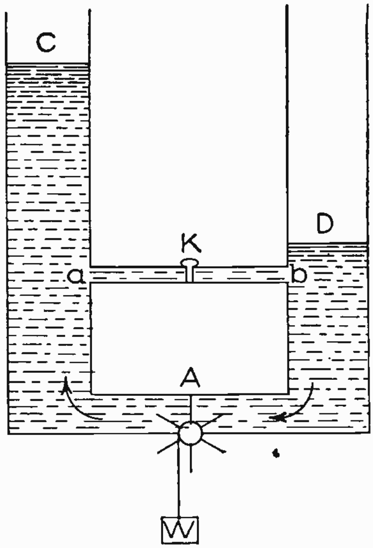


Fig. 42. Hydrostatic Analogy of Potential Difference.

Now, if the water reservoirs (Fig. 42) are put in communication by opening the stop-cock K, the difference in level between C and D will begin to fall, and the wheel will begin to build it up again. But if the carrying capacity of the pipe a b is small in comparison with the capacity of the wheel to remove water from D and to supply it to C, then the difference of level which permanently exists between C and D when K is open will not be appreciably smaller than when it is closed. In this case the current which flows through A B may obviously be taken as a measure of the difference in pressure which the pump is able to maintain between C and D when K is closed.

In precisely the same way, if the terminals C and D of the cell (Fig. 43) are connected by attaching to them the terminals a and b of any conductor, they at once begin to discharge through this conductor, and their P. D. therefore begins to fall. But if the chemical action in the cell is able to recharge C and D very rapidly in comparison with the ability of the wire to discharge them, then the P.D. between C and D will not be appreciably lowered by the presence of the connecting conductor. In this case the current which flows through the conducting coil, and therefore the deflection of the needle at its center, may be taken as a measure of the electrical pressure developed by the cell, that is, of the P. D. between its unconnected terminals.

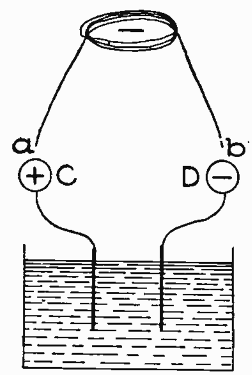


Fig. 43. Illustrating Principle of Common Voltmeter.

The common voltmeter is, then, exactly like an ammeter, save that its coil offers so high a resistance to the passage of electricity through it that it does not assist appreciably in discharging, that is, in reducing the P.D. between the points to which it is connected.

The unit of P. D. may be taken for practical purposes as the electrical pressure produced by a simple galvanic cell consisting of zinc and copper immersed in dilute sulphuric acid. It is named a *volt* in honor of Volta.

41. The Electromotive Forces of Galvanic Cells. When a voltmeter of any sort is connected to the terminals of a galvanic cell, it is found that the deflection produced is altogether independent of the shape or size of the plates or their distance apart. But if the nature of the plates is changed, the deflection changes. Thus, while copper and zinc in dilute sulphuric acid have an E. M. F. of one volt, carbon and zinc show an E. M. F. of at least 1.5 volts, while carbon and copper will show an E. M. F. of very much less than a volt. Similarly, by changing the nature of the liquid in which the plates are immersed, we can produce changes in the deflection of the voltmeter. We learn therefore that *the E. M. F. of a galvanic cell depends simply upon the materials of which the cell is composed and not at all upon the shape, size, or distance apart of the plates.*

42. Electrical Resistance. If the terminals of a galvanic cell are connected first to, say, ten feet of No. 30 copper wire, and then to ten feet of No. 30 German-silver wire, it is found that a compass needle placed at a given distance from the copper wire will show a much larger deflection than when placed the same distance from the German-silver wire. A cell, therefore, which is capable of developing a certain fixed electrical pressure is able to force very much more current through a given wire of copper than through an exactly similar wire of German-silver. We say, therefore, that German-silver offers a higher *resistance* to the passage of electricity than does copper. Similarly, every particular substance has its own characteristic power of transmitting electrical currents. Silver is the best conductor of any known substances. The resistances of different substances are commonly referred to silver as a standard, and the ratio between the resistance of a given wire of any substance and the resistance of an exactly similar silver wire is called the *specific resistance* of that substance. The specific resistances of some of the commoner metals are given below:

Fig. 44. Exact Size of No. 7 Copper Wire.

Silver	1.00	Soft iron	7.40	German silver	20.4
Copper	1.13	Nickel	7.87	Hard steel	21.0
Aluminum	2.00	Platinum	9.00	Mercury	62.7

The unit of resistance is the resistance at 0° of a column of mercury 106.3 cm. long and 1 sq. mm. in cross-section. It is called an *ohm,* in honor of the great German physicist, Georg Ohm (1789-1854). A length of 9.35 feet of No. 30 copper wire, or 6.2 inches of No. 30 German-silver wire, has a resistance of about one ohm.

Copper wire of the size shown in Fig. 44 has a resistance of about 2.62 ohms per mile.

The resistances of all of the metals increase with rise in temperature. The resistances of liquid conductors on the other hand usually decrease with rise in temperature. Carbon and a few other solids show a similar behavior: the filament in an incandescent lamp has only about half the resistance when hot that it has when cold. The resistances of wires of the same material are found to be directly proportional to their lengths, and inversely proportional to their cross-sections.

43. Ohm's Law. In 1827 Ohm announced the discovery that *the currents furnished by different galvanic cells, or combinations of cells, are always directly proportional to the E. M. F.'s existing in the circuits in which the currents flow, and inversely proportional to the total resistances of these circuits*; *i.e.*, if C represents the current in amperes, E the E. M. F. in volts, and R the resistance of the circuit in ohms, then Ohm's law as applied to the complete circuit is:

$$C = \frac{E}{R}; \; i.e., \text{Current} = \frac{\text{Electromotive force}}{\text{Resistance}}. \qquad (1)$$

As applied to any portion of an electrical circuit, Ohm's law is:

$$C = \frac{PD}{r}; \; i.e., \text{Current} = \frac{\text{Potential difference}}{\text{Resistance}}, \qquad (2)$$

where $P.D.$ represents the difference of potential in volts between any two points in the circuit, and r the resistance in ohms of the conductor connecting these two points. This is one of the most important laws in physics.

Both of the above statements of Ohm's law are included in the equation:

$$\text{Amperes} = \frac{\text{Volts}}{\text{Ohms}}. \qquad (3)$$

44. Internal Resistance of a Galvanic Cell. If the zinc and copper plates of a simple galvanic cell are connected to an ammeter, and the distance between the plates then increased, the deflection of the needle is found to decrease, or if the amount of immersion is decreased the current also will decrease. But since the E. M. F. of a cell was shown in § 41 to be wholly independent of the area of the plates immersed or of the distance between them, it will be seen from Ohm's law that the change in the current in these cases must be due to some change in the total resistance of the circuit. Since the wire which constitutes the outside portion of the circuit has remained the same, we must conclude that *the liquid within the cell, as well as the external wire, offers resistance to the passage of the current.* This internal resistance of the liquid is directly proportional to the distance between the plates, and inversely proportional to the area of the immersed portion of the plates. If, then, we represent the external resistance of the circuit of a galvanic cell by R_e and the internal by R_i, then Ohm's law as applied to the entire circuit takes the form:

$$C = \frac{E}{R_e + R_i}. \qquad (4)$$

Thus, if a simple cell has an internal resistance of 2 ohms and an E. M. F. of 1 volt, the current which will flow through the circuit when its terminals are connected by 9.3 ft. of No. 30 copper wire (1 ohm) is $\frac{1}{1 + 2} = .33$ ampere. This is about the current which is usually obtained from an ordinary Daniell cell (see § 49).

PRIMARY CELLS

45. The Action of a Simple Cell. If the simple cell already mentioned—namely, zinc and copper strips in dilute sulphuric acid—is carefully observed, it will be seen that, so long as the plates are not connected by a conductor, fine bubbles of gas are slowly formed at the zinc plate, but none at the copper plate. As soon, however, as the two strips are put into electrical connection, bubbles instantly appear in great numbers about the copper plate and at the same time a current manifests itself in the connecting wire (Fig. 45). The bubbles are of hydrogen. Their original appearance on the zinc plate may be prevented either by using a plate of chemically pure zinc, or by amalgamating impure zinc, that is, by coating it over with a thin film of mercury. But the bubbles on the copper cannot be thus disposed of. They are an invariable accompaniment of the current in the circuit. If the cur-

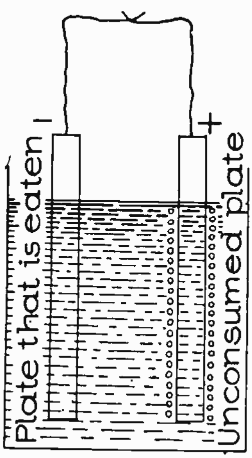


Fig. 45. Action of a Simple Cell.

rent is allowed to run for a considerable time, it will be found that the zinc wastes away, even though it has been amalgamated, but the copper plate does not undergo any change.

An electrical current in a simple cell is, then, accompanied by the eating up of the zinc plate by the liquid, and by the evolution of hydrogen bubbles at the copper plate. In every type of galvanic cell, actions similar to these two are always found. That is, *one of the plates is always eaten up, and on the other some element is deposited.* The plate which is eaten is always the one which is found to be negatively charged, while the other is always found to be positively charged; so that in all galvanic cells, when the terminals are connected through a wire, the positive electricity flows through this wire from the uneaten plate to the eaten plate. It will be remembered that the direction in which the *positive* electricity flows is taken for convenience as the direction of the current (see § § 19 and 28).

46. Theory of the Action of a Simple Cell. A simple cell may be made of any two dissimilar metals immersed in a solution of any acid or salt. For simplicity, let us examine the action of a cell composed of plates of zinc and copper immersed in a dilute solution of hydrochloric acid. The chemical formula for hydrochloric acid is HCl. This means that each molecule of the acid consists of one atom of hydrogen combined with one atom of chlorine. In accordance with the theory now in vogue among physicists and chemists, when hydrochloric acid is mixed with water so as to form a dilute solution, the HCl molecules split up into two electrically charged parts, called *ions*, the hydrogen ion carrying a positive charge and the chlorine ion an equal negative charge (Fig. 46). This phenomenon is known as *dissociation*. The solution as a whole is neutral; *i. e.*, it is uncharged, because it contains just as many positive as negative ions.

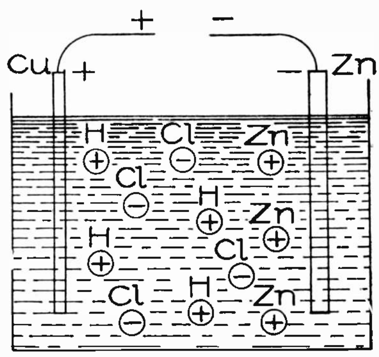


Fig. 46. Illustrating Dissociation of Ions and Theory of Action of a Simple Cell.

When a zinc plate is placed in such a solution, the acid attacks it and pulls zinc atoms into solution. Now, whenever a metal dissolves in an acid, its atoms, for some unknown reason, go into solution bearing little positive charges. *The corresponding negative charges must be left on the zinc plate* in precisely the same way in which a negative charge is left on silk when positive electrification is produced on a glass rod by rubbing it with the silk. It is in this way, then, that we attempt to account for the negative charge which we find upon the zinc plate in the experiment described in § 36.

The passage of positively charged zinc ions into solution gives a positive charge to the solution about the zinc plate, so that the hydrogen ions tend to be repelled toward the copper plate. When these repelled hydrogen ions reach the copper plate some of them give up their charges to it and then collect as bubbles of hydrogen gas. It is in this way that we account for the positive charge which we find on the copper plate in the experiment described in § 36.

If the zinc and copper plates are not connected by an outside conductor, this passage of positively charged zinc ions into solution continues but a very short time, for the zinc soon becomes so strongly charged negatively that it pulls back on the plus zinc ions with as much force as the acid is pulling them into solution. In precisely the same way the copper plate soon ceases to take up any more positive electricity from the hydrogen ions, since it soon acquires a large enough plus charge to repel them from itself with a force equal to that with which they are being driven out of solution by the positively charged zinc ions. It is in this way that we account for the fact that on open circuit no chemical action goes on in the simple galvanic cell, the zinc and copper plates simply becoming charged to a definite difference of potential which is called the E. M. F. of the cell.

When, however, the copper and zinc plates are connected by a wire, a current at once flows from the copper to the zinc, and the plates thus begin to lose their charges. This allows the acid to pull more zinc into solution at the zinc plate, and allows more hydrogen to go out of solution at the copper plate. These processes, therefore, go on continuously so long as the plates are connected. Hence a continuous current flows through the connecting wire until the zinc is all eaten up or the hydrogen ions have all been driven out of the solution, *i.e.*, until either the plate or the acid has become exhausted.

47. Polarization. If the simple cell which has been described is connected to an ammeter and the deflection observed for a few minutes, it is found to produce a current of continually decreasing strength; but if the hydrogen is removed from the copper plate by taking out the plate and drying it, the deflection returns to its first value. This phenomenon is called *polarization.*

The presence of the hydrogen on the positive plate causes a diminution in the strength of the current for two reasons: First, since hydrogen is a non-conductor, by collecting on the plate it diminishes the effective area of the plate and therefore increases the internal resistance of the cell; second, by collecting upon the copper plate it lowers the E. M. F. of the cell, because it virtually substitutes a hydrogen plate for the copper plate, and we have already seen (in § 41) that a change in any of the materials of which a cell is composed changes its E. M. F.

The different forms of galvanic cells in common use differ chiefly in different devices employed either for disposing of the hydrogen bubbles or for preventing their formation. The most common types of such cells are described in the following sections.

48. The Bichromate Cell. The bichromate cell (Fig. 47) consists of a plate of zinc immersed in sulphuric acid between two plates of carbon, carbon being used instead of copper because it gives a greater E. M. F. In the sulphuric acid is dissolved some bichromate of potassium or sodium, the function of which is to unite chemically with the hydrogen as fast as it is formed at the positive plate, thus preventing its accumulation upon this plate.* Such a cell has the high E. M. F. of 2.1 volts. Its internal resistance is low, from .2 to .5 ohm, since the plates are generally large and close together. It will be seen, therefore, that when the external resistance is very small it is capable of furnishing a current of from 5 to 10 amperes. Since, however, the chromic acid formed by the union of the sulphuric

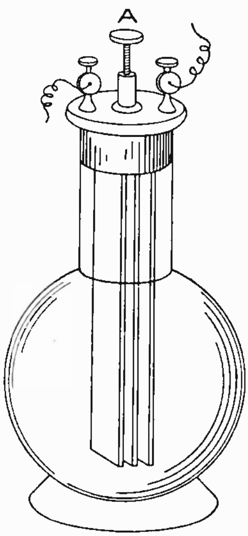


Fig. 47. Bichromate Cell.

*To set up a bichromate cell, dissolve 12 parts, by weight, of sodium bichromate in 180 parts of boiling water. After cooling, add 25 parts of commercial sulphuric acid.

acid with the bichromate attacks the zinc even when the circuit is open, it is necessary to lift the zinc from the liquid by the rod A, when the cell is not in use. Such cells are useful where large currents are needed for a short time. The great disadvantages are that the fluid deteriorates rapidly, and that the zinc cannot be left in the liquid.

49. The Daniell Cell. The Daniell cell consists of a zinc plate immersed in zinc sulphate, and a copper plate immersed in copper sulphate, the two liquids being kept apart either by means of a porous earthen cup, as in the type shown in Fig. 48, or else by gravity, as in the type shown in Fig. 49. This last type, commonly called the *gravity*, or *crowfoot* type, is used almost exclusively on telegraph lines. The copper sulphate, being the heavier of the two liquids, remains at the bottom about the copper plate, while the zinc sulphate remains at the top about the zinc plate.

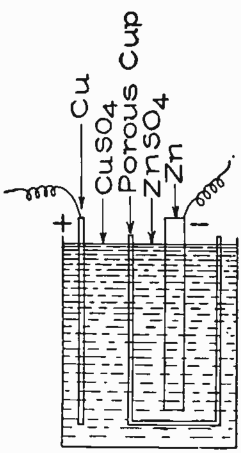


Fig. 48a. Typical Section of Daniell Cell.

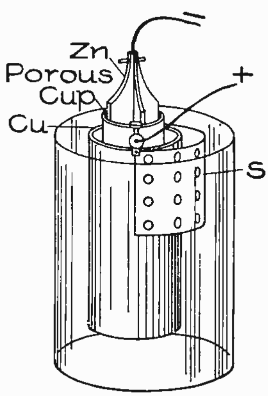


Fig. 48b. Daniell Cell (Commercial Type)

In this cell polarization is almost entirely avoided, for the reason that no opportunity is given for the formation of hydrogen bubbles. For, just as the hydrochloric acid solution described in § 46 consists of positive hydrogen ions and negative chlorine ions in water, so the zinc sulphate ($ZnSO_4$) solution consists of positive zinc ions and negative SO_4 ions. Now the zinc of the zinc plate goes into solution in the zinc sulphate in precisely the same way that it goes into solution in the hydrochloric acid of the simple cell described in § 46. This gives a positive charge to the solution about the zinc plate, and causes a movement of the positive ions between the two plates from the zinc towards the copper, and of negative ions in the opposite direction, both the Zn and the SO_4 ions being able to pass through the porous cup. Since the positive ions about the copper plate consist of atoms of copper, it will be seen that the material which is driven out of solution at the copper plate, instead of being hydrogen, as in the simple cell, is metallic copper. Since, then, the element which is deposited on the copper plate is the same as that of which it already consists, it is clear that neither the E. M. F. nor the resistance of the cell can be changed because of this deposit; *i.e.*, the cause of the polarization of the simple cell has been removed.

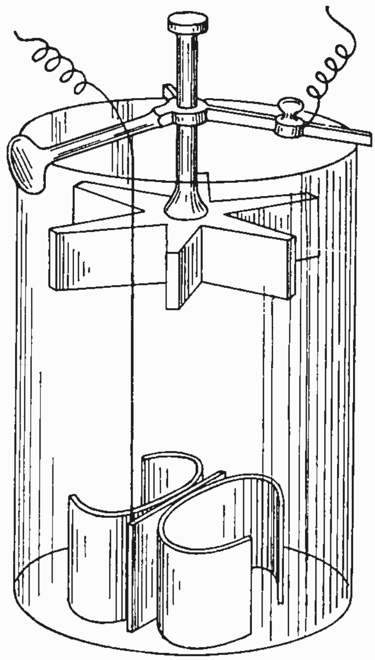


Fig. 49. Daniell Cell in which Zinc and Copper Plates are Kept Separate by Gravity.

The great advantage of the Daniell cell lies in the relatively high degree of constancy in its E. M. F. (1.08 volts). It has a comparatively high internal resistance (one to six ohms) and is therefore incapable of producing very large currents, about one ampere at most. It will furnish a very constant current, however, for a great length of time; in fact, until all of the copper is driven out of the copper sulphate solution. In order to keep a constant supply of the copper ions in the solution, copper sulphate crystals are kept in the compartment S of the cell of Fig. 48, or in the bottom of the gravity cell. These dissolve as fast as the solution loses its strength through the deposition of copper on the copper plate.

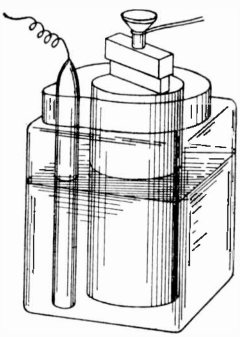


Fig. 50. Leclanché Cell.

The Daniell is a so-called *closed-circuit* cell, *i.e.*, its circuit should be left closed (through a resistance of thirty or forty ohms) whenever the cell is not in use. If it is left on open circuit, the copper sulphate diffuses through the porous cup, and a brownish muddy deposit of copper or copper oxide is formed upon the zinc. Pure copper is also deposited in the pores of the porous cup. Both of these actions damage the cell. When the circuit is closed, however, since the electrical forces always keep the copper ions moving toward the copper plate, these damaging effects are to a large extent avoided.

50. The Leclanché Cell. The Leclanché cell (Fig. 50) consists of a zinc rod in a solution of ammonium chloride (150 g. to a liter of water), and a carbon plate placed inside of a porous cup which is packed full of manganese dioxide and powdered graphite or carbon. As in the simple cell, the zinc dissolves in the liquid, and hydrogen is liberated at the carbon, or positive, plate. Here it is slowly attacked by the manganese dioxide. This chemical action is, however, not quick enough to prevent rapid polarization when large currents are taken from the cell. The cell slowly recovers when allowed to stand for a while on open circuit. The E. M. F. of a Leclanché cell is about 1.5 volts, and its initial internal resistance is somewhat less than an ohm. It therefore furnishes a momentary current of from one to three amperes.

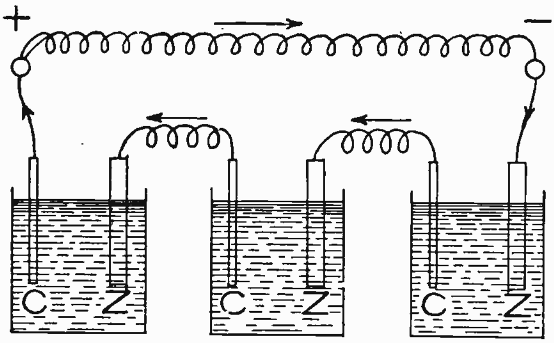


Fig. 51. Cells Connected in Series.

The immense advantage of this type of cell lies in the fact that the zinc is not at all eaten by the ammonium chloride when the circuit is open, and that, therefore, unlike the Daniell or bichromate cells, it can be left for an indefinite time on open circuit without deterioration. Leclanché cells are used almost exclusively where momentary currents only are needed, as, for example, on doorbell circuits. The cell requires no attention for years at a time, other than the occasional addition of water to replace loss by evaporation, and the occasional addition of ammonium chloride (NH_4Cl) to keep positive NH_4 and negative Cl ions in the solution.

51. The Dry Cell. The dry cell is only a modified form of the

Leclanché cell. It is not really *dry*, since the zinc and carbon plates are imbedded in moist paste which consists usually of one part of crystals of ammonium chloride, three parts of plaster of Paris, one part of zinc oxide, one part of zinc chloride, and two parts of water. The plaster of Paris is used to give the paste rigidity. As in the Leclanché cell, it is the action of the ammonium chloride upon the zinc which produces the current.

52. Combinations of Cells. There are two ways in which cells may be combined: First, in series; and second, in parallel. When they are connected in series the zinc of one cell is joined to the copper of the second, the zinc of the second to the copper of the third, etc., the copper of the first and the zinc of the last being joined to the ends of the external resistance (see Fig. 51). The E. M. F. of such a combination is the sum of the E. M. F.'s of the single cells. The internal resistance of the combination is also the sum of the internal resistances of the single cells. Hence, if the external resistances are very small, the current furnished by the combination will not be larger than that furnished by a single cell, since the total resistance of the circuit has been increased in the same ratio as the total E. M. F. But if the external resistance is large, the current produced by the combination will be very much greater than that produced by a single cell. Just how much greater can always be determined by applying Ohm's law, for if there are n cells in series, and E is the E. M. F. of each cell, the total E. M. F. of the circuit is $n\,E$. Hence if R_e is the external resistance and R_i the internal resistance of a single cell, then Ohm's law gives

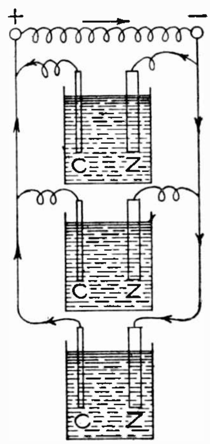


Fig. 52. Cells Connected in Parallel.

$$C = \frac{nE}{R_e + nR_i}.$$

If the n cells are connected in parallel, that is, if all the coppers are connected together and all the zincs, as in Fig. 52, the E. M. F. of the combination is only the E. M. F. of a single cell, while the internal resistance is $1/n$ of that of a single cell, since connecting the cells in this way is simply equivalent to multiplying the area of the plates n

times. The current furnished by such a combination will be given by the formula:

$$C = \frac{E}{R_e + \frac{R_i}{n}}.$$

If, therefore, R_e is negligibly small, as in the case of a heavy copper wire, the current flowing through it will be n times as great as that which could be made to flow through it by a single cell. These considerations show that the rules which should govern the combination of cells are as follows:

When the external resistance is large in comparison with the internal resistance of a single cell, the cells should be connected in series.

When the external resistance is small in comparison with the internal resistance of a single cell, the cells should be connected in parallel.

CHEMICAL EFFECTS OF THE ELECTRIC CURRENT

53. Electrolysis. If two platinum electrodes are dipped into a solution of dilute sulphuric acid, and the terminals of a battery producing an E. M. F. of 2 volts or more is applied to these *electrodes*, oxygen gas is found to be given off at the electrode at which the current enters the solution, called the *anode*, while hydrogen is given off at the electrode at which the current leaves the solution, called the *cathode*. The modern theory of this phenomenon is as follows: Sulphuric acid (H_2SO_4), when it dissolves in water, breaks up into positively charged hydrogen ions and negatively charged SO_4 ions. As soon as an electrical field is established in the solution by connecting the electrodes to the positive and negative terminals of a battery, the hydrogen ions begin to migrate toward the cathode, and there, after giving up their charges, unite to form molecules of hydrogen gas. On the other hand, the negative SO_4 ions migrate to the positive electrode (that is, the anode), where they give up their charges to it, and then act upon the water, H_2O, thus forming H_2SO_4 and liberating oxygen.

If the volumes of hydrogen and of oxygen are measured, the hydrogen is found to occupy in every case just twice the volume occupied by the oxygen. This is, indeed, one of the reasons for believing that water consists of two atoms of hydrogen and one of oxygen.

54. Electroplating. If the solution, instead of being sulphuric acid, had been one of copper sulphate, $CuSO_4$, the results would have been precisely the same in every respect, except that, since the hydrogen ions in the solution are now replaced by copper ions, the substance deposited on the cathode is pure copper instead of hydrogen. This is the principle involved in electroplating of all kinds. In commercial work, the positive plate, that is, the plate at which the current enters the bath, is always made from the same metal as that which is to be deposited from the solution; for in this case the SO_4 or other negative ions dissolve this plate as fast as the metal ions are deposited upon

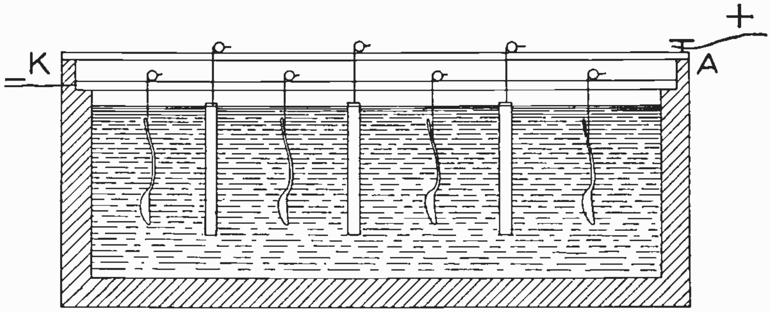


Fig. 53. Silver-Plating Bath.

the other. The strength of the solution, therefore, remains unchanged. In effect, the metal is simply taken from one plate and deposited on the other. Fig. 53 represents a silver-plating bath. The bars joined to the anode *A* are of pure silver. The spoons to be plated are connected to the cathode *K*. The solution consists of 500 g. of potassium cyanide and 250 g. of silver cyanide in 10 l. of water.

55. Chemical Method of Measuring Current. In 1834, Faraday found that a given current of electricity flowing for a given time always deposits the same amount of a given element from a solution, whatever be the nature of the solution which contains the element. For example, one ampere always deposits in an hour 4.025 g. of silver, whether the solution is of silver nitrate, silver cyanide, or any other silver compound. Similarly, an ampere will deposit in an hour 1.181 g. of copper, 1.203 g. of zinc, etc. This fact is made use of in calibrating fine ammeters, since it is possible to compute with great accuracy the strength of a current which will deposit a given weight of metal in a known time. In fact, the Electrical Congress held in Chicago in 1893 defined the ampere as *the amount of current which will deposit* .001188 *g. of silver per second.*

56. The Storage Battery. If two lead plates are immersed in sulphuric acid and the current sent through the cell, the anode or plate at which the current enters the solution will be found in the course of a few minutes to turn dark brown. This brown coat is a compound of lead with the oxygen which, in the case of the platinum electrodes, was evolved as a gas. The other lead plate is not affected by the hydrogen, which is, in this case, as in that

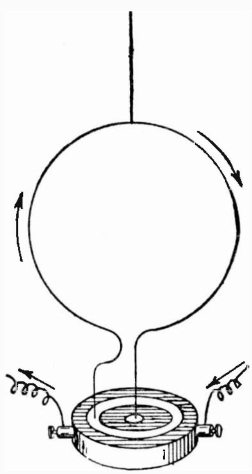


Fig. 54.

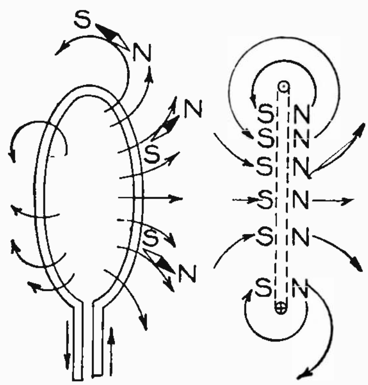


Fig. 55.

Illustrating the Magnetic Properties of a Loop.

of the platinum, evolved as a gas. Since, then, the passage of the current through this cell has left one plate unchanged, while it has changed the surface of the other plate to a new substance, namely, lead peroxide, PbO_2, it might be expected that if the charging battery were removed, and these two dissimilar plates connected with a wire, a current will flow through the wire, for the arrangement is now essentially a simple galvanic cell, which in its essentials consists simply of two dissimilar plates immersed in an electrolyte (a conducting liquid other than a molten metal). In this case the plate having the lead peroxide upon it corresponds to the copper of an ordinary cell, and the unchanged lead plate to the zinc. The arrangement will furnish a current until the lead peroxide is all used up. The only important

ELECTRICAL KITCHEN IN EDISON BUILDING, CHICAGO

difference between a commerical storage cell and the two lead plates just considered, is that the former is provided in the process of manufacture with a very much thicker coat of the *active material* (lead peroxide on the positive plate, and a porous, spongy lead on the negative) than can be formed by a single charging such as we considered. In one type of storage cell this active material is actually formed by the repeated charging and discharging of plates which are originally ordinary sheets of lead. With each new charging a slightly thicker layer of the lead peroxide is formed. In the more common type of commercial cell the active material is pressed into interstices of the plate in the form of a paste. It will be seen from this discussion that a storage battery is not, properly speaking, a device for storing electricity. It is rather a device in which the electrical current produces chemical changes, and these new chemicals, so long as they last, are capable of generating a new electrical current.

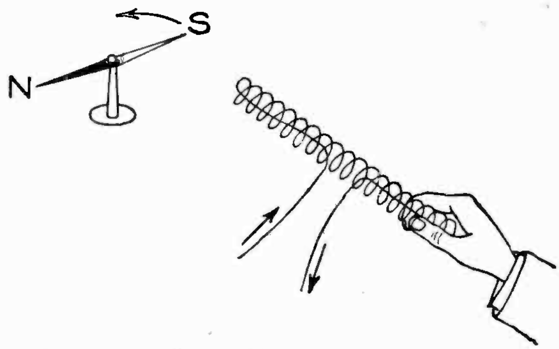


Fig. 56. Illustrating the Magnetic Properties of a Helix.

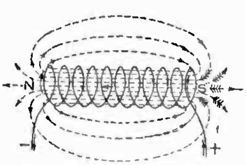


Fig. 57. Magnetic Field Surrounding a Helix.

ELECTROMAGNETISM

57. Magnetic Properties of a Loop. We have seen in § 38 that an electrical current is surrounded by a magnetic field the direction of which is given by the right-hand rule. We have seen also that a loop or coil of wire through which a current flows produces a magnetic field of the shape shown in Fig. 41. Now, if such a loop is suspended in the manner shown in Fig. 54 while a current is passed through it, it is found slowly to set itself in an east-and-west plane, and so that the face of the loop from which the magnetic lines emerge (see right-hand rule, § 38 and also Fig. 55) is toward the north. In other words, the loop will be found to behave with respect to the earth or to any other magnet precisely as though it were a flat magnetic disc whose boundary is the wire, the face which turns toward the north, that is, that from which the magnetic lines emerge, being an N pole and the other an S pole.

58. Magnetic Properties of a Helix. If a wire carrying a current be wound in the form of a helix and held near a suspended magnet as in Fig. 56, the coil will be found to act in every respect like a magnet, with an N pole at one end and an S pole at the other.

This result might have been predicted from the fact that a single loop is equivalent to a flat-disc magnet. For when a series of such discs is placed side by side, as in the helix, the result must be the same as placing a series of disc magnets in a row, the N pole of one

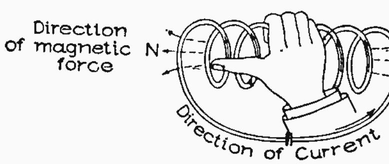


Fig. 58. Right-Hand Rule for Determining Direction of Magnetic Field of a Helix.

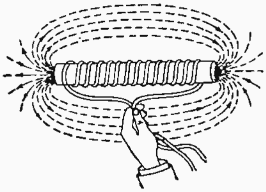


Fig. 59. A Simple Eletromagnet and Its Field.

being directly in contact with the S pole of the next, etc. These poles would therefore all neutralize each other except at the two ends. We therefore get a magnetic field of the shape shown in Fig. 57, the direction of the arrows representing as usual the direction in which an N pole tends to move.

59. Rules for North and South Poles of a Helix. The right-hand rule, as given in § 38, is sufficient in every case to determine which is the N and which the S pole of a helix, *i.e.*, from which end the lines of magnetic force emerge from the helix and at which end they enter it. But it is found convenient, in the consideration of coils, to restate the right-hand rule in a slightly different way, thus:

If the coil is grasped in the right hand in such a way that the fingers point in the direction in which the current is flowing in the wires, the thumb will point in the direction of the north pole of the helix (*see Fig.* 58).

Similarly, if the sign of the poles is known, but the direction of the current unknown, the latter may be determined as follows:

If the right hand is placed against the coil with the thumb pointing in the direction of the lines of force (i.e., toward the north pole of the

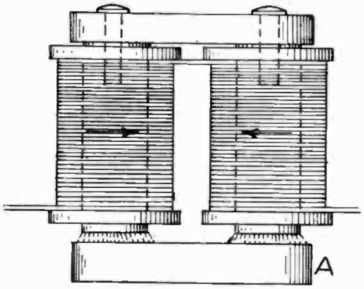


Fig. 60. Horseshoe Electromagnet, with Armature.

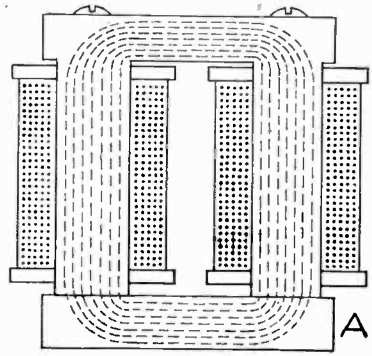


Fig. 61. Showing Lines of Force in Horseshoe Electromagnet.

helix), the fingers will pass around the coil in the direction in which the current is flowing.

60. The Electromagnet. If a core of soft iron be inserted in the helix (Fig. 59), the poles will be found to be enormously stronger than before. This is because the core is magnetized by induction from the field of the helix in precisely the same way in which it would be magnetized by induction if placed in the field of a permanent magnet. The new field strength about the coil is now the sum of the fields due to the core and that due to the coil.

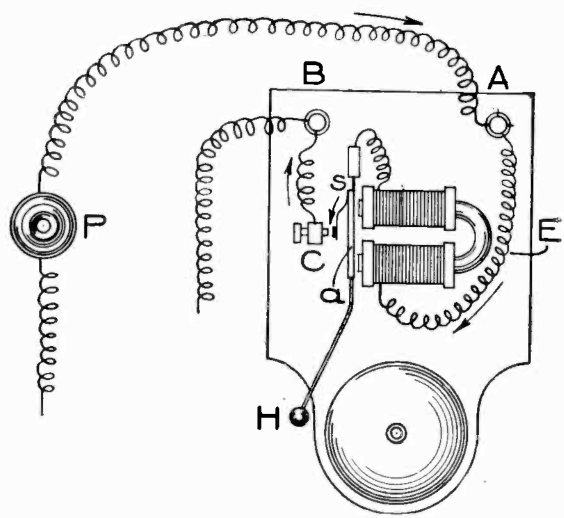


Fig. 62. Simple Electric Bell, and Connections.

If the current is broken, the core will at once lose the greater part of its magnetism. If the current is reversed, the polarity of the core will be reversed. Such a coil with a soft-iron core is called an *electromagnet*.

The strength of an electromagnet can be very greatly increased by giving it such form that the magnetic lines can remain in iron throughout their entire length instead of emerging into air, as they do in Fig. 59. For this reason electromagnets are usually built in the horseshoe form and provided with an armature *A* (Fig. 60)

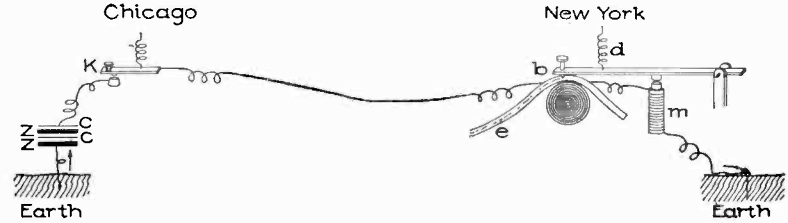


Fig. 63. Illustrating the Principle of the Electric Telegraph.

through which a complete iron path for the lines of force is established, as shown in Fig. 61. The strength of such a magnet depends chiefly upon the number of *ampere-turns* which encircle it, the expression *ampere-turns* denoting the product of the number of turns of wire about the magnet by the number of amperes flowing in each turn. Thus a current of $\frac{1}{100}$ ampere flowing 1,000 times around a core will make an electromagnet of precisely the same strength as a current of 1 ampere flowing 10 times about the core.

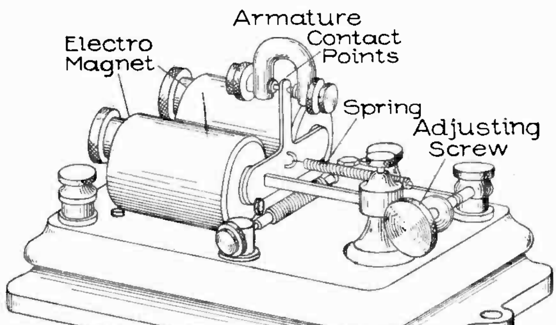


Fig. 64. Telegraphic Relay.

61. The Electric Bell. The electric bell (Fig. 62) is one of the simplest applications of the electromagnet. When the button *P* is pressed, the electric circuit of the battery is closed and a current flows in at *A*, through the magnet, over the closed contact *C*, and out again at *B*. But no sooner is this current established than the electromagnet *E* pulls over the armature *a*, and in so doing breaks the contact at C. This stops the current and demagnetizes the magnet *E*. The armature is then thrown back against *C* by the elasticity of the spring *s* which supports it. No sooner is the contact made at *C* than the current again begins to flow and the former operation is repeated. Thus the circuit is automatically made and broken at *C* and the hammer *H* is in consequence set into rapid vibration against the rim of the bell.

62. The Telegraph. The electric telegraph is another simple application of the electromagnet. The principle is illustrated in Fig. 63. As soon as the key *K* at Chicago, for example, is closed, the current flows over the line to, we will say, New York. There it passes through the electromagnet *m*, and thence back to Chicago through the earth. The armature *b* is held down by the electromagnet *m* as long as the key *K* is kept closed. As soon as the circuit is broken at *K*, the armature is pulled up by the spring *d*. By means of a clockwork device the tape *e* is drawn along at a uniform rate beneath the pencil or pen carried by the armature *b*. A very short time of closing of *K* produces a dot upon the tape, a longer time a dash. As the Morse, or telegraphic, alphabet consists of certain combinations of dots and dashes, any desired message may be sent from Chicago and recorded in New York.

AMERICAN MORSE CODE

A	. —	J	— . — .	S	. . .	2	. . — . .
B	— . . .	K	— . —	T	—	3	. . . — .
C	. . .	L	——	U	. . —	4	. . . . —
D	— . .	M	— —	V	. . . —	5	— — —
E	.	N	— .	W	. — —	6	. . . . . .
F	. — .	O	. .	X	. — . .	7	— — . .
G	— — .	P	. . . . .	Y	. . . .	8	— . . . .
H	. . . .	Q	. . — .	Z	. . . .	9	— . . —
I	. .	R	. . .	1	. — — .	0	——

In modern practice the message is not ordinarily recorded on a tape, for operators have learned to read messages by ear, a very short interval between two clicks being interpreted as a dot, a longer interval as a dash.

The first commercial telegraph line was built by S. F. B. Morse between Baltimore and Washington. It was opened on May 24, 1844, with the now famous message: "What hath God wrought?"

63. The Relay and Sounder. On account of the great resistance of long lines, the current which passes through the electromagnet is so weak that the armature of this magnet must be made very light in order to respond to the action of the current. The clicks of such an armature are not sufficiently loud to be read easily by an operator. Hence at each station there is introduced a local circuit which contains a local battery, and a second and heavier electromagnet which is called a *sounder*. The electromagnet on the main line is then called the *relay* (see Figs. 64, 65, and 66). The sounder has a very heavy armature (*A*, Fig. 65), which is so arranged that it clicks both when it is drawn down by its electromagnet against the stop *S* and when it is pushed up again by its spring, on breaking the current, against the stop *t*. The interval which elapses between those two clicks indicates to the operator whether a dot or dash is sent. The

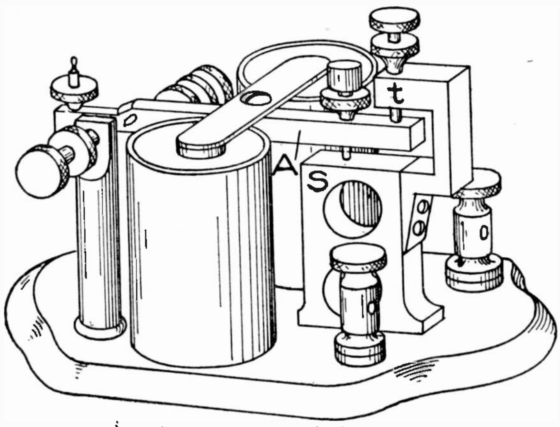


Fig. 65. Telegraphic Sounder.

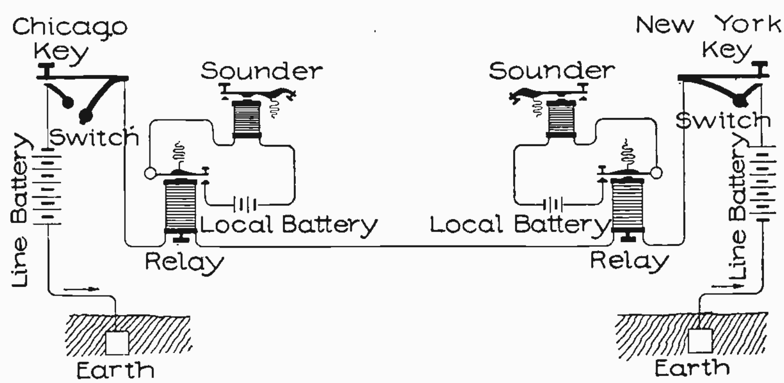


Fig. 66. Diagram of Arrangement of Parts in a Telegraphic System between Chicago and New York.

current in the main line simply serves to close and open the circuit in the local battery which operates the sounder (see Fig. 66). The electromagnets of the relay and the sounder differ in that the former consists of many thousand turns of fine wire, usually having a resistance of about 150 ohms, while the latter consists of a few hundred turns of coarse wire having ordinarily a resistance of about 4 ohms.

64. Plan of a Telegraph System. The actual arrangement of the various parts of a telegraphic system is shown in Fig. 66. When an operator at Chicago wishes to send a message to New York, he first opens the switch which is connected to his key, and which is always kept closed except when he is sending a message. He then begins to operate his key, thus controlling the clicks of both his own sounder and that at New York. When the Chicago switch is closed and the one at New York open, the New York operator is able to send a message back over the same line. In practice a message is not usually sent as far as from Chicago to New York over a single line, save in the case of trans-oceanic cables. Instead, it is automatically transferred at, say, Cleveland, to a second line which carries it on to Buffalo, where it is again transferred to a third line which carries it on to New York. The transfer is made in precisely the same way as the transfer from the main circuit to the sounder circuit. If, for example, the sounder circuit at Cleveland is lengthened so as to extend to Buffalo, and if the sounder itself is replaced by a relay (called in this case a *repeater*), and the local battery by a main battery, then the sounder circuit has been transformed into a repeater circuit, and all the conditions are met for an automatic transfer of the message at Cleveland to the Cleveland-Buffalo line. There is, of course, no time lost in this automatic transfer.

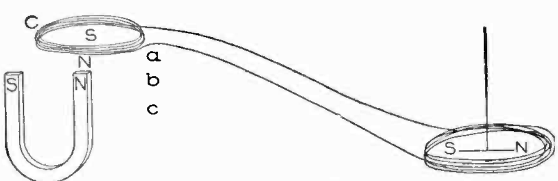


Fig. 67. Illustrating the Principle of Electromagnetic Induction.

INDUCED CURRENTS

65. Induction of Currents by Magnets. If a coil of wire C is connected to any sensitive current detector, as in Fig. 67, and then thrust over the pole of a magnet from the position a to the position c, a momentary current is observed to flow through the circuit. If the coil is held stationary over the magnet, the needle will come to rest in its natural position. If the coil is removed suddenly from the pole, the needle will move in the direction opposite to that of its first deflection, which shows that a reverse current is now being generated in the coil.

These experiments show that *a current of electricity may be induced in a conductor by causing the latter to move through a magnetic field.* This discovery, one of the most important in the history of science, was announced by Faraday in 1831. From it have sprung directly most of the modern industrial developments of electricity.

When we test the direction in which the current is induced in the coil C (Fig. 67) by applying the right-hand rule to the direction of deflection of the needle, we find that while the coil C was moving from a down to c the induced current flowing through it was in such a direction as to make its lower face an N pole and its upper face an S pole. Now if we split up this motion into two parts, namely, that from a to b and that from b to c, we see that while the coil is being moved from a to b the repulsion of the N pole of the magnet for the N pole of the coil is greater than the attraction of the N pole of the magnet for the S pole of the coil, so that the motion must be made *against an opposing force.* Similarly, while the coil is going from b to c, the S pole of the coil is nearer the N pole of the magnet than is the N pole of the coil, and consequently the attraction of the N pole of the magnet for this S pole of the coil is greater than the repulsion of the two N poles. Hence the motion from B to C also must be made against an opposing force. When the coil was moving from c to a, the current was in the reverse direction, hence the poles of the coil were reversed, so that *at every point the motion had to be made against an opposing force.*

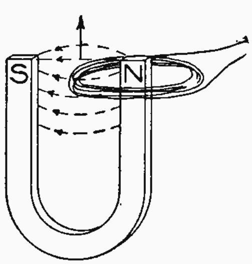


Fig. 68. Showing that a Conductor must Cut Lines of Magnetic Force in order to Induce an E. M. F.

From these experiments and others of a similar kind, it has been discovered that *whenever a current is induced in a conductor by the relative motion of the conductor and the magnetic field, the direction of the induced current is always such as to set up a magnetic field which opposes the motion.* This is known as *Lenz's law.* It is a law which might have been predicted beforehand from the principle of the conservation of energy, for, since an electrical current possesses energy, the principle of conservation of energy tells us that no such current can possibly be created without the expenditure of work of some sort. In this case there is no place for the energy to come from except from the mechanical work done in pushing the coil against some resisting force.

If, instead of moving the coil up and down over the pole, we had held it in the position shown in Fig. 68, and moved it back and forth so that its motion was *parallel* to the line *N S*, no induced current would have been observed. By experiments of this sort it is found that an *E. M. F. is induced in a coil only when the motion takes place in such a way as to change the total number of magnetic lines of force which are enclosed in the coil.* Or, to state this rule in a more general form: *An E. M. F. is induced in any element of a conductor when and only when that element is moving in such a way as to cut magnetic lines of force.*

It will be noticed that the first statement of the rule is included in the second, for whenever the number of lines of force which pass through a coil changes, some lines of force must cut across the coil from the inside to the outside, or *vice versâ.*

In the preceding statement we have used the expression *induced E. M. F.* instead of *induced current* for the reason that whether or not a continuous current flows in a conductor in which an E. M. F. (*i. e.*, a pressure tending to produce a current) exists, depends simply on whether or not the conductor is a portion of a closed electrical circuit. In our experiment the portion of the wire in which the E. M. F. was being generated by its passage across the lines of force running from *N* to *S* was a part of such a closed circuit, and hence a current resulted. If we had moved a straight conductor like that shown in Fig. 69, the E. M. F. would have been induced precisely as before; but since the circuit would then have been open, the only effect of this E. M. F. would have been to establish a P. D. between the ends of the wire, *i. e.*, to cause a positive charge to appear at one of its ends and a negative charge at the other, in precisely the same way that the E. M. F. of a battery causes positive and negative charges to appear on the terminals of the battery when it is on open circuit.

66. Strength of the Induced E. M. F. The strength of an induced E. M. F. is found to depend simply upon *the number of lines of force cut per second by the conductor*, or, in the case of a coil, upon the *rate of change* in the number of lines of force which pass through the coil. The strength of the current which flows is then given by Ohm's law; *i. e.*, it is equal to the induced E. M. F. divided by the resistance of the circuit. The number of lines of force which the conductor cuts per second may always be determined if we know the velocity of the conductor and the strength of the magnetic field through which it moves.*

In a conductor which is cutting lines at the rate of 100,000,000 lines per second, there is an induced electromotive force of exactly one volt.

67. The Dynamo Rule. Since the experiment illustrated in Fig. 67 shows that reversing the direction in which a conductor is

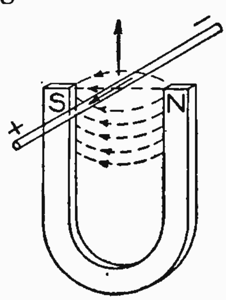


Fig. 69. Showing Relation between Directions of Motion of Conductor, Magnetic Lines, and Induced Current.

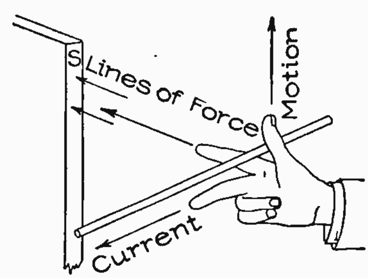


Fig. 70. Illustrating the "Dynamo Rule."

cutting lines of force also reverses the direction of the induced electromotive force, it is clear that a fixed relation must exist between these two directions and the direction of the magnetic lines. What this relation is may be obtained easily from Lenz's law. When the conductor was moving upward (Fig. 68), the current flowed in such a direction as to oppose the motion, that is, so as to make the lower face of the coil an *S* pole. This means that in the portion of the conductor between *N* and *S* where the E. M. F. was being generated,

*A magnetic pole of unit strength is by definition a pole which when placed at a distance of one centimeter from an exactly similar pole repels it with a force of one dyne (about one thousandth of a gram, or $\frac{1}{28000}$ of an ounce). A magnetic field of unit strength is, by definition, a field in which a unit-pole is acted upon by a force of one dyne. Hence, if a unit-pole is found in a given field to be acted upon by a force of one thousand dynes, we say that the field strength is one thousand units. Now, it is customary to represent a magnetic field by drawing as many lines per square centimeter taken at right angles to the direction of the field as the field has units of strength. Thus, a field of unit strength is said to contain one line per square centimeter, a field of a thousand units strength a thousand lines per square centimeter, etc. The magnetic fields used in powerful dynamos will have sometimes as high as 20,000 lines per square centimeter.

its direction was from back to front, that is, toward the reader (see arrow, Fig. 69). We therefore set up the following rule, which is found to apply in every case:

If the forefinger of the right hand points in the direction of the magnetic lines (see Fig. 70), and the thumb in the direction in which the conductor is cutting these lines, then the middle finger, held at right angles to both thumb and forefinger, will point in the direction of the induced current.

This rule is known as the *dynamo rule.*

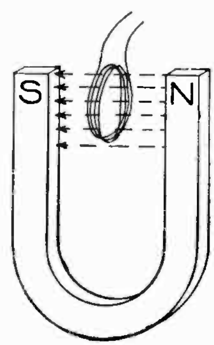


Fig. 71. Illustrating the Principle of the Dynamo.

68. The Principle of the Dynamo. A dynamo is essentially nothing but a coil of wire rotating continuously between the poles of a magnet. Thus, suppose that starting with the coil in the position shown in Fig. 71, it be rotated through 180 degrees from left to right as one looks down upon it. During the first half of the revolution the wires on the right side of the loop are cutting the lines of force while moving toward the reader, while the lines on the left side are cutting the same lines while moving away from the reader. Hence, by applying the dynamo rule, we find that a current is being generated which flows down on the right side of the coil and up on the left side. It will be seen that both currents flow around the coil in the same direction. The induced current is strongest when the coil is in the position shown in Fig. 72, because there the lines of force are being cut most rapidly. Just as the coil is being moved into or out of the position shown in Fig. 71, it is moving *parallel* to the lines of force and hence no current is induced, since no lines of force are being cut. As the coil is now moved through the last 180 degrees of a complete revolution, both sides are cutting the same lines of force as before, but they are cutting them while moving in an opposite direction from that in which they were first moving, hence the current generated during this last half is opposite in direction to that of the first half. If the coil is continuously rotated in the field, therefore, an alternating current is set up in

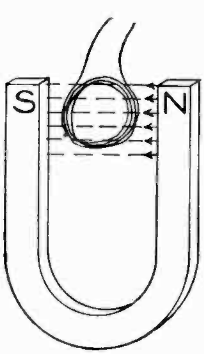


Fig. 72. Position of Revolving Coil when Current is Strongest.

it, which reverses direction every time the coil passes through the position shown in Fig. 71. This is the essential principle of the alternating-current dynamo. The direct-current dynamo differs from the alternating-current dynamo, only in that a so-called *commutator* is used for the purpose of changing the direction of the current in the external circuit every time the coil passes through the position shown in Fig. 71, so that the current always flows in the same direction through this external portion of the circuit in spite of the fact that in the rotating coil it changes direction every half-revolution.

69. The Principle of the Electric Motor. If a vertical wire *a b* is made to pass between the poles of a magnet in the manner shown in Fig. 73, and the current from an outside source—for example, a Leclanché cell—sent through it from *a* to *b*, the wire *a b* will be found to move through the mercury, into which its lower end dips, in the direction indicated by the arrow *f*, namely, at right angles to the direction of the lines of magnetic force. If the direction of the current in *a b* is reversed the direction of the motion of the wire will be found to be reversed also. This experiment shows that *a wire carrying a current in a magnetic field tends to move in a direction at right angles both to the direction of the field and to the direction of the current.* The experiment illustrates the essential principle of the electric motor. The relation between the direction of the magnetic lines, the direction of the current, and the direction of the force, is often remembered by means of the following rule, known as the *motor rule.* It differs from the dynamo rule, only in that it is applied to the fingers of the *left hand* instead of to those of the right.

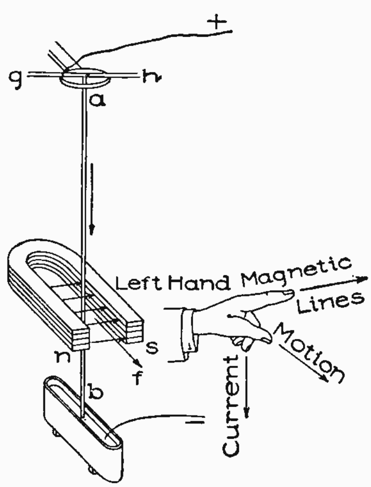


Fig. 73. Illustrating the Principle of the Electric Motor.

Let the forefinger of the left hand point in the direction of the magnetic lines of force and the middle finger in the direction of the current sent through the wire; the thumb will then point in the direction of the mechanical force acting to move the wire (see Fig. 73).

In practice the motor does not differ in construction at all from the dynamo. Thus, if a current is sent into the right side of the coil shown in Fig. 72, and out of the left side, the wires on the left side of the coil will be seen, by an application of the motor rule, to be urged toward the reader, while the wires on the right side are urged away from the reader. Hence the coil begins to rotate. After it has rotated through the position shown in Fig. 71, if the direction in which the current flows through it were not changed, it would be urged to rotate back to the position of Fig. 71; but in the actual motor, at the instant at which the coil passes through the position shown in Fig. 71, the commutator reverses the direction of the current as it enters the coil. Hence the coil is always impelled to rotate in the same direction.

70. The Principle of the Induction Coil and Transformer. If a coil of wire *p* is wound about an iron core, as in Fig. 74, and connected to the circuit of a battery, and if another coil of wire is wrapped about the same core, and its terminals connected to any current detector as shown in the figure, it is found that when the key *K* is closed, the deflection of the detector indicates that a temporary current has been induced in one direction through the coil *s*, but when it is opened an equal but opposite deflection will indicate an equal induced current in the opposite direction.

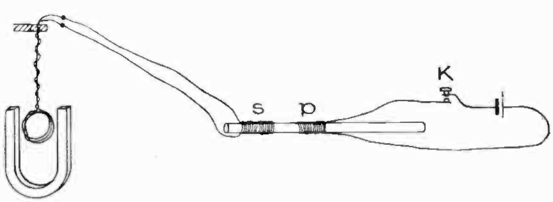


Fig. 74. Illustrating the Principle of the Induction Coil and Transformer.

The experiment illustrates the principle of the induction coil and the transformer. The coil *p*, which is connected to the source of the current, is called the *primary* coil, and the coil *s*, in which the currents are induced, is called the *secondary* coil. Causing lines of force to spring into existence inside of *s*—in other words, magnetizing the space inside of *s* (that is, the core about which the coils are wound) —has caused an induced current to flow in *s*; and demagnetizing the space inside of *s* has also induced a current in *s* in accordance with the general principle stated in § 65 that any change in the number of magnetic lines of force which thread through a coil induces a current in the coil. We may think of the lines which suddenly appear within the iron core upon magnetization as springing from without across the loops into the core, and as springing back again upon demagnetization, thus cutting the loops while moving in opposite directions in the two cases.

71. Direction of the Induced Current. Lenz's law, which, it will be remembered, followed from the principle of conservation of energy, enables us to predict at once the direction of the induced currents in the above experiments; and an observation of the deflections of the galvanometer enables us to verify the correctness of the predictions. Consider first the case in which the primary circuit is made and the core thus magnetized. According to Lenz's law, the current induced in the secondary circuit must be in such a direction as to *oppose* the change which is being produced by the primary current, *i. e.* in such a direction as *to tend to magnetize the core oppositely to the direction in which it is being magnetized by the primary.* This means, of course, that the induced current in the secondary must encircle the core in a direction opposite to the direction in which the primary current encircles it. We learn, therefore, that *on making the current in the primary, the current induced in the secondary is opposite in direction to that in the primary.*

When the current in the primary is *broken,* the magnetic field created by the primary tends to die out. Hence, by Lenz's law, the current induced in the secondary must be in such a direction as to tend to oppose this process of demagnetization, *i.e.*, in such a direction as to magnetize the core in the same direction in which it is magnetized by the decaying current in the primary. Therefore, *at break, the current induced in the secondary is in the same direction as that which is dying out in the primary.*

72. E. M. F. of the Secondary. If half of the turns of the secondary s (Fig. 74) are unwrapped, the deflection when K is opened or closed, will be found to be just half as great as before. Since the resistance of the circuit has not been changed, we learn from this that the *E. M. F. of the secondary is proportional to the number of turns of wire upon it.* This result followed also from the statement made in § 66 that the electromotive force induced in any circuit is equal to the rate of cutting of lines of force by that circuit. For all of the lines which pass through the core cut all of the coils on s. If, therefore, there are twice as many coils in one case as in another, twice as many lines of force cut the circuit, and hence the E. M. F. is twice as great. If, then, we wish to develop a very high E. M. F. in the secondary, we have only to make it of a very large number of turns of fine wire. The wire must not, however, be wrapped so far away from the core as to include the lines of force which are returning through the air (see Fig. 59), for, when this happens, the coils are threaded in both directions by the same lines, and hence have no current induced in them.

73. E. M. F. at Make and Break. If the secondary coil *s* is replaced by a spool or paper cylinder upon which are wound 5,000 or 10,000 turns of No. 36 copper wire, and if the ends of the coil are attached to metal handles and held in the moistened hands, then, when the key *K* is closed, no shock whatever will be felt; but a very marked one will be observable when the key is opened. The experiment can easily be tried with an inexpensive medical coil. It shows that the E. M. F. developed at the *break* of the circuit is enormously greater than that at the *make*. The explanation is found in the fact that the E. M. F. developed in a coil depends upon the *rate* at which the number of lines of force passing through it is made to change (see § 66). When the circuit of the primary was *made*, the current required an appreciable time, perhaps a tenth of a second, to rise to its full value, just as a current of water, started through a hose, requires an appreciable time to rise to its full height, on account of the inertia of the water. An electrical current possesses a property similar to inertia. Hence the magnetic field about the primary also rises equally gradually to its full strength, and therefore its lines pass into the coil comparatively slowly. At break, however, by separating the contact point very quickly, we can make the current in the primary fall to zero in an exceedingly short time, perhaps not more than .00001 of a second; *i.e.*, we can make all of its lines pass out of the coil in this time. Hence the rate at which lines thread through, or cut, the secondary is perhaps 10,000 times as great at break as at make, and therefore the E. M. F. is also something like 10,000 times as great. It should be remembered, however, that in a closed secondary the make current lasts as much longer than the break current as its E. M. F. is smaller; hence the total energy of the two is the same, as was indeed indicated by the equal deflections in § 65.

INDUCTION COIL AND TRANSFORMER

74. The Induction Coil. The induction coil, as usually made (Fig. 75), consists of a soft iron core *C*, which is composed of a bundle of soft iron wires; a primary coil *p* wrapped around this core, and consisting of, say, 200 turns of coarse copper wire (*e. g.*, No. 16), which is connected into the circuit of a battery through the contact point at the end of the screw *d*; a secondary coil *s* surrounding the primary in the manner indicated in the diagram, and consisting generally of between 30,000 and 1,000,000 turns of No. 36 copper wire the terminals of which are the points *t* and *t'*; and a hammer *b*, or

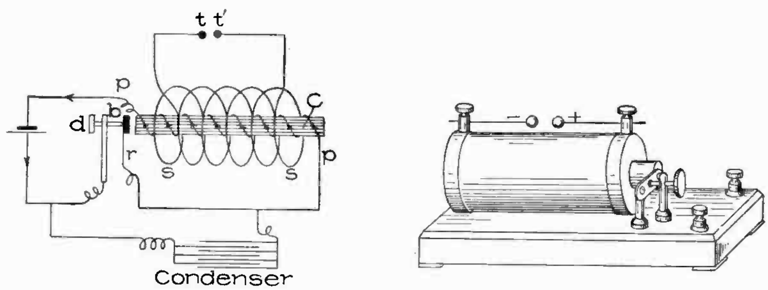
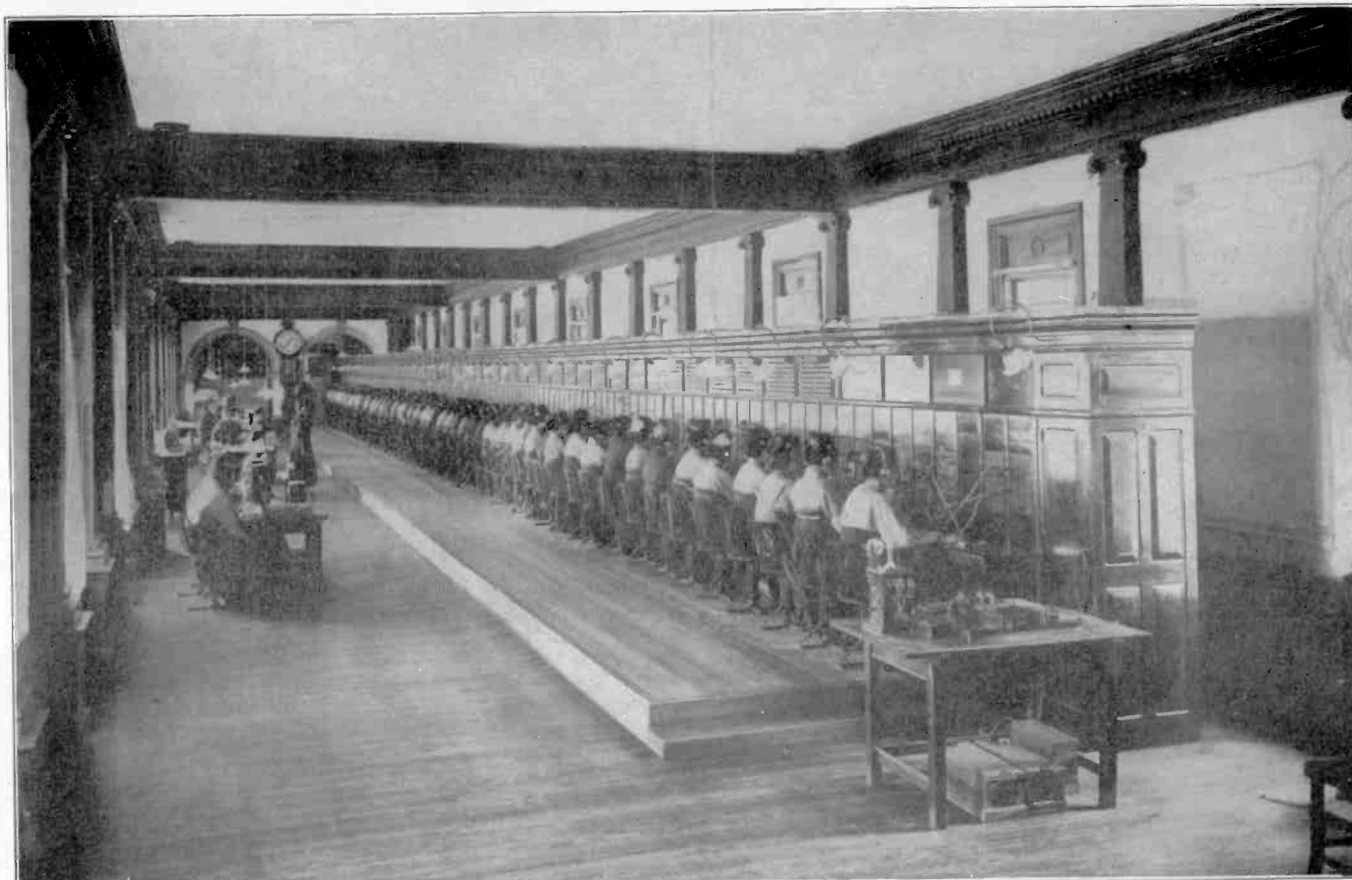


Fig. 75. Induction Coil, and Diagrammatic Representation of Same.

other automatic arrangement for making and breaking the circuit of the primary.

When the current is first started in the primary, it magnetizes the core *C*. Thereupon the iron hammer *b* is drawn away from its contact with *d* and the current is thus suddenly stopped. This instantly demagnetizes the core and induces in the secondary *s* an E. M. F. which is usually sufficient to cause a spark to leap between *t* and *t'*. As soon as the core is demagnetized, the spring *r* which supports the hammer restores the contact with *d* and the operation is repeated. The condenser, shown in the diagram with its two sets of plates connected to the conductors on either side of the spark gap between *r* and *d*, is not an essential part of a coil; but when it is introduced, it is found that the length of the spark which can be sent across between *t* and *t'* is considerably increased. The reason is as follows: When the circuit is broken at *b*, the inertia of the current tends to make a spark jump across from *d* to *b*; and if this happens, the current continues to flow through this spark (or arc) until the terminals have become separated through a considerable distance.



OPERATING ROOM AT TOKYO, JAPAN

This makes the current die down gradually instead of suddenly, as it ought to do to produce a high E. M. F. But when a condenser is inserted, as soon as *b* begins to leave *d*, the current begins to flow into the condenser, and this gives the hammer time to get so far away from *d* that an arc cannot be formed. This means a sudden break and a high E. M. F. Since a spark passes between *t* and *t′* only at break, § 73, it must always pass in the same direction. Coils which give 24-inch sparks (perhaps 500,000 volts) are not uncommon. Such coils usually have hundreds of miles of wire upon their secondaries.

75. The Transformer. The commercial transformer is a modified form of the induction coil. The chief difference is that the core *R* (Fig 76), instead of being straight, is bent into the form of a ring or is given some other shape such that the magnetic lines of force have a continuous iron path, instead of being obliged to push out into the air, as in the induction coil. Furthermore, it is always an alternating instead of an intermittent current which is sent through the primary *A*. Sending such a current through *A* is equivalent to magnetizing the core first in one direction, then demagnetizing it, then magnetizing it in the opposite direction, etc. The result of these changes in the magnetism of the core is of course an induced alternating current in the secondary *B*.

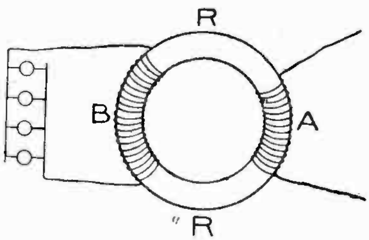


Fig. 76. Diagrammatic Representation of Commercial Transformer.

76. Pressure in Primary and Secondary. If there are a few turns in the primary and a large number in the secondary, the transformer is called a *step-up* transformer, because the P. D. produced at the terminals of the secondary is greater than that applied at the terminals of the primary. Thus, an induction coil is a step-up transformer. In electric lighting, however, transformers are mostly of the *step-down* type; *i. e.*, a high P. D., say 2,200 volts, is applied at the terminal of the primary, and a lower P. D., say 110 volts, is obtained at the terminals of the secondary. In such a transformer the primary will have twenty times as many turns as the secondary. In general, *the ratio between the voltages at the terminals of the primary and secondary is the ratio of the number of turns of wire upon the two.*

77. The Simple Telephone. The telephone was invented in 1876 by Elisha Gray, of Chicago, and Alexander Graham Bell, of Washington. In its simplest form it consists, at each end, of a permanent bar magnet *A* (Fig. 77) surrounded by a coil of fine wire *B*, in series with the line, and an iron disc or diaphragm *E* mounted close to one end of the magnet. When a sound is made in front of the diaphragm, the vibrations produced by the sounding body are transmitted by the air to the diaphragm, thus causing the latter to vibrate back and forth in front of the magnet. These vibrations of the diaphragm produce slight backward and forward movements of the lines of force which are continually passing into the disc or diaphragm from the magnet. Some of these lines of force, therefore, cut across the coil *B*, first in one direction and then in the other, and in so doing induce currents in it. These induced currents are transmitted by the line to the receiving station, where those in one direction pass around *B′* in such a way as to *increase* the strength of the magnet *A′*, and thus increase the pull which it exerts upon *E′*; while the opposite currents pass around *B′* in the opposite direction, and therefore *weaken* the magnet *A′* and diminish its pull upon *E′*. When, therefore, *E* moves in one direction, *E′* also moves in one direction; and when *E* reverses its motion, the direction of motion of *E′* is also reversed. In other words, the induced currents transmitted by the line force *E′* to reproduce the motions of *E*. *E′*, therefore, sends out sound waves exactly like those which fell upon *E*. In exactly the same way, a sound made in front of *E′* is reproduced at *E*. Telephones of this simple type will work satisfactorily for a distance of several miles. This simple form of instrument is still used at the receiving end of the modern telephone, the only innovation which has been introduced consisting in the substitution of a U-shaped magnet for the bar magnet. The instrument used at the transmitting end has, however, been changed, as explained in the next paragraph, and the circuit is now completed through a return wire instead of through the earth. A modern telephone receiver is shown in Fig. 78. *G* is the mouthpiece, *E* the diaphragm, *A* the U-shaped

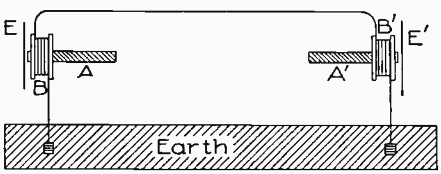


Fig. 77. Simplest Form of Electric Telephone.

magnet, B the coils, consisting of many turns of fine wire, and D the terminals of the line.

78. The Modern Transmitter. To increase the distance at which telephoning may be done, it is necessary to increase the strength of the induced currents. This is done in the modern transmitter by replacing the magnet and coil by an arrangement which is essentially an induction coil, the current in the primary of which is caused to vary by the motion of the diaphragm. This is accomplished as follows: The current from the battery (B, Fig. 79) is led first to the back of the diaphragm E, whence it passes through a little chamber C filled with granular carbon to the conducting back d of the transmitter, and thence through the primary p of the induction coil, and back to the battery. As the diaphragm vibrates it varies the pressure upon the many contact points of the granular carbon through which the primary current flows. This produces considerable variation in the resistance of the primary circuit, so that as the diaphragm moves forward, *i.e.*, toward the carbon, a comparatively large current

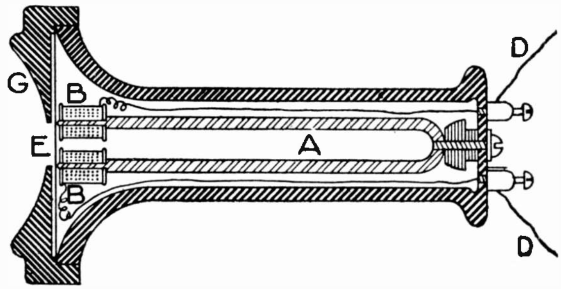


Fig. 78. Sectional View of Modern Telephone Receiver.

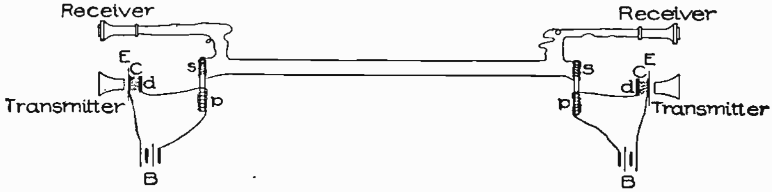


Fig. 79. Connections of Modern Transmitter.

flows through p, and as it moves back, a much smaller current. These changes in the current strength in the primary p produce changes in the magnetism of the soft-iron core of the induction coil. Currents are therefore induced in the secondary s of the induction coil, and these currents pass over the line and affect the receiver at the other end in the manner explained in the preceding paragraph. Fig. 80 shows a section of a complete long-distance transmitter.

79. The Subscriber's Telephone Connections. In the most recent practice of the Bell Telephone Company, the local battery at the subscriber's end is done away with altogether, and the primary current is furnished by a battery at the central station. Fig. 81 shows the essential elements of such a system. A battery *B*, usually of 25 volts pressure, is always kept connected at *central* to all the lines which enter the exchange. No current flows through these lines, however, so long as the subscriber's receivers *R* are upon their hooks *H*; for the line circuit is then open at the contact points *t*. It would be closed through the bell *b* were it not for the introduction of the condenser *C* in series with the bell. This makes it impossible for any *direct* current to pass from one side of the line to the other, so long as the receiver is upon the hook. But if the operator at central wishes to call up the subscriber, she has only to throw upon the line an *alternating* current from the magneto *M*, or from any alternating-current generator whose terminals she can connect to the subscriber's line by turning a switch. This alternating current surges back and forth through the bell into the

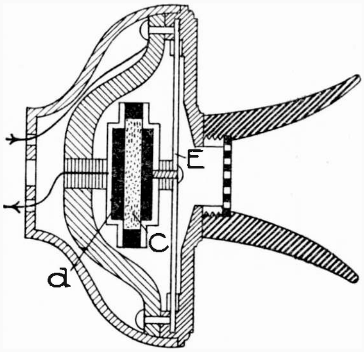


Fig. 80. Sectional View of Modern Transmitter.

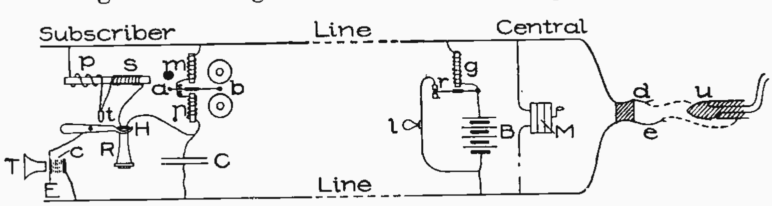
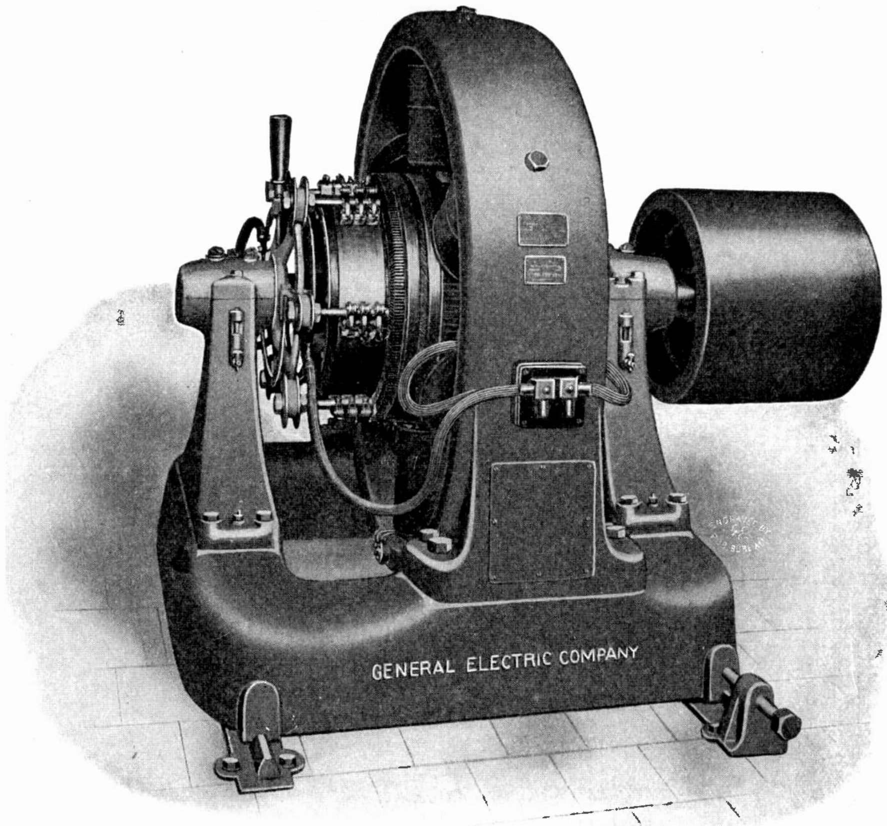


Fig. 81 Essential Elements of Subscriber's Telephone Connections.

condenser and out again, first charging the condenser plates in one direction, then in the other. By making the capacity of this condenser sufficiently large, this alternating current is made strong enough to pull the armature *a* first toward the electromagnet *m*, then toward *n*. In this way it rings the bell.

On the other hand, if the subscriber wishes to call up central, he has only to lift the receiver from the hook. This closes the line circuit at t, and the direct current which at once begins to flow from the battery B through the electromagnet g closes the circuit of B through the glow lamp l and the contact point r. This lights up the lamp l which is upon the switchboard in front of the operator. Upon seeing this signal, the latter moves a switch which connects her own telephone to the subscriber's line. Then, as the latter talks into the transmitter T, the strength of the direct current from the battery B, through the primary p, is varied by the varying pressure of the diaphragm E upon the granular carbon c, and these variations induce in the secondary s the talking currents which pass over the line to the receiver of the operator. Although with this arrangement the primary and secondary currents pass simultaneously over the same line, speech is found to be transmitted quite as distinctly as when the two circuits are entirely separate, as is the case with the arrangement of Fig. 79. When the operator finds what number the subscriber wishes, she connects the ends d and e of his line with the ends of the desired line by means of a flexible conducting cord which terminates in a metallic plug u, suitable for making contact with d and e. As soon as the subscriber replaces his receiver upon its hook, the lamp l is extinguished, and the operator thereupon withdraws u and thus disconnects the two lines.



250 VOLT BELT-DRIVEN DIRECT-CURRENT GENERATOR
General Electric Company

THE ELECTRIC CURRENT.

Electromotive Force. When a difference of electrical potential exists between two points, there is said to exist an *electromotive force*, or tendency to cause a current to flow from one point to the other. In the voltaic cell one plate is at a different potential from the other, which gives rise to an electromotive force between them. Also in the induction coil, an electromotive force is created in the secondary circuit caused by the action of the primary. This electromotive force is analogous to the *pressure*, caused by a difference in level of two bodies of water connected by a pipe. The pressure tends to force the water through the pipe, and the electromotive force tends to cause an electric current to flow.

The terms potential difference and electromotive force are commonly used with the same meaning, but strictly speaking the potential difference gives rise to the electromotive force. Electromotive force is commonly designated by the letters *E. M. F.* or simply *E.* It is also referred to as *pressure* or *voltage.*

Current. A current of electricity flows when two points, at a difference of potential, are connected by a wire, or when the circuit is otherwise completed. Similarly water flows from a high level to a lower one, when a path is provided. In either case the flow can take place only when the path exists. Hence to produce a current it is necessary to have an electromotive force and a closed circuit. The current continues to flow only as long as the electromotive force and closed circuit exist.

The strength of a current in a conductor is defined as the quantity of electricity which passes any point in the circuit in a unit of time.

Current is sometimes designated by the letter *C*, but the letter *I* will be used for current throughout this and following sections. The latter symbol was recommended by the International Electrical Congress held at Chicago in 1893, and has since been universally adopted.

Resistance. Resistance is that property of matter in virtue of which bodies oppose or resist the free flow of electricity. Water passes with difficulty through a small pipe of great length or through a pipe filled with stones or sand, but very readily through a large clear pipe of short length. Likewise a small wire of considerable length and made of poor conducting material offers great resistance to the passage of electricity, but a good conductor of short length and large cross section offers very little resistance.

Resistance is designated by the letter *R*.

Volt, Ampere and Ohm. The *volt* is the practical unit of electromotive force.

The *ampere* is the practical unit of current.

The *ohm* is the practical unit of resistance. The *microhm* is one millionth of an ohm and the *megohm* is one million ohms.

The standard values of the above units were very accurately determined by the International Electrical Congress in 1893, and are as follows:

The International ohm, or true ohm, as nearly as known, is the resistance of a uniform column of mercury 106.3 centimeters long and 14.4521 grams in mass, at the temperature of melting ice.

The ampere is the strength of current which, when passed through a solution of silver nitrate, under suitable conditions, deposits silver at the rate of .001118 gram per second. Current strength may be very accurately determined by electrolysis, and it is used therefore in determining the standard unit.

The volt is equal to the E. M. F. which, when applied to a conductor having a resistance of one ohm, will produce in it a current of one ampere. One volt equals $\frac{1000}{1434}$ of the E. M. F. of a Clark standard cell at 15° Centigrade.

RESISTANCE.

All substances resist the passage of electricity, but the resistance offered by some is very much greater than that offered by others. Metals have by far the least resistance and of these, silver possesses the least of any. In other words, silver is the best conductor. If the temperature remains the same, the resistance of a conductor is not affected by the current passing through it. A current of ten, twenty or any number of amperes may pass through a circuit, but its resistance will be unchanged with constant temperature. Resistance is affected by the temperature and also by the degree of hardness. Annealing decreases the resistance of a metal.

Conductance is the inverse of resistance; that is, if a conductor has a resistance of R ohms, its conductance is equal to $\frac{1}{R}$.

Resistance Proportional to Length. The resistance of a conductor is directly proportional to its length. Hence, if the length of a conductor is doubled, the resistance is doubled, or if the length is divided, say into three equal parts, then the resistance of each part is one third the total resistance.

Example. — The resistance of 1283 feet of a certain wire is 6.9 ohms. What is the resistance of 142 feet of the same wire?

Solution. — As the resistance is directly proportional to the length we have the proportion,

$$\text{required resistance} : 6.9 :: 142 : 1283$$

or,

$$\frac{\text{required resistance}}{6.9} = \frac{142}{1283}$$

Hence,

$$\text{required resistance} = 6.9 \times \frac{142}{1283}$$

$$= .76 \text{ ohm (approx.)}$$

Ans. .76 ohm.

Example. — The resistance of a wire having a length of 521 feet is .11 ohm. What length of the same wire will have a resistance of .18 ohm?

Solution. — As the resistance is proportional to length, we have the proportion,

$$\text{required length} : 521 :: .18 : .11$$

or,

$$\frac{\text{required length}}{521} = \frac{.18}{.11}$$

Hence,

$$\text{required length} = 521 \times \frac{.18}{.11}$$

$$= 852 \text{ feet (approx.)}$$

Ans. 852 feet.

Resistance Inversely Proportional to Cross-Section. The resistance of a conductor is inversely proportional to its cross-sectional area. Hence the greater the cross-section of a wire the less is its resistance. Therefore, if two wires have the same length, but one has a cross-section three times that of the other, the resistance of the former is one-third that of the latter.

Example.—The ratio of the cross-sectional area of one wire to that of another of the same length and material is $\frac{257}{101}$. The resistance of the former is 16.3 ohms. What is the resistance of the latter ?

Solution.—As the resistances are inversely proportional to the cross-sections, the smaller wire has the greater resistance, and we have the proportion :

$$\text{required resist.} : 16.3 : : 257 : 101$$

or,

$$\frac{\text{required resist.}}{16.3} = \frac{257}{101}$$

Hence,

$$\text{required resist.} = 16.3 \times \frac{257}{101}$$

$$= 41.5 \text{ ohms (approx.)}$$

Ans. 41.5 ohms.

Example.—If the resistance of a wire of a certain length and having a cross-sectional area of .0083 square inch is 1.7 ohms, what would be its resistance if the area of its cross-section were .092 square inch ?

Solution.—Since increasing the cross-sectional area of a wire decreases its resistance, we have the proportion,

$$\text{required resist.} : 1.7 : : .0083 : .092$$

or,

$$\frac{\text{required resist.}}{1.7} = \frac{.0083}{.092}$$

Hence,

$$\text{required resist.} = 1.7 \times \frac{.0083}{.092}$$

$$= .15 \text{ ohm (approx.)}$$

Ans. .15 ohm.

As the area of a circle is proportional to the square of its diameter, it follows that the resistances of round conductors are inversely proportional to the squares of their diameters.

Example.—The resistance of a certain wire having a diam.

eter of .1 inch is 12.6 ohms. What would be its resistance if the diameter were increased to .32 inch?

Solution. — The resistances being inversely proportional to the squares of the diameters, we have,

$$\text{required resist.} : 12.6 :: .1^2 : .32^2$$

or,

$$\frac{\text{required resist.}}{12.6} = \frac{.1^2}{.32^2}$$

Hence,

$$\text{required resist.} = 12.6 \times \frac{.1^2}{.32^2}$$

$$= \frac{12.6 \times .01}{.1024}$$

$$= 1.23 \text{ ohms (approx.)}$$

Ans. 1.23 ohms.

Specific Resistance. The specific resistance of a substance is the resistance of a portion of that substance of unit length and unit cross-section at a standard temperature. The units commonly used are the centimeter or the inch, and the temperature that of melting ice. The specific resistance may therefore be said to be the resistance (usually stated in microhms) of a centimeter cube or of an inch cube at the temperature of melting ice. If the specific resistances of two substances are known then their relative resistance is given by the ratio of the specific resistances.

Conductivity is the reciprocal of specific resistance.

Example. — A certain copper wire at the temperature of melting ice has a resistance of 29.7 ohms. Its specific resistance (resistance of 1 centimeter cube in microhms) is 1.594, and that of platinum is 9.032. What would be the resistance of a platinum wire of the same size and length of the copper wire, and at the same temperature?

Solution. — The resistance would be in direct ratio of the specific resistances, and we have the proportion:

$$\text{required resist.} : 29.7 :: 9.032 : 1.594$$

Hence,

$$\text{required resist.} = 29.7 \times \frac{9.032}{1.594}$$

$$= 168. \text{ ohms (approx.)}$$

Ans. 168. ohms.

Calculation of Resistance. From the preceding pages it is evident that resistance varies directly as the length, inversely as the cross-sectional area, and depends upon the specific resistance of the material. This may be expressed conveniently by the formula,

$$R = s\frac{L}{A}$$

in which R is the resistance, L the length of the conductor, A the area of its cross section, and s the specific resistance of the material.

Example.—A telegraph relay is wound with 1,800 feet of wire .010 inch in diameter, and has a resistance of 150 ohms. What will be its resistance if wound with 400 feet of wire .022 inch in diameter?

Solution.—If the wires were of equal length, we should have the proportion,

$$\text{Required resistance} : 150 :: (.010)^2 : (.022)^2$$

or,

$$\text{Required resistance} = 150 \times \frac{(.010)^2}{(.022)^2} = 30.99+ \text{ ohms.}$$

For a wire 400 feet long, we have, therefore, by direct proportion,

$$\text{Required resistance} = \frac{400}{1,800} \times 30.99 = 6.88+.$$

Ans. 6.88+ ohms.

If a circuit is made up of several different materials joined in series with each other, the resistance of the circuit is equal to the sum of the resistances of its several parts. In calculating the resistance of such a circuit, the resistance of each part should first be calculated, and the sum of these resistances will be the total resistance of the circuit.

The table on page 9 gives the resistance of chemically pure substances at 0° Centigrade or 32° Fahrenheit in International ohms. The first column of numbers gives the relative resistances when that of annealed silver is taken as unity. For example, mercury has 62.73 times the resistance of annealed silver. The second and third columns give the resistances of a foot of wire .001 inch in diameter, and of a meter of wire 1 millimeter in diameter, respectively. The fourth and fifth columns give respectively the resistance in microhms of a cubic inch and cubic centimeter, that is, the specific resistances.

Table Showing Relative Resistance of Chemically Pure Substances at Thirty-two Degrees Fahrenheit in International Ohms.

Metal	Relative Resistance.	Resistance of a wire 1 foot long, .001 inch in diameter.	Resistance of a wire 1 meter long, 1 millimeter in diameter.	Resistance in Microhms.	
				Cubic Inch.	Cubic Centimeter.
Silver, annealed.	1.000	9.023	.01911	.5904	1.500
Copper, annealed.	1.063	9.585	.02028	.6274	1.594
Silver, hard drawn.	1.086	9.802	.02074	.6415	1.629
Copper, hard drawn.	1.086	9.803	.02075	.6415	1.629
Gold, annealed.	1.369	12.35	.02613	.8079	2.052
Gold, hard drawn.	1.393	12.56	.02661	.8224	2.088
Aluminum, annealed	1.935	17.48	.03700	1.144	2.904
Zinc, pressed.	3.741	33.76	.07143	2.209	5.610
Platinum, annealed.	6.022	54.34	.1150	3.555	9.032
Iron, annealed.	6.460	58.29	.1234	3.814	9.689
Lead, pressed.	13.05	117.7	.2491	7.706	19.58
German silver.	13.92	125.5	.2659	8.217	20.87
Platinum-silver alloy ($\frac{1}{3}$ platinum, $\frac{2}{3}$ silver.)	16.21	146.3	.3097	9.576	24.32
Mercury.	62.73	570.7	1.208	37.05	94.06

It should be noted that the resistances in the above table are for chemically pure substances, and also at 32° Fahrenheit. A very small portion of foreign matter mixed with a metal greatly increases its resistance. An alloy of two or more metals always has a higher specific resistance than that of any of its constituents. For example, the conductivity of silver mixed with 1.2 per cent in volume of gold, will be 59 when that of pure silver is taken as 100. Annealing reduces the resistance of metals.

The following examples are given to illustrate the use of the table above in connection with the formula at the top of page 8, and to show the application of preceding laws.

Example.—From the specific resistance of annealed aluminum as given in the next to the last column of the table, calculate the resistance given in the second column of figures for that substance.

Solution.—The resistance in microhms of a cubic inch of annealed aluminum at 32° F. is 1.144, which is equal to .000001144 ohms. The resistance of a wire 1 foot long and .001

inch in diameter is required. In the formula on page 8, we have $s = .000001144$, $L = 1$ foot $= 12$ inches and

$$A = \frac{\pi d^2}{4} = \frac{3.1416 \times .001^2}{4} = .0000007854 \text{ sq. in.}$$

Substituting these values in the formula,

$$R = s\frac{L}{A}$$

we have,

$$R = .000001144 \times \frac{12}{.0000007854}$$

$$= 17.48 \text{ ohms.}$$

Ans. 17.48 ohms.

Example.—The resistance in microhms of a cubic centimeter of annealed platinum at 32° F. is 9.032. What is the resistance of a wire of the same substance one meter long and one millimeter in diameter at the same temperature?

Solution.—In the formula for resistance we have the quantities $s = 9.032$ microhms $= .000009032$ ohms; $L = 1$ meter $=$ 100 centimeters; and

$$A = \frac{\pi\, d^2}{4} = \frac{3.1416 \times .1^2}{4} = .007854 \text{ sq. cm.}$$

the diameter being equal to 1 millimeter $= .1$ cm.

Substituting these values we have,

$$R = .000009032 \times \frac{100}{.007854}$$

$$= .1150 \text{ ohms.}$$

Ans. .115 ohms.

Example.—From the table the resistance of 1 ft. of pure annealed silver wire .001 inch in diameter at 32° F. is 9.023 ohms. What is the resistance of a mile of wire of the same substance .1 inch in diameter at that temperature?

Solution.—As the resistance of wires is directly proportional to their length and inversely proportional to the squares of their diameters, the required resistance is found by multiplying the resistance per foot by 5,280 and the product by the inverse squares of the diameters.

$$\text{Therefore } R = 9.023 \times 5280 \times \left\{\frac{.001}{.1}\right\}^2$$

$$= 4.76 \text{ ohms (approx.)}$$

Ans. 4.76 ohms.

Example.—A mile and one-half of an annealed wire of pure iron has a resistance of 46.1 ohms. What would be the resistance of hard drawn wire of pure copper of the same length and diameter, assuming each to be at the temperature of melting ice?

Solution.—The only factor involved by this example is the relative resistance of the two metals. From the table, page 9, annealed iron has 6.460 and hard-drawn copper 1.086 times the resistance of annealed silver. Hence the resistance of the copper is to that of the iron as 1.086 is to 6.460, and the required resistance is

$$R = 46.1 \times \frac{1.086}{6.460} = 7.75 \text{ ohms (approx.)}$$

Ans. 7.75 ohms.

Example.—If the resistance of a wire 7,423 feet long is 18.7 ohms, what would be its resistance if its length were reduced to 6,253 feet and its cross-section made one half again as large?

Solution.—As resistance is directly proportional to the length, and inversely proportional to the area of the cross-section, the required resistance is

$$R = 18.7 \times \frac{6253}{7423} \times \frac{2}{3} = 10.5 \text{ ohms (approx.)}$$

Ans. 10.5 ohms.

Resistance Affected by Heating. The resistance of metals depends upon the temperature, and the resistance is increased by heating. The heating of some substances, among which is carbon, causes a decrease in their resistance. The resistance of the filament of an incandescent lamp when lighted is only about half as great as when cold. All *metals*, however, have their resistance increased by a rise in temperature. The percentage increase in resistance with rise of temperature varies with the different metals, and varies slightly for the same metal at different temperatures. The increase is practically uniform for most metals throughout a considerable range of temperature. The resistance of copper increases about .4 per cent. per degree Centigrade, or about .22 per cent. per degree Fahrenheit. The percentage increase in resistance for alloys is much less than for the simple metals. Standard resistance coils are therefore made of alloys, as it is desirable that their resistance should be as nearly constant as possible.

The change in resistance of one ohm per degree rise in temperature for a substance is called the *temperature coefficient* for that substance. The following table gives the temperature coefficients for a few substances.

TEMPERATURE COEFFICIENTS.

MATERIAL.	RISE IN R. OF 1 OHM WHEN HEATED: 1° F.	1° C.
Platinoid	.00012	.00022
Platinum-silver	.00014	.00025
German silver	.00022	.00040
Platinum	.0019	.0035
Silver	.0021	.0038
Copper, aluminum	.0022	.0040
Iron	.0026	.0046

If the resistance of a conductor at a certain temperature is known, the resistance the conductor will have at a higher temperature may be found by multiplying the temperature coefficient for the substance, by the number of degrees increase and by the resistance at the lower temperature, and adding to this result the resistance at the lower temperature. The product of the temperature coefficient by the number of degrees increase gives the increase in resistance of one ohm through that number of degrees, and multiplying this by the number of ohms gives the increase in resistance for the conductor. The result obtained is practically correct for moderate ranges of temperature.

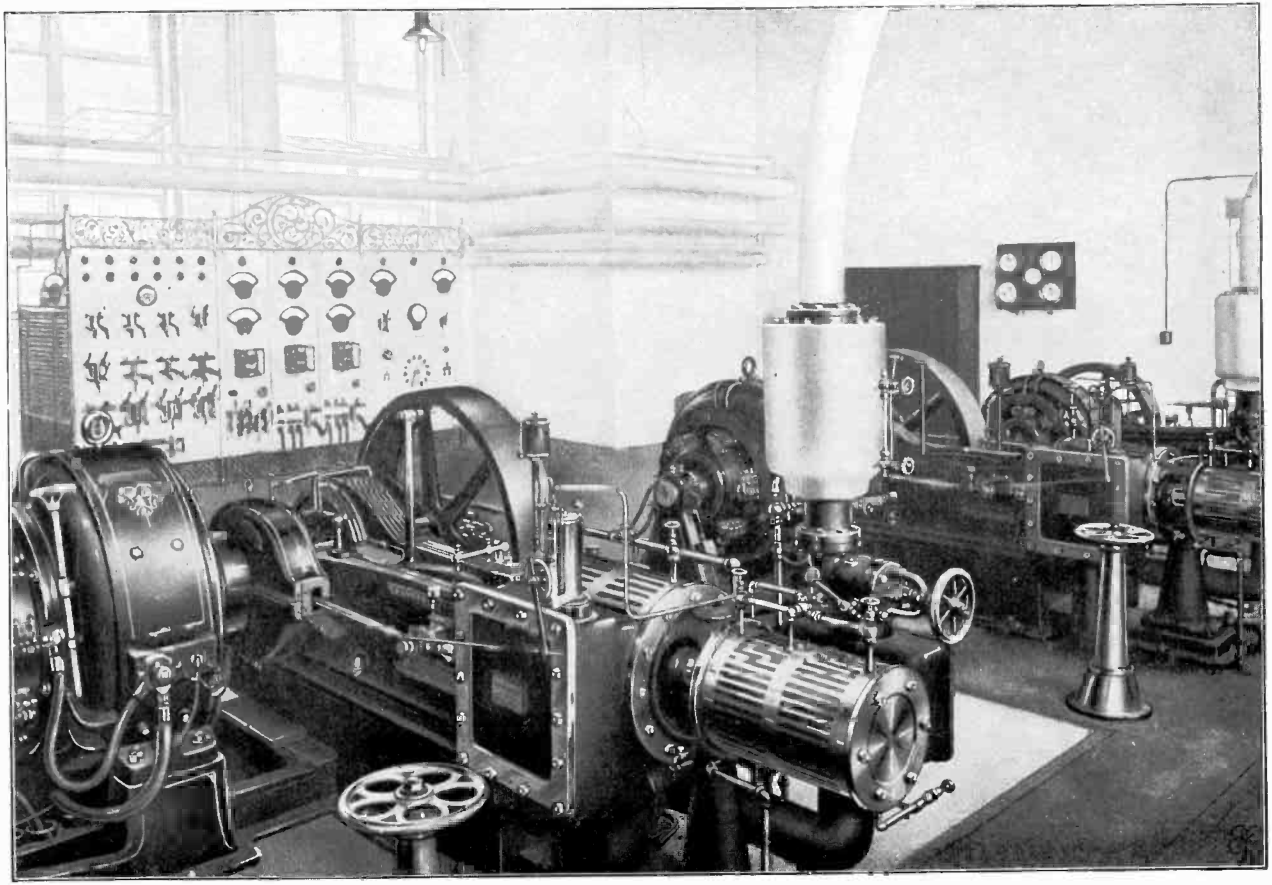
The above method of calculating the resistance of conductors at increased temperatures is conveniently expressed by the following formula:

$$R_2 = R_1\ (1 + a\ t)$$

where R_2 is the resistance at the higher temperature, R_1 that at the lower temperature, a the temperature coefficient for the substance and t the number of degrees change.

From the preceeding formula it follows that if the resistance at the higher temperature is known, that at the lower temperature will be given by the formula:

$$R_1 = \frac{R_2}{1 + at}$$



INSTALLATION OF 125-H. P. TANDEM-COMPOUND AUTOMATIC STEAM ENGINES, DIRECT-CONNECTED TO GENERATORS
Skinner Engine Co., Erie, Penna.

In calculating resistances at different temperatures, the temperature coefficient based on the Fahrenheit scale should be used if the number of degrees change is given in degrees Fahrenheit, and that based on the Centigrade scale if given in degrees Centigrade.

Example.— The resistance of a coil of German silver wire at 12° C. is 1304 ohms. What would be its resistance at a temperature of 60° C.?

Solution.— From the statement of the example $R_1 = 1304$, $t = 60 - 12 = 48$, and from the table page 12, $a = .0004$. Substituting these values in the first of the preceding formulas we have,

$$\begin{aligned} R_2 &= 1304\ (1 + .0004 \times 48) \\ &= 1304 \times 1.0192 \\ &= 1329 \text{ ohms (approx.)} \end{aligned}$$

Ans. 1329 ohms.

Example. — If the resistance of a copper conductor at 95° F. is 48.2 ohms, what would be the resistance of the same conductor at 40° F.?

Solution. — In this case $R_2 = 48.2$, $t = 95 - 40 = 55$, and from the table $a = .0022$. Substituting these values in the formula at the foot of page 12, we have,

$$R_1 = \frac{48.2}{1 + .0022 \times 55} = \frac{48.2}{1.121}$$
$$= 43. \text{ ohms (approx.)}$$

Ans. 43 ohms.

The first table on page 14 gives the resistance of the most common sizes of copper wire according to the American or Brown and Sharpe (B. & S.) gauge. The resistance given is for pure copper wire at a temperature of 75° F. or 24° C.

The first column gives the number of the wire, the second the diameter in thousandths of an inch or mils, and the third the diameter in millimeters, The fourth column gives the equivalent number of wires each one mil or one thousandth of an inch in diameter. This is called the size of the wire in circular mils and is equal to the square of the diameter in mils. The fifth column gives the ohms per thousand feet and the resistance per mile is found by multiplying these values by 5.28. Ordinary commercial copper has a conductivity of about 95 to 97 per cent. of that of pure copper. The resistance of commercial wire is therefore about 3 to 5 per cent. greater than the values given in the table. The resistance for any metal other than copper may be found by multiplying the resistance given in the table by the ratio of the specific resistance of the given metal to the specific resistance of copper.

American Wire Gauge (B. & S.)

No.	Diameter in Mils.	Diameter in Millim.	Circular Mils.	Ohms per 1000 Ft.	No.	Diameter in Mils.	Diameter in Millim.	Circular Mils.	Ohms per 1000 Ft.
0000	460.00	11.684	211600.0	.051	19	35.89	.912	1288.0	8.617
000	409.64	10.405	167805.0	.064	20	31.96	.812	1021.5	10.566
00	364.80	9.266	133079.4	.081	21	28.46	.723	810.1	13.323
0	324.95	8.254	105592.5	.102	22	25.35	.644	642.7	16.799
1	289.30	7.348	83694.2	.129	23	22.57	.573	509.5	21.185
2	257.63	6.544	66373.0	.163	24	20.10	.511	404.0	26.713
3	229.42	5.827	52634.0	.205	25	17.90	.455	320.4	33.684
4	204.31	5.189	41742.0	.259	26	15.94	.405	254.0	42.477
5	181.94	4.621	33102.0	.326	27	14.19	.361	201.5	53.563
6	162.02	4.115	26250.5	.411	28	12.64	.321	159.8	67.542
7	144.28	3.665	20816.0	.519	29	11.26	.286	126.7	85.170
8	128.49	3.264	16509.0	.654	30	10.03	.255	100.5	107.391
9	114.43	2.907	13094.0	.824	31	8.93	.227	79.7	135.402
10	101.89	2.588	10381.0	1.040	32	7.95	.202	63.2	170.765
11	90.74	2.305	8234.0	1.311	33	7.08	.180	50.1	215.312
12	80.81	2.053	6529.9	1.653	34	6.30	.160	39.7	271.583
13	71.96	1.828	5178.4	2.084	35	5.61	.143	31.5	342.443
14	64.08	1.628	4106.8	2.628	36	5.00	.127	25.0	431.712
15	57.07	1.450	3256.7	3.314	37	4.45	.113	19.8	544.287
16	50.82	1.291	2582.9	4.179	38	3.96	.101	15.7	686.511
17	45.26	1.150	2048.2	5.269	39	3.53	.090	12.5	865.046
18	40.30	1.024	1624.1	6.645	40	3.14	.080	9.9	1091.865

The following table gives the size of the English or Birmingham wire gauge. The B. & S. is however much more frequently used in this country. The Brown and Sharpe gauge is a little smaller than the Birmingham for corresponding numbers.

Stubs' or Birmingham Wire Gauge (B. W. G.)

No.	Diameter in Mils.	Diameter in Millim.	No.	Diameter in Mils.	Diameter in Millim.	No.	Diameter in Mils.	Diameter in Millim.
0000	454	11.53	8	165	4.19	18	49	1.24
00	380	9.65	10	134	3.40	20	35	0.89
1	300	7.62	12	109	2.77	24	22	0.55
4	238	6.04	14	83	2.11	30	12	0.31
6	203	5.16	16	65	1.65	36	4	0.10

EXAMPLES FOR PRACTICE.

1. What is the resistance of an annealed silver wire 90 feet long and .2 inch in diameter at 32° F.? Ans. .02+ ohm.

2. What is the resistance of 300 meters of annealed iron wire 4 millimeters in diameter when at a temperature of 0° C.? Ans. 2.31+ ohms.

3. What is the resistance of 2 miles of No. 27 (B. & S.) pure copper wire at 75° F.? Ans. 565.+ ohms.

4. The resistance of a piece of copper wire at 32°F. is 3 ohms. What is its resistance at 49°F.? Ans. 3.11+ ohms.

5. The resistance of a copper wire at 52°F. is 7 ohms. What is its resistance at 32°F.? Ans. 6.70+ ohms.

6. What is the resistance of 496 ft. of No. 10 (B. & S.) pure copper wire at 45°F.? Ans. .483+ ohms.

On pages 16 and 17 is given a table disclosing among other data the resistance of various primary cells. The resistance of a circuit of which a battery forms a part, is made up of the external resistance, or the resistance of outside wires and connections, and the internal resistance, or the resistance of the battery itself. The table referred to gives in the first column the name of the cell. In the second and third column appears the name of the anode and kathode respectively. These terms are commonly used with reference to electrolysis but may also be applied to primary cells. The current passes from the anode to the kathode through the cell, and therefore with reference to the cell itself, the anode may be considered the positive element and the kathode the negative element. In regard to the outside circuit however, the current passes of course, from the kathode to the anode, and hence with reference to the outside circuit the kathode is positive and the anode negative; ordinarily the external circuit is considered. As the anode of almost all primary cells is zinc it may readily be remembered that the current passes from the other element *to* the zinc through the *external* circuit. The fourth and fifth columns of the table give the excitant and depolarizer respectively. The sixth column gives the E. M. F. of each cell when it is supplying no current, and the last column gives the internal resistance in ohms.

TABLE IN RELATION TO PRIMARY CELLS, ELECTROMOTIVE FORCE, RESISTANCE, ETC.

NAME OF CELL.	ANODE.	KATHODE.	EXCITANT.	DEPOLARIZER.	E. M. F. IN VOLTS.	INTERNAL RESISTANCE IN OHMS.
Volta (Wollaston, etc.)	Zinc	Copper	Solution of Sulphuric Acid (H_2SO_4)	None	1 to 0.5	
Smee	Zinc	Platinized Silver	Solution of Sulphuric Acid (H_2SO_4)	None	1 to 0.5	0.5
Law	Zinc	Carbon	Solution of Sulphuric Acid (H_2SO_4)	None	1 to 0.5	
Poggendorff (Grenet)	Zinc	Graphite (Carbon)	Solution of Sulphuric Acid (H_2SO_4)	Potassium Dichromate ($K_2Cr_2O_7$)	2.1	
Poggendorff (Grenet) two fluid	Zinc	Graphite (Carbon)	Saturated Solution of Potassium Dichromate and Sulphuric Acid	None Separate	1.98	.001 to .08
Grove	Zinc	Platinum	Sulphuric Acid dilute (H_2SO_4)	Nitric Acid (HNO_3)	1.96	0.1 to 0.12
Bunsen	Zinc	Graphite (Carbon)	Sulphuric Acid dilute (H_2SO_4)	Nitric Acid	1.8 to 1.98	0.08 to 0.11
				Chromic Acid	1.8	0.1 to 0.12
Leclanche	Zinc	Graphite (Carbon)	Ammonium Chloride (NH_4Cl)	Manganese Dioxide (MnO_2)	1.4 to 1.6	1.13 to 1.15
Lalande Lalande—Chaperon	Zinc	Graphite (Carbon)	Caustic Potash or Potassium Hydrate (KOH)	Cupric Oxide	0.8 to 0.98	1.3
Upward	Zinc	Graphite (Carbon)	Zinc Chloride ($ZnCl_2$)	Chlorine (Cl)	2.0	
Fitch	Zinc	Graphite (Carbon)	Ammonium Chloride (NH_4Cl)	Sodium & Potassium Chlorates ($NaClO_3$ + $KClO_3$)	1.1	
Papst	Iron	Graphite (Carbon)	Ferric Chloride (Fe_2Cl_6)	(Fe_2Cl_6)	0.4	
Obach (dry)	Zinc	Graphite (Carbon)	Ammonium Chloride (NH_4Cl) in Calcium Sulphate ($CaSO_4$)	Manganese Dioxide (MnO_2)	1.46	
Daniell (Meidinger Minotto, etc.)	Zinc	Copper	Zinc Sulphate ($ZnSO_4$)	Copper Sulphate ($CuSO_4$)	1.079	2 to 5
De la Rue	Zinc	Silver	Ammonium Chloride	Silver Chloride (AgCl)	1.03 to 1.42	0.4 to 0.6
Marie Davy	Zinc	Graphite (Carbon)	Sulphuric Acid dilute (H_2SO_4)	Paste of Sulphate of Mercury (Hg_2SO_4)	1.52	0.75 to 1
Clark (Standard)	Zinc	Mercury	Zinc Sulphate ($ZnSO_4$)	Mercurous Sulphate (Hg_2SO_4)	1.434*	0.2 to 0.5
Weston	Cadmium	Mercury	Cadmium Sulphate ($CdSO_4$)	Mercurous Sulphate (Hg_2SO_4)	1.025	

NAME OF CELL.	ANODE.	KATHODE.	EXCITANT.	DEPOLARIZER.	E. M. F. IN VOLTS.	INTERNAL RESISTANCE IN OHMS.
Von Helmholtz	Zinc	Mercury	Zinc Chloride ($Zn\,Cl_2$)	Mercurous Chloride ($Hg_2\,Cl_2$)	1.0	
Chromic Acid single fluid	Zinc	Graphite (Carbon)	Sulphuric and Chromic Acids, dilute mixed	None Separate	2.2	.016 to .08
Fuller	Zinc	Graphite (Carbon)	Sulphuric Acid ($H_2\,SO_4$)	Potassium Dichromate ($K_2\,Cr_2\,O_7$)	2.0	0.5 to 0.7
Gaiffe	Zinc	Silver	Zinc Chloride ($Zn\,Cl_2$)	Silver Chloride ($Ag\,Cl$)	1.02	0.5 to 0.6
Maiche	Zinc scraps in bath of Mercury	Platinized Carbon	Common Salt Solution *i. e.* Sodium Chloride ($NaCl$)	None Separate	1.25	1 to 2
Niaudet	Zinc	Graphite (Carbon)	Common Salt Solution *i. e.* Sodium Chloride ($NaCl$)	Chloride of Calcium (Lime) ($Ca\,Cl_2$)	1.0 to 1.6	5 to 6
Schanschieff	Zinc	Graphite (Carbon)	Mercurial Solution	None Separate	1.56	0.05 to 0.75
Skrivanoff	Zinc	Silver	Caustic Potash or Potassium Hydrate (KOH)	Chloride of Silver ($Ag\,Cl$)	1.5	1.5

* At 15 degrees Centigrade or 59 degrees Fahrenheit.

Resistances in last column measured in cells standing 6″ × 4″

OHM'S LAW.

One of the most important and most used laws of electricity is that first formulated by Dr. G. S. Ohm, and known as Ohm's law. This law is as follows:

The current is directly proportional to the electromotive force and inversely proportional to the resistance.

That is, if the electromotive force applied to a circuit is increased, the current will be increased in the same proportion, and if the resistance of a circuit is increased then the current will be decreased proportionally. Likewise a decrease in the electromotive force causes a proportional decrease in current and a decrease in resistance causes a proportional increase in current. The current depends only upon the electromotive force and resistance and in the manner expressed by the above simple law. The law may be expressed algebraically as follows:

$$\text{current } \textit{varies as } \frac{\text{electromotive force}}{\text{resistance}}$$

The units of these quantities, the ampere, volt and ohm, have been so chosen that an electromotive force of 1 volt applied to a resistance of 1 ohm, causes 1 ampere of current to flow. Ohm's law may therefore be expressed by the following equation:

$$I = \frac{E}{R}$$

where I is the current in amperes, E the electromotive force in volts and R the resistance in ohms.

It is therefore evident, that if the electromotive force and resistance are known the current may be found, or if any two of the three quantities are known the third may be found. If the current and resistance are known the electromotive force may be found from the formula:

$$E = R\,I$$

and if the current and electromotive force are known, the resistance may be found from the formula:

$$R = \frac{E}{I}$$

Simple Applications. The following examples are given to illustrate the simplest applications of Ohm's law.

Example.—If the E.M.F. applied to a circuit is 4 volts and its resistance is 2 ohms, what current will flow?

Solution.—By the formula for current,

$$I = \frac{E}{R} = \frac{4}{2} = 2 \text{ amperes.}$$

Ans. 2 amperes.

Example.—What voltage is necessary to cause a current of 23 amperes to flow through a resistance of 820 ohms?

Solution.—By the formula for E.M.F.,

$$E = RI = 820 \times 23 = 18{,}860 \text{ volts.}$$

Ans. 18,860 volts.

Example.—The E.M.F. applied to a circuit is 110 volts, and it is desired to obtain a current of .6 ampere. What should be the resistance of the circuit?

Solution.—By the formula for resistance,

$$R = \frac{E}{I} = \frac{110}{.6} = 183. + \text{ohms.}$$

Ans. 183 ohms.

Series Circuits. A circuit made up of several parts all joined in series with each other, is called a series circuit and the resistance of the entire circuit is of course the sum of the separate resistances. In calculating the current in such a circuit the total resistance must first be obtained, and the current may then be found by dividing the applied or total E.M.F. by the total resistance. This is expressed by the formula,

$$I = \frac{E}{R_1 + R_2 + R_3 + \text{etc.}}$$

Example. — Three resistance coils are connected in series with each other and have a resistance of 8, 4 and 17 ohms respectively. What current will flow if the E.M.F. of the circuit is 54 volts?

Solution. — By the preceding formula,

$$I = \frac{E}{R_1 + R_2 + R_3} = \frac{54}{8 + 4 + 17} = \frac{54}{29} = 1.8+ \text{ amperes.}$$

Ans. 1.8+ amperes.

Example. — Six arc lamps, each having a resistance of 5 ohms, are connected in series with each other and the resistance of the connecting wires and other apparatus is 3.7 ohms. What must be the pressure of the circuit to give a desired current of 9.6 amperes?

Solution. — The total resistance of the circuit is $R = (6 \times 5) + 3.7 = 33.7$ ohms and the current is to be $I = 9.6$ amperes. Hence by the formula for E.M.F.,

$$E = R\,I = 33.7 \times 9.6 = 323.+ \text{ volts.}$$

Ans. 323.+ volts.

Example. — The current passing in a certain circuit was 12 amperes and the E.M.F. was 743 volts. The circuit was made up of 4 sections all connected in series, and the resistance of three sections was 16, 9 and 26 ohms respectively. What was the resistance of the fourth section?

Solution. — Let x = the resistance of the fourth section, then $R = 16 + 9 + 26 + x = 51 + x$, $I = 12$, and $E = 743$. By the formula for resistance,

$$R = \frac{E}{I} \text{ or, } 51 + x = \frac{743}{12} = 61.9 \text{ ohms (approx.)}$$

If $51 + x = 61.9$ we have, by transposing **51** to the other side of the equation,

$$x = 61.9 - 51 = 10.9 \text{ ohms.}$$

Ans. 10.9 ohms.

Example. — A current of 54 amperes flowed through a circuit when the E.M.F. was 220 volts. What resistance should be added in series with the circuit to reduce the current to 19 amperes?

Solution. — The resistance in the first case was,

$$R = \frac{220}{54} = 4.07 \text{ ohms (approx.)}$$

The resistance in the second must be,

$$R = \frac{220}{19} = 11.58 \text{ ohms (approx.)}$$

The required resistance to insert in the circuit is the difference of these two resistances, or $11.58 - 4.07 = 7.51$ ohms.

Ans. 7.51 ohms.

Fall of Potential in a Circuit. Fig. 1 illustrates a series circuit in which the resistances A, B, C, D and E are connected in series with each other and with the source of electricity. If the E. M. F. is known, the current may be found by dividing the E. M. F. by the sum of all the resistances. Ohm's law may, however, be applied to any part of a circuit separately, as well as to the complete circuit. Suppose the resistances of A, B, C, D and E are 4, 3, 6, 3 and 4 ohms respectively, and assume that the source has no resistance. Suppose the current flowing to be 12 amperes. The E. M. F. necessary to force a current of 12 amperes through the resistance A of 4 ohms is, by applying Ohm's law, equal to $E = RI = 4 \times 12 = 48$ volts. Hence between the points a and b outside of the resistance A, there must be a difference of potential of 48 volts to force the current through this resistance. Also to force the same current through B, the voltage necessary is $3 \times 12 = 36$. Similarly, for each part C, D and E, there are required 72, 36 and 48 volts respectively.

As 48 volts are necessary for part A and 36 volts for part B, it is evident that to force the current through both parts a difference of potential of $48 + 36 = 84$ volts is required; that is, the voltage between the points *a* and *c* must be 84 volts. For the three parts *A*, *B* and *C*, 48 + 36 + 72 = 156 volts are necessary, and for the entire circuit, 240 volts must be applied to give the current of 12 amperes. From the above it is evident that there is a gradual fall of potential throughout the circuit, and if the voltage between any two points of the circuit be measured, the E. M. F. obtained would depend upon the resistance included between these two points. For example, the voltage between points *b* and *d* would be found to be 72 + 36 = 108 volts, or between *d* and *e* 36, volts, etc. From the preceding it is apparent that the fall of potential in a part of a circuit is equal to the current multiplied by the resistance of that part.

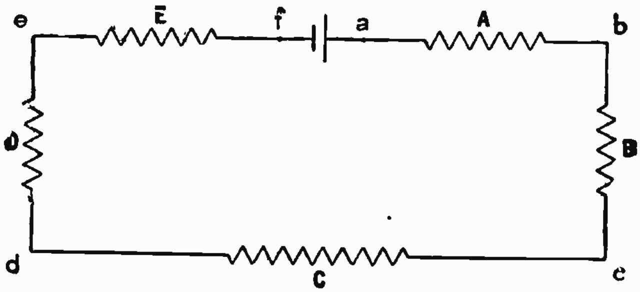


Fig. 1.

This gradual fall of potential, or *drop* as it is commonly called, throughout a circuit, enters into the calculations for the size of conductors or mains supplying current to distant points. The resistances of the conductors cause a certain drop in transmitting the current, depending upon their size and length, and it is therefore necessary that the voltage of machines at the supply station shall be great enough to give the voltage necessary at the receiving stations as well as the additional voltage lost in the conducting mains.

For example, in Fig. 1 the voltage necessary between the points *e* and *b* is 144 volts, but to give this voltage the source must supply in addition the voltage lost in parts *A* and *E*, which equals 96 volts.

Example.—The voltage required by 17 arc lamps connected in series is 782 volts and the current is 6.6 amperes. The resistance of the connecting wires is 7 ohms. What must be the E. M. F. applied to the circuit?

Solution.—The drop in the connecting wires is $E = RI = 7 \times 6.6 = 46.2$ volts. The E. M. F. necessary is therefore $782 + 46.2 = 828.2$ volts. Ans. 828.2 volts.

Example.—The source of E. M. F. supplies 114 volts to a circuit made up of incandescent lamps and conducting wires. The lamps require a voltage of 110 at their terminals, and take a current of 12 amperes. What should be the resistance of the conducting wires in order that the lamps will receive the necessary voltage?

Solution.—The allowable drop in the conducting wires is $114 - 110 = 4$ volts. The current to pass through the wires is 12 amperes. Hence the resistance must be

$$R = \frac{E}{I} = \frac{4}{12} = .33 + \text{ohms.}$$

Ans. .33 + onms.

Divided Circuits. When a circuit divides into two or more parts, it is called a *divided* circuit and each part will transmit a portion of the current.

Such a circuit is illustrated in Fig. 2, the two branches being represented by *b* and *c*. The current passes from the positive pole of the battery through *a* and then divides; part of the current passing through *b* and part through *c*. The current then unites and passes through *d* to the negative pole of the battery. The part *c* may be considered as the main part of the circuit and *b* as a by-pass about it. A branch which serves as a by-pass to another circuit is called a *shunt* circuit, and the two branches are said to be connected in *parallel*.

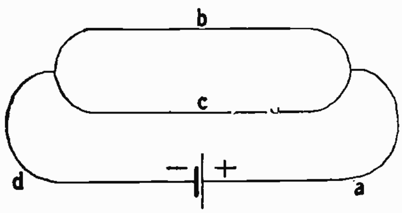


Fig. 2.

In considering the passage of a current through a circuit of this sort, it may be necessary to determine how much current will pass through one branch and how much through the other. Evidently this will depend upon the relative resistance of the two branches, and more current will pass through the branch offering the lesser resistance than through the branch having the higher resistance. If the two parts have equal resistances, then one half of the total current will pass through each branch. If one branch has twice the resistance of the other, then only one-half as much of the total current will pass through that branch as through the other; that is, $\frac{1}{3}$ of the total current will pass through the first branch and the remaining $\frac{2}{3}$ will pass through the second.

The relative strength of current in the two branches will be inversely proportional to their resistances, or directly proportional to their conductances.

Suppose the resistance of one branch of a divided circuit is r_1 (see Fig. 3), and that of the other is r_2. Then by the preceding law,

$$\text{current in } r_1 : \text{current in } r_2 :: r_2 : r_1$$

Also,

$$\text{current in } r_1 : \text{total current} :: r_2 : r_1 + r_2$$

and

$$\text{current in } r_2 : \text{total current} :: r_1 : r_1 + r_2$$

Let I represent the total current, i_1 the current through the resistance r_1 and i_2 the current through the resistance r_2. Then the two preceding proportions are expressed by the following formulas:

$$i_1 = \frac{I r_2}{r_1 + r_2} \quad \text{and} \quad i_2 = \frac{I r_1}{r_1 + r_2}$$

Example.—The total current passing in a circuit is 24 amperes. The circuit divides into two branches having resistances of 5 and 7 ohms respectively. What is the current in each branch?

Solution.—In this case $I = 24$, $r_1 = 5$ and $r_2 = 7$. Substituting these values in the above formulas we have,

$$i_1 = \frac{I r_2}{r_1 + r_2} = \frac{24 \times 7}{5 + 7} = 14 \text{ amperes.}$$

and

$$i_2 = \frac{I r_1}{r_1 + r_2} = \frac{24 \times 5}{5 + 7} = 10 \text{ amperes.}$$

Ans. { In 5 ohm branch, 14 amperes.
In 7 ohm branch, 10 amperes.

Joint Resistance of Divided Circuits. As a divided circuit offers two paths to the current, it follows that the joint resistance of the two branches will be less than the resistance of either branch alone. The ability of a circuit to conduct electricity is represented by its conductance, which is the reciprocal of resistance; and the conductance of a divided circuit is equal to the sum of the conductances of its parts.

For example, in Fig. 3, the conductance of the upper branch equals $\frac{1}{r_1}$ and that of the lower branch equals $\frac{1}{r_2}$. If R represents the joint resistance of the two parts then the joint conductance equals:

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} = \frac{r_1 + r_2}{r_1 r_2}$$

Having thus obtained the joint conductance, the joint resistance is found by taking the reciprocal of the conductance, that is,

$$R = \frac{r_1 r_2}{r_1 + r_2}$$

This formula may be stated as follows:

The joint resistance of a divided circuit is equal to the product of the two separate resistances divided by their sum.

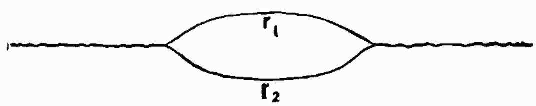


Fig. 3.

For example, suppose the resistance of each branch to be 2 ohms. The conductance of the circuit will be,

$$\frac{1}{R} = \frac{1}{2} + \frac{1}{2} = 1\text{, and hence } R = 1 \text{ ohm.}$$

Also by the preceding formula,

$$R = \frac{2 \times 2}{2 + 2} = 1 \text{ ohm.}$$

The resistance of a divided circuit in which each branch has a resistance of 2 ohms is therefore 1 ohm.

Example.—The resistances of two separate conductors are 3 and 7 ohms respectively. What would be their joint resistance if connected in parallel?

Solution.—In this case $r_1 = 3$ and $r_2 = 7$, hence by the formula,

$$R = \frac{3 \times 7}{3 + 7} = 2.1 \text{ ohms.} \qquad \text{Ans. } 2.1 \text{ ohms.}$$

Suppose, as illustrated in Fig. 4, the conductors having resistances equal to r_1, r_2 and r_3 respectively, are connected in parallel. The joint total conductance will then be equal to,

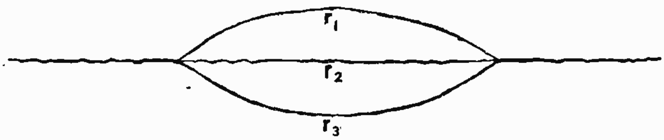


Fig. 4.

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} = \frac{r_2 r_3 + r_1 r_3 + r_1 r_2}{r_1 r_2 r_3}$$

and as the joint resistance is the reciprocal of the joint conductance, the joint resistance R of the three branches is expressed by the formula,

$$R = \frac{r_1 r_2 r_3}{r_2 r_3 + r_1 r_3 + r_1 r_2}$$

Example.—What is the joint resistance when connected in parallel, of three wires whose respective resistances are 41, 52 and 29 ohms respectively?

Solution.—In this case $r_1 = 41$, $r_2 = 52$ and $r_3 = 29$. Hence, by the preceding formula,

$$R = \frac{41 \times 52 \times 29}{52 \times 29 + 41 \times 29 + 41 \times 52} = 12.8 + \text{ ohms.}$$

Ans. 12.8 + ohms.

In general, for any number of conductors connected in parallel, the joint resistance is found by taking the reciprocal of the sum of the reciprocals of the separate resistances.

Example.—A circuit is made up of five wires connected in parallel, and their separate resistances are respectively 12, 21, 28. 8 and 42 ohms. What is the joint resistance?

Solution.—The sum of the conductances is:

$$\frac{1}{12}+\frac{1}{21}+\frac{1}{28}+\frac{1}{8}+\frac{1}{42}=\frac{53}{168}$$

Hence the joint resistance equals:

$$R=\frac{168}{53}=3.1+\text{ ohms.}$$

Ans. 3.1 + ohms.

If the resistance of each branch is known and also the potential difference between the points of union, then the current in each branch may be found by applying Ohm's law to each branch separately. For example, if this potential difference were 96 volts, and the separate resistances of the 4 branches were 8, 24, 3 and 48 ohms respectively, then the current in the respective branches would be 12, 4, 32 and 2 amperes respectively.

If the current in each branch is known and also the potential difference between the points of union, then the resistance of each branch may likewise be found from Ohm's law.

The following examples are given to illustrate the application of the preceding principles.

EXAMPLES FOR PRACTICE.

1. Two conductors having resistances of 71 and 19 ohms respectively are connected in parallel, and the total current passing in the circuit is 37 amperes. What current passes in the conductor whose resistance is 71 ohms? Ans. 7.8 + amperes.

2. What is the joint resistance of two wires connected in parallel if their separate resistances are 2 and 8 ohms respectively? Ans. 1.6 ohms.

3. What is the joint resistance of three wires when connected in parallel, whose separate resistances are 5, 7 and 9 ohms respectively? Ans. 2.2 + ohms.

4. Three wires, the respective resistances of which are 8, 10 and 20 ohms, are joined in parallel. What is their joint resistance? Ans. 3.6 + ohms.

5. Four wires are joined in parallel, and their separate resistances are 2, 4, 6 and 9 ohms respectively. What is the joint resistance of the conductor thus formed?

Ans. .97 + ohm.

Battery Circuits. Fig. 5 illustrates a simple circuit having a single cell C connected in series with a resistance. This is the customary manner of representing a cell, the short, heavy line representing the zinc and the long light line representing the copper or carbon plate. In determining the amount of current which will flow in such a circuit, the total resistance of the circuit must be considered. This is made up of the external resistance R and the internal resistance r, or the resistance of the cell itself. If E represents the total E.M.F. of the cell, then the current I which will flow is expressed by the formula,

$$I = \frac{E}{R + r}$$

It has been shown that whenever a current passes through any resistance, there is always a certain *drop* or fall of potential. The total E.M.F. above referred to, expresses the total potential difference between the plates of the cell and is the E.M.F. of the cell on *open* circuit. When the current flows, however, there is a fall of potential or loss of voltage within the cell itself, and hence the E.M.F. of the cell on closed circuit is less than on open circuit. That is, if the voltage be measured when the cell is supplying current, it will be found to be less than when the voltage is measured on open circuit, or when the cell is supplying no current. The voltage on closed circuit is that available for the external circuit, and is therefore called the *external* or *available* voltage or E.M.F.

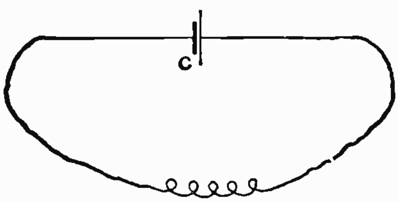


Fig. 5.

The external E.M.F. depends of course upon the strength of current the cell is supplying, and may be calculated as follows:

If the current passing is I and the resistance of the cell is r, then from Ohm's law the voltage lost in the cell equals $r\,I$. If E represents the total E.M.F. of the cell and E_1 the external E.M.F., then,

$$E_1 = E - r\,I$$

The E. M. F. of a cell is understood to be the total E. M. F. unless otherwise stated.

When two or more cells are interconnected they are said to form a *battery*.

Fig. 6 illustrates three cells connected in series with each other and with the external circuit. That is, the positive terminal of one cell is connected to the negative of the next, and the positive of that cell to the negative of the adjacent, etc. By this method of connecting, the E. M. F. of each cell is added to that of the others, so that the total E. M. F. of the circuit is three times that of a single cell. If one of the cells were connected so that its E. M. F. opposed that of the other two, it would offset the E. M. F. of one of the cells and the resultant E. M. F. would be that of a single cell. The connecting of cells in series as in

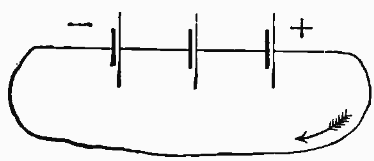


Fig. 6.

Fig. 6 not only increases the E. M. F. of the circuit but also increases the internal resistance, the resistance of each cell being added to that of the others. If E equals the E. M. F. of each cell, r the internal resistance of each and R the external resistance, then the current that will flow is expressed by the formula,

$$I = \frac{3\,E}{R + 3\,r}$$

or for n cells connected in series the formula for current is,

$$I = \frac{n\,E}{R + n\,r}$$

Fig. 7 illustrates two cells connected in parallel, and supplying current to an external circuit. Here the two positive terminals are connected with each other and also the two negative. The E. M. F. supplied to the circuit is equal to that of a single cell only. In

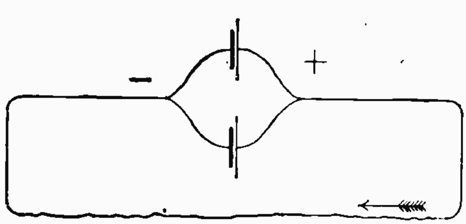
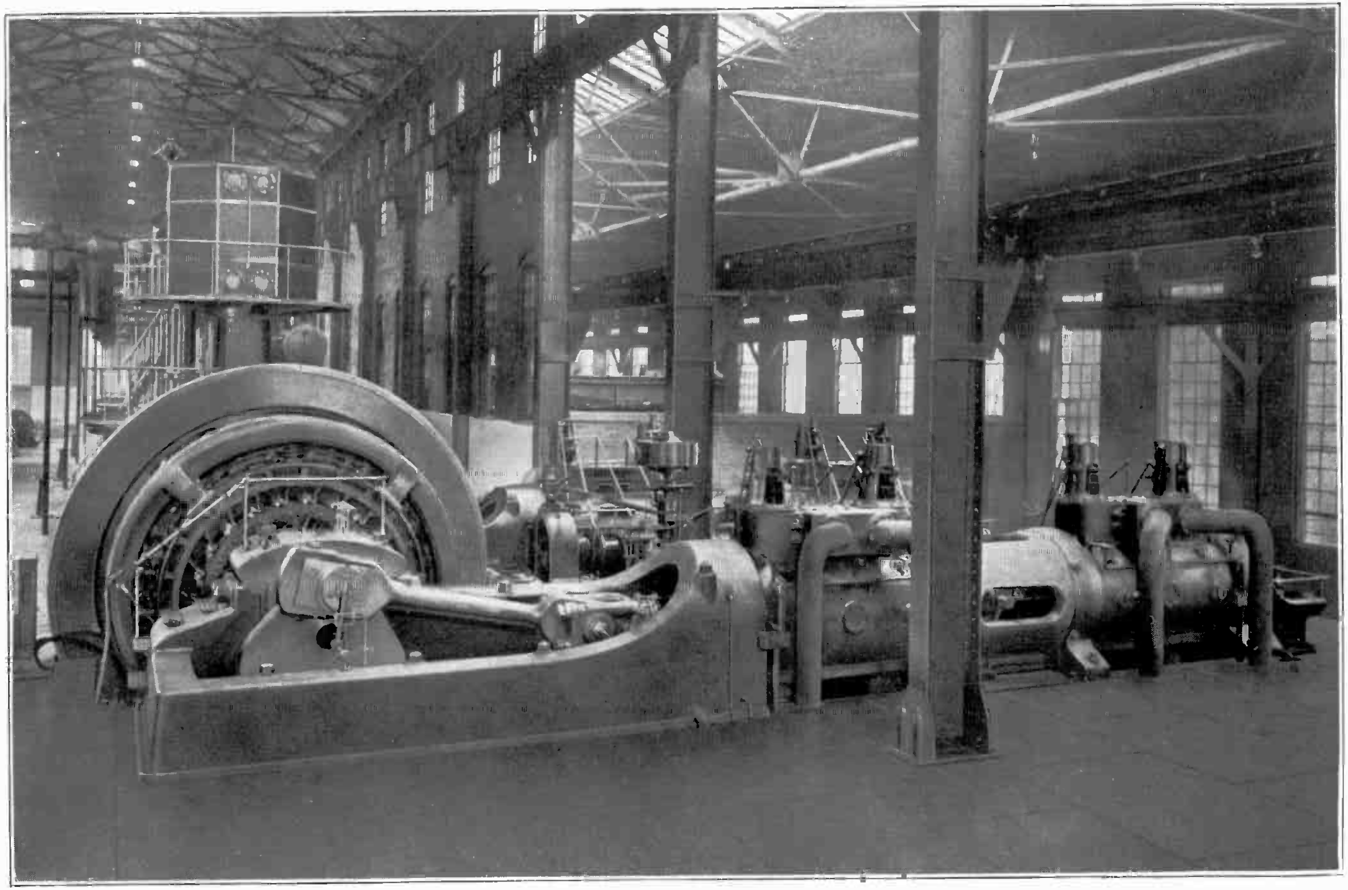


Fig. 7.

fact connecting cells in parallel, is equivalent to enlarging the



1000 H. P., FOUR-CYCLE, DOUBLE-ACTING, TWIN-TANDEM GAS ENGINE DRIVING DIRECT-CURRENT GENERATOR
Allis-Chalmers Co., Milwaukee, Wis.

plates, and the only effect is to decrease the internal resistance. It is evident that coupling two cells in parallel affords two paths for the current and so decreases the resistance of the two cells to one-half that of a single cell. The formula expressing the current that would flow in the external circuit with two cells in parallel is therefore,

$$I = \frac{E}{R + \frac{r}{2}}$$

or for n cells connected in parallel, the formula for current is,

$$I = \frac{E}{R + \frac{r}{n}}$$

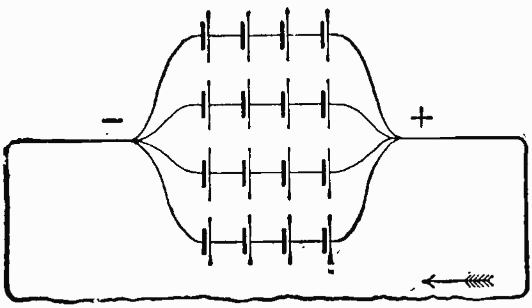


Fig. 8.

Fig. 8 represents a combination of the series and parallel method of connecting and represents four files of cells joined in parallel and each file having four cells connected in series. The E. M. F. of each file and consequently of the circuit is $4\,E$. The resistance of each file is $4\,r$ and that of all the files $\frac{4\,r}{4}$. Hence, the formula for current is,

$$I = \frac{4\,E}{R + \frac{4r}{4}}$$

If there were n files connected in parallel and m cells were connected in series in each file, the formula expressing the current in the external circuit would be,

$$I = \frac{m E}{R + \frac{m r}{n}}$$

where E is the E. M. F. of each cell, R the external resistance, and r the internal resistance of each cell.

The most advantageous method of connecting cells depends upon the results desired, the resistance of the cell and the external resistance. Suppose it is desired to pass a current through an external resistance of 2 ohms, and that Daniell's cells are to be used each having an E. M. F. of 1 volt and an internal resistance of 3 ohms.

With one cell only in circuit, the current will be,

$$\frac{E}{R + r} = \frac{1}{2 + 3} = .2 \text{ ampere,}$$

and with 5 cells all in series the current will be,

$$\frac{5 E}{R + 5 r} = \frac{5}{2 + 15} = .3 \text{ ampere (approx).}$$

Therefore with 5 cells in series the current is only .1 ampere greater than with a single cell, and with 100 cells in series the current is only,

$$\frac{100 E}{R + 100 r} = \frac{100}{2 + 300} = .33 \text{ ampere.}$$

Hence with a comparatively low external resistance, there is but little gain in current strength by the addition of cells in series. This is due to the fact that, although the E. M. F. is increased 1 volt by each cell, the resistance is increased by 3 ohms.

Now suppose 5 Daniell cells to be connected in parallel with the external circuit of 2 ohms. The E. M. F. of the circuit will then be that of a single cell and the current will be,

$$\frac{E}{R + \frac{r}{5}} = \frac{1}{2 + \frac{3}{5}} = .4 \text{ ampere (nearly),}$$

and with 100 cells connected in parallel the current will be,

$$\frac{E}{R+\frac{r}{100}} = \frac{1}{2+\frac{3}{100}} = .5 \text{ ampere (nearly).}$$

A larger current is therefore obtained in this case by connecting the cells in parallel than by connecting them in series.

With a large external resistance on the other hand, a larger current is obtained by connecting the cells in series. For example, suppose the external resistance to be 500 ohms. One cell will then give a current of .00198 + ampere, and 5 cells in series will give about .0097 ampere, whereas 100 cells will give .125 ampere. With 5 cells connected in parallel the current will be .00199 + ampere, and with 100 cells the current will amount to approximately .002 ampere. With an external resistance of 500 ohms, there is practically no advantage in connecting the cells in parallel. The only effect of the latter method is to decrease the internal resistance which is almost negligible in comparison with the external resistance.

It may be shown mathematically that for a given external resistance and a given number of cells, the largest current is obtained when the internal resistance is *equal* to the external resistance. In order to obtain this result the values of m and n in the formula on page 30, should be so chosen that $\frac{m\,r}{n}$ equals R. This arrangement, although giving the largest current strength, is not the most economical. With the internal resistance equal to the external resistance there is just as much energy used up in the battery itself as is expended usefully in the external circuit.

In order to obtain the most economical arrangement, the internal resistance should be made as small as possible, that is, all the cells should be connected in parallel. The loss of power in the battery is then the smallest amount possible.

In order to obtain the quickest action of the current the cells should be connected in series. When the external circuit possesses considerable self-induction, as is the case when electromagnets are connected in the circuit, the action of the current is retarded.

This retardation may be decreased by having a high internal resistance, which is obtained by connecting the cells in series.

Example.—Sixteen cells, each having an internal resistance of .1 ohm are to be connected with a circuit whose resistance is .4 ohm. How should the cells be connected to obtain the greatest current?

Solution.—Here the external resistance R, equals .4 ohm and the resistance r of each cell equals .1 ohm. For maximum current,

$$\frac{m\,r}{n} = R, \text{ or } \frac{.1\,m}{n} = .4$$

Therefore, $m = 4\,n$

and as $m\,n = 16$, the only values of m and n which will be true for both of these equations are $m = 8$ and $n = 2$. Hence there must be 2 files of cells, with 8 cells in series in each file.

Ans. 2 files, 8 cells in each.

Example.—The external resistance in a circuit is 4 ohms. The cells used each have an E. M. F. of 1.2 volts and an internal resistance of 3.8 ohms. If 20 cells were used, which method of connecting would supply the larger current,—5 files with 4 cells in series, or 4 files with 5 cells in series?

1st Solution.—Applying the formula on page 30, we have $R = 4$, $E = 1.2$, $r = 3.8$ and with 5 files and 4 in series, $m = 4$ and $n = 5$. Hence, the current is,

$$\frac{m\,E}{R + \frac{m\,r}{n}} = \frac{4 \times 1.2}{4 + \frac{4 \times 3.8}{5}} = .681 + \text{ ampere.}$$

With 4 files and 5 cells in series, $m = 5$ and $n = 4$. Hence the current is,

$$\frac{5 \times 1.2}{4 + \frac{5 \times 3.8}{4}} = .685 + \text{ ampere.}$$

The larger current is therefore supplied by having 4 files with 5 cells in series. Ans. 4 files, with 5 cells in series.

2nd Solution.—The maximum current is supplied when the internal resistance equals the external resistance or when

$$\frac{m\,r}{n} = R.$$

With 5 files and 4 cells in series,

$$\frac{m\,r}{n} = \frac{4 \times 3.8}{5} = 3.04 \text{ ohms},$$

and with 4 files and 5 cells in series,

$$\frac{m\,r}{n} = \frac{5 \times 3.8}{4} = 4.75 \text{ ohms}.$$

The latter value is nearer to 4 ohms, which is the external resistance, than is 3.04, hence the larger current will be supplied with 4 files and 5 cells in series. Ans. 4 files, with 5 cells in series.

Example.—It is desired to pass a current of .025 ampere through an external resistance of 921 ohms. The cells are to be connected in series and each has an E. M. F. of .8 volt and an internal resistance of 1.3 ohms. What number of cells must be used?

Solution.—From page 28, the general formula for cells in series is,

$$I = \frac{n\,E}{R + n\,r}$$

and in this case $I = .025$, $E = .8$, $R = 921$ and $r = 1.3$. Substituting these values gives,

$$.025 = \frac{n\,.8}{921 + n\,1.3}$$

Multiplying by $921 + 1.3\,n$ gives

$$23.025 + .0325\,n = .8\,n$$

Transposing $.0325\,n$ gives

$$.8\,n - .0325\,n = 23.025$$

or $$.7675\,n = 23.025$$

hence, $$n = 30$$

Ans. 30 cells.

EXAMPLES FOR PRACTICE.

1. Ten cells in series have an E. M. F. of 1 volt each and an internal resistance of .2 ohm. The external resistance is 3 ohms. What is the current? Ans. 2 amperes.

2. Six cells, each of which has an E. M. F. of 1.2 volts and a resistance of 2 ohms, are connected in parallel. With an external resistance of 10 ohms, what is the current? Ans. .116 + ampere.

3. What is the current supplied by the same cells if joined in series and the external resistance is 20 ohms?

Ans. .225 ampere.

4. A single cell whose E. M. F. on open circuit is 1.41 volts and whose internal resistance is .5 ohm is supplying a current of .3 ampere. What is the available E. M. F. of the cell?

Ans. 1.26 volts.

5. What would be the available E. M. F. with 8 of the cells referred to in example 4, when connected in series and supplying the same current? Ans. 10.08 volts.

6. Eight Daniell cells (E. M. F. = 1.05, resistance = 2.5 ohms each) are joined in series. Three wires *A*, *B* and *C* of 9, 36 and 72 ohms resistance respectively are arranged to be connected to the poles of the battery. Find the current when each wire is inserted separately, and when all three wires are connected in parallel.

Ans. Through *A*, .29 ampere nearly; through *B*, .15 ampere; through *C*, .091 + ampere; and through all three, .31 + ampere.

7. A battery of 28 Bunsen cells (E. M. F. = 1.8, resistance = .1 ohm each) are to supply current to a circuit having an external resistance of 30 ohms. Find the current (*a*) when all the cells are joined in series, (*b*) when all the cells are in parallel, (*c*) when there are 2 files each having 14 cells in series, (*d*) when there are 7 files each having 4 cells in series.

Ans. (*a*) 1.53 +; (*b*) .06 nearly; (*c*) .82 +; (*d*) .23 + ampere.

QUANTITY, ENERGY AND POWER.

Quantity. The strength of a current is determined by the amount of electricity which passes any cross section of the conductor in a second; that is, current strength expresses the *rate* at which electricity is conducted. The *quantity* of electricity conveyed evidently depends upon the current strength and the time the current continues.

The Coulomb. The coulomb is the unit of quantity and is equal to the amount of electricity which passes any cross-section of the conductor in one second when the current strength is one ampere. If a current of one ampere flows for two seconds, the quantity of electricity delivered is two coulombs, and if two amperes flow for one second the quantity is also two coulombs. With a current of four amperes flowing for three seconds, the quantity delivered is 12 coulombs. The quantity of electricity in coulombs is therefore equal to the current strength in amperes multiplied by the time in seconds, or

$$Q = I \times t$$

where Q is the quantity in coulombs, I the current in amperes and t the time in seconds.

The coulomb is also called the *ampere-second*. The quantity of electricity delivered in one hour when the current is one ampere is called one *ampere-hour*. The ampere-hour is equal to 3,600 coulombs, as it is equal to one ampere for 3,600 seconds.

From the formula $Q = It$, it follows that

$$I = \frac{Q}{t} \text{ and } t = \frac{Q}{I}$$

Example.—A current of 18 amperes flows through a circuit for $2\frac{1}{4}$ hours. What quantity of electricity is delivered?

Solution.—Reducing $2\frac{1}{4}$ hours to seconds gives 8,100 seconds, and $8{,}100 \times 18 = 145{,}800$. Ans. 145,800 coulombs.

Example.—What is the strength of current when $1\frac{1}{2}$ ampere-hours pass in a circuit in 89 seconds?

Solution.—One and one-half ampere-hours equal 5,400 coulombs and as current strength is expressed by quantity divided by time, the current is $5{,}400 \div 89 = 60.+$ amperes.

Ans. $60.+$ amperes.

EXAMPLES FOR PRACTICE.

1. How many coulombs are delivered in 9 minutes, when the current is $17\frac{1}{2}$ amperes? Ans. 9,450 coulombs.

2. What is the current when 480 coulombs are delivered per minute? Ans. 8 amperes.

3. In what time will 72,000 coulombs be delivered when the current is 80 amperes? Ans. 15 minutes.

4. How many ampere-hours pass in a circuit in $2\frac{3}{4}$ hours when the current is 22 amperes? Ans. 60.5 ampere-hours.

Energy. Whenever a current flows, a certain amount of energy is expended, and this may be transformed into heat, or mechanical work, or may produce chemical changes. The unit of mechanical energy is the amount of work performed in raising a mass of one pound through a distance of one foot, and is called the foot-pound. The work done in raising any mass through any height, is found by multiplying the number of pounds in that mass by the number of feet through which it is lifted. Electrical work may be determined in a corresponding manner by the amount of electricity transferred through a difference of potential.

The Joule. The joule is the unit of electrical energy, and is the work performed in transferring one coulomb through a difference of potential of one volt. That is, the unit of electrical energy is equal to the work performed in transferring a unit quantity of electricity through a unit difference of potential. It is evident that if 2 coulombs pass in a circuit and the difference of potential is one volt, the energy expended is 2 joules. Likewise if 1 coulomb passes and the potential difference is 2 volts, then the energy expended is also 2 joules. Therefore, to find the number of joules expended in a circuit, multiply the quantity of electricity by the potential difference through which it is transferred. This is expressed by the formula,

$$W = Q\,E, \text{ or } W = I\,E\,t,$$

where W is the work in joules, Q the quantity in coulombs, E the potential difference in volts, I the current in amperes and t the time in seconds.

By Ohm's law $E = R\,I$ and by substituting this value of E in the equation for energy, we obtain the formula,

$$W = I^2\,R\,t,$$

which may be used when the current, resistance, and time are known, R being the resistance in ohms.

Example.—With a potential difference of 97 volts and a current of 14 amperes, what energy is expended in 20 minutes?

Solution.—Work is expressed by the product of the quantity and potential difference. The time in seconds equals $20 \times 60 = 1200$, and the work $W = 14 \times 1200 \times 97 = 1,629,600$ joules.

Ans. 1,629,600 joules.

Example. — The resistance of a circuit is .9 ohm, and the current is 25 amperes. What energy is expended in half an hour?

Solution.— Substituting these values of resistance, current and time in the formula $W = I^2 R t$, we have, $W = 25^2 \times .9 \times 30 \times 60 = 1,012,500$ joules. Ans. 1,012,500 joules.

Power. Power is the *rate* of doing work, and expresses the amount of work done in a certain time. The horse-power is the unit of mechanical energy, and is equal to 33,000 foot-pounds per minute or 550 foot-pounds per second. A certain amount of work may be done in one hour or two hours, and in stating the work done to be so many foot-pounds or so many joules, the rate at which the work is done is not expressed. Power on the other hand, includes the rate of working.

It is evident that if it is known that a certain amount of work is done in a certain time, the rate at which the work is done, or the power, may be obtained by dividing the work by the time, giving the work done per unit of time.

The Watt. The electrical unit of power is the watt, and is equal to one joule per second, that is, when one joule of work is expended in one second, the power is one watt. If the number of joules expended in a certain time is known, then the power in watts is obtained by dividing the number of joules by the time in seconds. The formulas for the work done in joules as given on the preceding pages are,

$$W = I E t, \text{ and } W = I^2 R t.$$

By dividing each of these by the time t, we obtain the corresponding formulas for power as follows:

$P = I E$, and $P = I^2 R$, where P is the power in watts, I the current in amperes, E the potential difference in volts, and R the resistance in ohms.

The power is obtained therefore, by multiplying the current by the voltage, or by multiplying the square of the current by the resistance.

The watt is sometimes called the *volt-ampere*.

For large units the *kilowatt* is used, and this is equal to 1,000 watts. The common abbreviation for kilowatt is K. W. The *kilowatt-hour* is a unit of energy, and is the energy expended in one hour when the power is one kilowatt.

EXAMPLES FOR PRACTICE.

1. A current of 40 amperes is supplied to a circuit and the voltage is 110. What is the power in watts? Ans. 4400 watts.

2. What is the power in kilowatts supplied to a number of incandescent lamps when the current is 84 amperes and the voltage of the circuit 97? Ans. 8.1+ kilowatts.

3. A circuit has a resistance of 50 ohms and the current is 12 amperes. What power is expended in the circuit?

Ans. 7.2 K. W.

4. The voltage of an incandescent lamp circuit is 220 volts, and the resistance 2 ohms. What power is expended in the circuit? Ans. 24.2 K. W.

NOTE. — First find current by Ohm's law.

Equivalence of Electrical Energy in Heat Units. Whenever there is any resistance to the flow of a current there is always a certain amount of electrical energy transformed into heat. The current in passing through such resistance expends a certain amount of energy in overcoming the resistance, and this energy is dissipated as heat. The entire electrical energy of a circuit may be transformed into heat, as in a lamp circuit, or only part of the energy may appear as heat, the remainder being transformed into mechanical or chemical work. The energy which appears as heat raises the temperature of the circuit to an amount depending upon its radiating surface, and the temperature of the surrounding medium.

When the resistance of a circuit and the current are known, the electrical energy expended may be calculated by finding the product of the square of the current, the resistance, and the time, as by the formula at the foot of page 36. All this energy is transformed into heat. Other work may be done by the current, as would be the case if an electric motor were connected to the circuit, but this requires additional energy to that which is dissipated as heat. The formula referred to gives only the energy lost as heat, which is the total energy when no other work is done.

This formula, which gives the energy in joules, is in accordance with Joule's law, which is as follows:

The number of heat units developed in a conductor is proportional to its resistance, to the square of the current, and to the time the current lasts.

As we have seen, the unit of electrical energy is the joule. The common unit of heat is the calorie, which is the amount of heat necessary to raise the temperature of 1 gram of water through 1 degree Centigrade. By careful investigations it has been found that the joule is equivalent to .24 of a calorie; that is, one joule of electrical energy when transformed into heat is equal to .24 calorie. Electrical energy may therefore be expressed in heat units by multiplying the number of joules by .24; that is,

$$U = I^2 \times R \times t \times .24$$

where U is the heat in calories.

As one joule is equivalent to .24 calorie, it follows that one calorie is equivalent to 4.2 joules approximately.

EXAMPLES FOR PRACTICE.

1. How many calories will be developed by a current of 30 amperes flowing through a resistance of 12 ohms for 10 seconds?

Ans. 25,920 calories.

2. What amount of heat will a current of 20 amperes develop if it flows through a resistance of 80 ohms for 2 seconds?

Ans. 15,360 calories.

Equivalent of Electrical Energy in Mechanical Units. The common unit of mechanical energy is the foot-pound, and from experiment it has been found that one joule is equivalent to .7373 foot-pound; that is, the same amount of heat will be developed by one joule as by .7373 foot-pound of work.

As one horse-power is equal to 550 foot-pounds per second, it follows that this rate of working is equivalent to

$$\frac{550}{.7373} = 746 \text{ joules per second (approx.).}$$

Hence one horse-power is equivalent to 746 watts. Therefore to find the equivalent of mechanical power in electrical power multiply the horse-power by 746, and to find the equivalent of electrical power in mechanical power divide the number of watts by 746.

EXAMPLES FOR PRACTICE.

1. A power of 287 watts is equivalent to how many horse-power? Ans. .38 + H. P.

2. The voltage applied to a circuit is 500 and the current is 196 amperes. What is the equivalent horse-power of the circuit? Ans. 131 + H. P.

3. What is the equivalent of 43 H. P. in kilowatts? Ans. 32 + K. W.

4. How many horse-power approximately are equivalent to one kilowatt? Ans. $1\frac{1}{3}$ H. P.

THE SUPPLY OF ELECTRICAL ENERGY.

Electrical energy is now made use of on such a large scale for lighting, power, heating, etc., that it is generated or produced by machines of great capacity. The dynamo is used for this purpose and machines having a capacity of several thousand kilowatts are now common.

Central Stations. Large central stations or power houses are built at convenient places and here are collected the generating, controlling and measuring apparatus. Usually steam engines or turbines are used to drive the dynamos, and from the latter, large copper mains conduct the current to the switchboard located within the station. Here are assembled all the regulating devices, instruments, and switches for the control of the system. From the switchboard conducting mains run out to various distant points, where the energy is to be used, to the receiving apparatus, such as electric motors, lamps, heating devices, etc. A complete system is therefore made up of three sub-divisions — the generating plant, the conducting mains, and the receiving apparatus.

Isolated Plants. Besides large central stations which occupy one or more entire buildings and which are usually built and designed especially for such purpose, there are the comparatively small and simple plants called isolated power plants. They are purely local systems and supply energy to a single building, or to buildings in the immediate vicinity. The generating apparatus in this case is usually located in the basement of the building.

Large hotels and office buildings are frequently provided with individual generating plants.

Losses in Energy. In operating an electrical machine there is always some loss in energy, that is, the machine does not give out an amount of energy equivalent to the amount it receives. Besides ordinary mechanical losses there is in addition the electrical loss, which always occurs when a current flows through any resistance. This loss as previously explained, is equal to the square of the current multiplied by the resistance.

The ratio of the amount of energy which a machine gives out, to the amount which it receives is called the **commercial efficiency** of the machine. For example, if the commercial efficiency of a dynamo is stated to be 80%, then 20% of the energy given to the dynamo is lost, partly in overcoming friction and partly in electrical losses.

Where electricity is transmitted some distance by means of conducting mains, there takes place a loss in the line due to heating, which is frequently as much as 10%. Also at the receiving station, if the electrical energy is converted into mechanical by means of an electric motor, there will be a further loss.

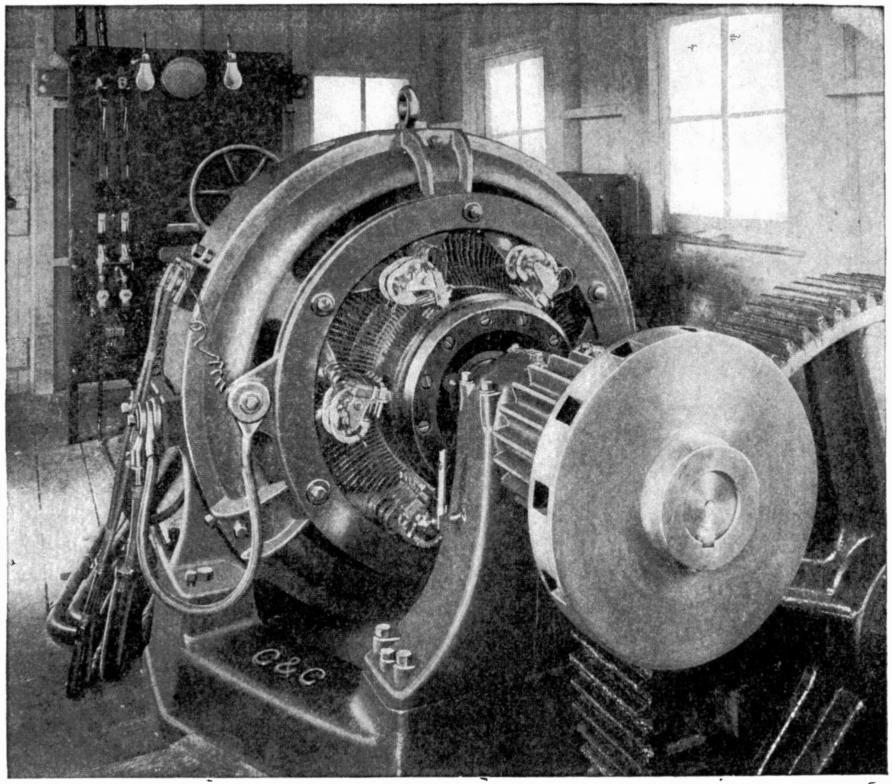
Illustrative Example. For example, suppose it is desired to ascertain the losses in a system which comprises a generator, conducting mains and an electric motor. Suppose the efficiency of the generator is 92% and that 1000 horse-power are imparted to it by the driving engine. The output of the dynamo will be $.92 \times 1000$, or 920 horse-power, and this is equivalent to 920×746, or 686,320 watts. The energy lost in the dynamo will be 80×746, or 59,680 watts. We will assume the voltage of the dynamo and the circuit to be 1000, and as the power in watts is equal to the product of the voltage and current, the current must be $686{,}320 \div 1000$, or 686 amperes approximately.

Now suppose the resistance of the conducting mains is equal to .11 ohms. Knowing the current in the mains and the resistance, the loss therein is obtained by applying the formula $I^2 R$ giving $686^2 \times .11$, or 51,765 watts. The energy available at the receiving end of the line will therefore be $686{,}320 - 51{,}765$, or 634,555 watts.

The remaining loss to be considered is that in the electric motor. Assuming the efficiency of the motor to be 90%, the power lost therein will be .10 × 634,555, or 63,455 watts. The output of the motor is therefore equivalent to 634,555 — 63,455, or 571,100 watts. This in mechanical units is equal to 571,100 ÷ 746, or 765 horse-power approximately.

Hence from an input of 1,000 horse-power at the generating station, the work the motor is capable of performing at the receiving station is 765 horse-power. The efficiency of the entire system under the assumed conditions is therefore 765 ÷ 1,000, or 76.5%.

Among the great variety of generating machines, systems of distribution and auxiliary devices, each has its particular advantage for special conditions, and the selection of the type of machine and system of distribution depends almost entirely upon the special circumstances. For example, a low voltage system is best adapted for isolated plants, whereas for the transmission of power long distances very high voltages are used. The various types of machines, systems, etc., with their special advantages and disadvantages, will be fully considered in the following Instruction Papers.



100 H. P. DOUBLE COMMUTATOR MOTOR WITH SERIES PARALLEL CONTROLLER OPERATING DRY-DOCK PUMP

C. & C. Electric Company

ELECTRICAL MEASUREMENTS

PART I—ELEMENTARY

SYSTEMS OF UNITS

Physical quantities are measured in terms of quantities called units. These units, as a rule, are related to one another and form systems; as, for example, the *British* system and the *C. G. S.* system.

Fundamental Units. The arbitrarily chosen units of a system are called *fundamental* in distinction to the related units depending on them, which are called *derived* units. The C. G. S. system, universally used in electrical measurements, takes its name from three of its fundamental units—the *centimeter*, the *gram*, and the *second of mean solar time.* Besides the three units from which it takes its name, the C. G. S. system includes other fundamental units; for example, the *degree centigrade*, the *calorie*, and the *unit magnetic pole.* Whenever the arbitrary choice of a property of a substance enters into the choice of a unit, the unit itself becomes fundamental. Thus the calorie depends on the thermal capacity of water; the unit magnetic pole depends on the magnetic property of air, etc.

Derived Units. Geometrical units, such as area and volume, are derived from the unit of length. That is, areas are measured in square centimeters, and volumes in cubic centimeters, involving units of the second and third degree with reference to the unit of length. We say that an area has a dimension of 2 and a volume of 3 in terms of a length. Put algebraically, an area may be expressed as L^2, and a volume as L^3 in terms of a length L. In mechanics we use derived units depending on length L, mass M, and time T. Thus velocity, which may be measured by the ratio of length and time, has as dimensions LT^{-1}, and acceleration LT^{-2}. Force is more complicated and may be defined in terms of the acceleration of a mass. The dimensions of force are then LMT^{-2}. The C. G. S. unit of force is called the *dyne.* Work and energy may be measured in terms of force exerted through space, and the unit, equal to one dyne acting through one centimeter, is called the *erg*. The dimensions of the erg are $L^2 M T^{-2}$. In the same way power (time rate of doing work) may be expressed in ergs per second. This unit of power is so small that for practical purposes we use the *watt* which is 10,000,000 ergs per second. Even the watt is small and so we frequently use the *kilowatt* (one thousand watts) for measurement of power. As we shall see later, the watt is used also for the measurement of power for electric circuits. Besides the C. G. S. units we use many units which are multiples or submultiples and so are related. For example, we use the meter (100 centimeters) and the kilometer (100,000 centimeters) and the millimeter (0.1 centimeter). Evidently the meter was intended to be the fundamental unit, the centimeter and the millimeter submultiples, and the kilometer a multiple; but in the C. G. S. system the meter becomes a multiple of the fundamental unit.

In electrical measurements the unit of resistance—the *ohm*—is practically taken as 1,000,000,000 C. G. S. units; the unit of electromotive force (e. m. f.)—the *volt*—is taken as 100,000,000 C. G. S. units; and the unit of current—the *ampere*—is taken as 0.1 C. G. S. unit. These units were originally recommended by a committee of the British Association for the advancement of science in 1873, and were internationally adopted at Paris in 1881. The watt is the practical unit of power and is equal to an e. m. f. of one volt multiplied by a current of one ampere. If the current is constant the product of current and e. m. f. gives the power. If the current is not constant, the average product of current and e. m. f. gives the average power. As we shall see later in the case of alternating currents, the readings of alternating-current voltmeters and ammeters cannot be multiplied together to get the power; but an instrument called a *wattmeter* must be used. The wattmeter gives the correct result. The watt is 10,-000,000, *i. e.*, 10^7 C. G. S. units.

The unit of charge (or quantity)—the *coulomb*—is the quantity of electricity equal to a flow of one ampere for one second. The coulomb is 0.1 C. G. S. unit. The *farad* is the unit of capacity. A condenser has one farad capacity if it can store one coulomb with a potential difference of one volt at its terminals. Potential difference, like e. m. f., is practically measured in volts. At higher potential differences a condenser takes a proportionately higher charge. The farad is a very large capacity and condensers are practically rated in microfarads, *i. e.*, in millionths of a farad. The *henry* is the unit of inductance. When a current is started in a coil of wire a magnetic field is produced. This requires more e. m. f. than to maintain the current when once started. If the coil requires one volt more to increase the current at the rate of one ampere per second than to maintain it, we say the inductance of the coil is one henry. The henry is 1,000,000,000, *i. e.*, 10^9 C. G. S. units. These practical units are all related, as is seen above, to the C. G. S. units by factors, of powers of 10. There are other units in the electro-magnetic system for which the reader is referred to more advanced works.

Relation of C. G. S. to British Units. To reduce British to C. G. S. units and *vice versâ*, we make use of the relations between them. One inch equals 2.54 centimeters; one pound mass equals 453.59 grams mass; and a like relation between pounds weight (force) and grams weight. The second of mean solar time is the same in both systems. It should be kept in mind that for equal quantities the number of units is inversely proportional to the size of the unit.

ELECTRICAL MEASURING APPARATUS

Galvanometers. In the year 1819 Oersted discovered that a current flowing through a conductor produced an effect on a magnet. This effect is now explained by saying that lines of force surround the conductor, and that the north pole of the magnet tends to move along the lines of force in one direction and the south pole in the opposite direction. In other words the magnet, if free to move, tends to take a direction across the conductor. In the case of a long, straight wire the lines of force are circumferences of circles with the conductor at the center. The force on the magnet pole in this case falls off in proportion to the increase in the distance from the center of the conductor; *i. e.*, the force is inversely proportional to the distance. If the magnet is already in a magnetic field, such as that of the earth for instance, a current in a north and south wire above or below the magnet, tends to turn the magnet away from the

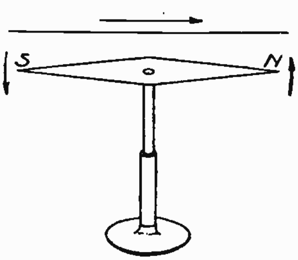


Fig. 1. Oersted's Experiment.

magnetic north and south, the tangent of the angle through which it turns being proportional to the current, Fig. 1. The effect of a single wire is small unless the current is very large.

Tangent Galvanometer. If the conductor is wound in a coil whose plane is north and south and vertical, the effect on a magnet at the center is multiplied many times, Fig. 2. Such an instrument is called a *tangent galvanometer.* If the thumb of the right hand is placed along the outside of the conductor pointing in the direction

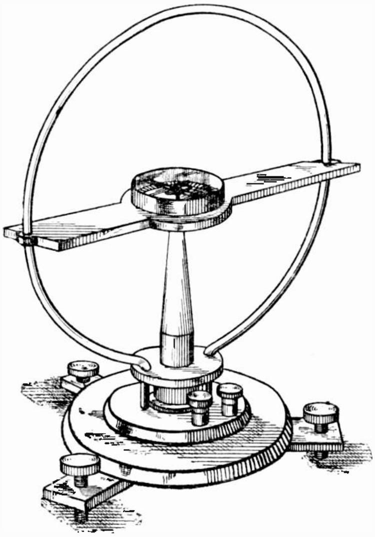


Fig. 2. Tangent Galvanometer.

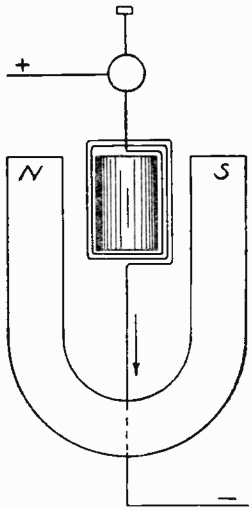


Fig. 3. Diagram of D'Arsonval Galvanometer.

of the current, the fingers of the hand may be curled around the conductor and will point in the direction toward which the north pole of the magnet will be urged by the field produced. A similar arrangement of the left hand will indicate the direction in which the south pole will be urged.

D'Arsonval Galvanometer. If the magnet is fixed and the coil free to turn, the latter will turn in the reverse direction. If the magnet is of the horse-shoe type with the coil of wire between the poles a similar rule will determine the direction of motion. Galvanometers of the moving coil type were invented by D'Arsonval and Deprez, and are usually called *D'Arsonval galvanometers,* Fig. 3.

Astatic Galvanometer. An improvement may be made in the tangent galvanometer, if greater sensitiveness is desired, by mounting on the same support two magnets of nearly but not quite equal strength, care being taken to turn the poles in exactly opposite directions. This is very important. One magnet is placed at the center of the coil through which the current is sent and the other magnet is above or below the coil and influenced relatively little by the current, Fig. 4. The directive action of the earth's magnetic field is little on such a system—called *astatic*—and a small current consequently turns the system more easily from the magnetic meridian. A similar effect is produced if part of the coil is about one magnet and the rest, with reversed direction of the current, about the other magnet. Another way to produce an equivalent effect on a single, suspended magnet is to mount a powerful control magnet near by (above, below, or behind) so as to reduce to a very small amount the magnetic field due to the earth and the control magnet at the center of the coil.

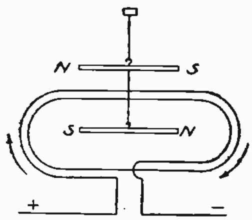


Fig. 4. Astatic System.

An extremely sensitive galvanometer may be made by combining the control magnet with the astatic system of magnets. The magnet (or system of magnets) of tangent and astatic galvanometers is suspended generally either by a fine silk or quartz fiber. The current is led into and out of the coil of the D'Arsonval galvanometer through two wires, both above in the bifilar suspension, one above and one below in the unifilar suspension.

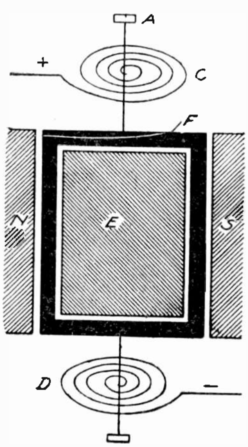


Fig. 5. Section of Suspension of Portable Galvanometer.

Less sensitive galvanometers may have their moving parts mounted on pivots or other bearings, and in such galvanometers of the D'Arsonval type the current is brought in and out through spiral springs which tend to hold the coil in its zero position, Fig. 5. Galvanometers of this type are used for ammeters—to measure amperes of current; or for voltmeters — to measure e. m. f. in volts. Such instruments are provided with some damping arrangement so that they come to rest quickly. The deflection of such galvanometers is indicated by a pointer moving on a scale. If the poles of the magnet are properly shaped the deflection may be made proportional to the current passing.

Mirror Galvanometers. Very sensitive galvanometers must be made with moving parts of little weight. It is, however, very desirable

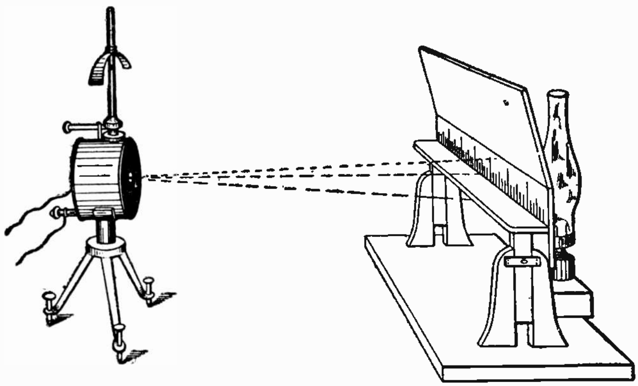


Fig. 6. Thomson Mirror Galvanometer with Lamp and Scale.

that the pointer be very long so that a large number of scale parts may correspond to small deflections. This may be accomplished by using a pencil of light rays for a pointer, as shown in Fig. 6, which illustrates the lamp-and-scale method, in which a lamp is placed behind a slit in a screen on which the scale is mounted. A concave mirror carried on the moving part of the galvanometer focuses an image of the slit at the reference point of the scale (usually the middle). When current passes, the mirror is deflected, thus deflecting the rays of light to another part of the scale. If the mirror turns through 1°, the image is deflected 2°. In place of a slit an opening of another form with cross wires may be substituted. Also if desired the lamp may be mounted at the side, and its light reflected by another mirror to the mirror on the galvanometer. In this last case it is more convenient to have the scale printed on a strip of translucent ground glass or paper, and to view the image through the glass or paper. If a telescope is substituted for the lamp, an image of the reference point of the scale may be made to coincide with the cross wire of the telescope when no current is passing, and other parts of the scale will take the place of the reference point when a deflection is produced, Fig. 7. In this case a plane mirror may take the place of the concave. The telescope-and-scale method is more satisfactory for very sensitive galvanometers than the lamp-and-scale method, though the latter, usually used in a darkened room, is easier on the eyes unless an excellent galvanometer mirror and telescope are used.

Choice of Galvanometers. In choosing a galvanometer for use, it is desirable that the instrument should not be too sensitive for the experiment. As a rule the D'Arsonval galvanometer is the most satisfactory galvanometer for general use, as it is not much affected

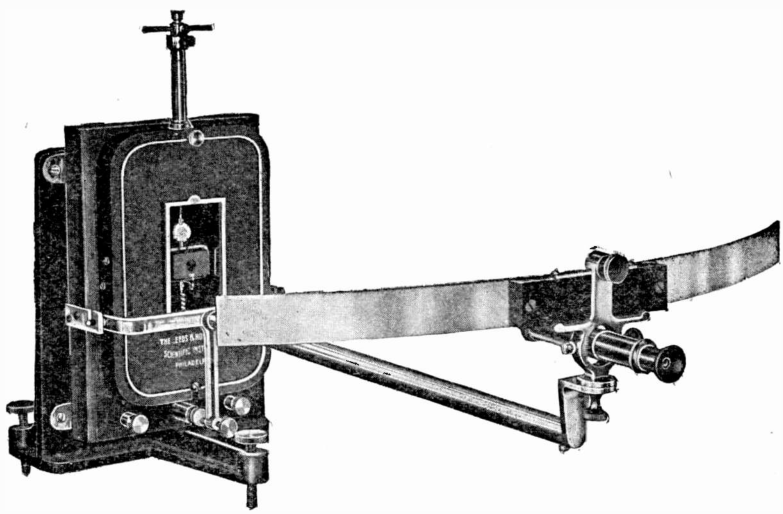


Fig. 7. Ballistic D'Arsonval with Telescope and Scale.

by changes in the magnetic field, even if of as great amount as produced by dynamo-electric machinery or moving of masses of iron in the neighborhood. The astatic galvanometer is, however, as a rule, far more sensitive and for certain purposes must be used.

Use of the Control Magnet. In using astatic or other galvanometers with moving magnets, the use of the control magnet is sometimes very puzzling to beginners. The galvanometer should be set up with its coils in a north and south plane. The mirror then faces to the west (or east sometimes). The control magnet is then placed in position as far away as its support will allow and turned with its north pole to the north. The magnets and the mirror of the galvanometer, as a rule, are somewhat deflected because of the presence of the control magnet. If the latter is slightly turned in one direction, the mirror should turn in the opposite direction. As the control magnet is brought nearer, the period of swing of the mirror should increase, and the sensibility should increase in a greater proportion (as the square). If by chance the control magnet is with its south pole to the north, the mirror will turn in the same direction as the control magnet is turned, and the period of swing will decrease as the control magnet is brought nearer. Control magnets as a rule have the north pole marked in some way, so that there is no need for any mistake. When the control magnet is brought so close that the effect of the earth's field is overcome, the magnets and mirror of the galvanometer will try to turn half way around, thus turning the back of the mirror to the observer, if the construction of the galvanometer will allow. As a rule it does not pay to increase the sensitiveness of the galvanometer to the highest possible limit, as the zero reading will become very easily influenced by slight magnetic changes due to movement of small masses of iron, or the currents in neighboring conductors, or even the variation in the magnetic field due to a cloud cutting the sunlight off from the walls of a red brick laboratory, small as such an effect must be. If the galvanometer is of the astatic type, it is presupposed in the above that the support for the control magnet is arranged to weaken the field of the stronger magnet of the astatic pair more than it does the field of the weaker magnet. In some poorly adjusted galvanometers, the control magnet may produce the contrary result, and it may be necessary to make appropriate allowance. If the magnets of the astatic galvanometer take an east and west position before the control magnet is put on, it is evident that the magnets of the astatic pair are not exactly in opposite directions and that the result is a magnetic system having its effective or resultant north pole about half way between the north poles, and its resultant south pole about half way between the south poles of the two magnets. The line joining these resultant poles lies in the magnetic meridian and the magnets of the astatic pair lie nearly east and west. To correct this error in adjustment is a very delicate matter and should not be attempted by the novice.

Ballistic Galvanometer. When a charge condenser is discharged through a circuit containing a galvanometer, the galvanometer deflects. The period of swing should be long enough for practically the whole charge to pass during the early part of the swing. If the galvanometer has a short period, the return swing may begin before the discharge is complete. It may be assumed that the first deflection is a measure of the quantity discharged; but it is evident that this is an error if the discharge is slow in comparison with the time occupied by the deflection. To be on the safe side the period of swing should be large. Galvanometers which are suitable for measuring discharges are called *ballistic*. Depending on circumstances, their period may be between, say, five and twenty seconds for the complete swing. The D'Arsonval galvanometer may be made with high enough period and sensibility to give satisfaction as a ballistic instrument; but for extreme sensibility an instrument of the astatic type is more generally used. The D'Arsonval galvanometer is more nearly free from the drift of the reference point, which is due mostly to varying magnetic field and somewhat to elastic fatigue or subpermanent set in the suspension. Freedom from drift is very important, as the deflection is uncertain in proportion as the reference point is in doubt.

Damping of Vibrations. The motion of the moving system of a galvanometer may be impeded by damping. This may be accomplished by mounting vanes on the system so that the air in an enclosed chamber impedes the motion, or by electromagnetic damping produced by eddy currents induced in metal moving in a strong magnetic field. In D'Arsonval galvanometers if the coil is wound on a metal frame, currents will be induced in the frame while the coil is in motion. Such damping ensures a speedy coming to rest after a deflection and is very helpful, especially in ballistic galvanometers where certainty of zero is important. It is evident that any damping reduces the sensibility of a galvanometer. Some galvanometers are provided with so much damping that on the return swing the system does not swing past the zero or reference point. Galvanometers without a period of complete vibration are said to be *aperiodic* (the *a* denoting without). As a rule galvanometers have a complete period, that is, they are damped less than the aperiodic galvanometer. The effect of damping is to shorten the time and amplitude of the outward part of the swing (though it lengthens the complete period), and to this extent damping is objectionable. There are, however, counter-balancing advantages and so for most purposes some damping is considered wise.

Plunger Type Instruments If in place of the magnet of a galvanometer, some soft iron is substituted in such a position that the action of the current is to magnetize the soft iron and to draw it into a stronger part of the magnetic field, we have a *current indicator* of the plunger type. The coil frequently takes the form of a solenoid and the soft iron that of a rod which is drawn by the action of the current into the solenoid. The restraining force may be gravitational or that of a spring. Such an instrument is shown in Fig. 8. It is evident that the direction of the deflection does not depend on the direction of the current. In fact, plunger type instruments may be used to measure alternating currents. There are many possible variations of this type of instrument. As the iron has a certain amount of residual magnetization, the deflection with smaller following large currents is more than would have been produced by the same current following a smaller one. For this reason the plunger type of instrument is less reliable than the usual types of galvanometers. The scale is usually of unequal divisions as the pull increases more rapidly than the current.

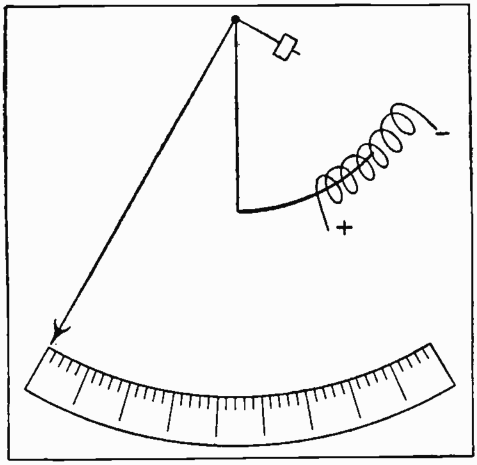


Fig. 8. Diagram of Plunger Instrument.

Electrodynamometers. If the magnet of a galvanometer is replaced by a coil through which the current passes in series with the other coil, we have what is known as an *electrodynamometer*. As in the case of the plunger type instruments, the electrodynamometer deflects in the same direction for all currents unless disturbed by being placed in a magnetic field of outside origin. It is desirable to set up an electrodynamometer with the moving coil (or coils, if more than one) with its axis (or their axes) along the magnetic meridian.

The disturbing effect of a permanent field is negligible when the electrodynamometer is used to measure alternating currents. For direct currents, the action of the outside field is eliminated by reversing the connections. The deflection is approximately proportional to the square of the current. For the best types of electrodynamometers the suspended coil is brought back to its zero position by twisting a torsion head which operates through a spiral spring on the suspended coil. The current in this type of instrument is proportional to the square root of the reading of the torsion head necessary to restore the moving coil to its zero position. A direct current producing the same deflection as an alternating current is said to be the effective value of the alternating current. Fig. 9 illustrates the usual type of electrodynamometer. Fig. 10 illustrates another form invented by Lord Kelvin and called a *Kelvin balance*. The figure shows the connections viewed from the back of the balance. The fixed coil is subdivided into four parts *B*, and the moving coil into two parts *A*, placed symmetrically between the parts of *B*. The parts of *A* are supported on opposite arms of a balance and the balance is restored to its zero position by displacing a weight along the beam.

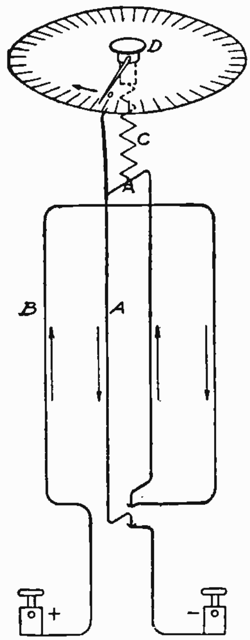


Fig. 9. Electrodynamometer Diagram.

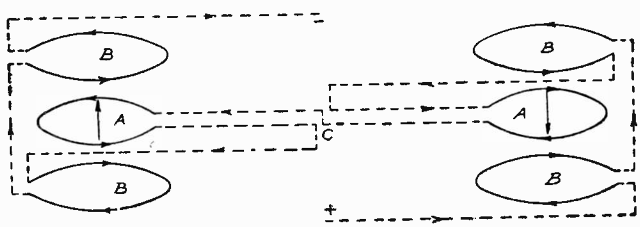


Fig. 10. Diagram of Coils in Kelvin Balance.

The action of the current is thus weighed, and the square of the current is proportional to the distance the weight is moved along the beam. The beam is divided accurately into equal parts and it is possible to obtain the reading with a high degree of accuracy. The current is proportional to the square root of the reading. The effect of dividing the two parts of A is to free the instrument from the disturbing effect of the earth's magnetic field or any other stray field of fairly uniform intensity.

Electrometers. Electrometers depend on the attraction between electrostatic charges of opposite signs. The only electrometer which we shall describe is the *electrostatic voltmeter* which consists of fixed and movable metallic parts of relatively large surface. These surfaces may be plane or curved. The terminals are connected, as a rule, one to the fixed part and the other to the movable part—the vane. These parts take charges proportional to the potential difference between them—e. m. f. applied—and a certain attraction results therefrom. If the vane is allowed to move, the electrostatic capacity of the combination increases somewhat, thus increasing the amount of the charges and the attractive force. If it is desired, the vane may be brought back to its zero position by some counter force. As a rule electrostatic instruments are allowed to deflect and are calibrated by comparison with other forms of voltmeters. More complicated forms of electrostatic instruments may have two sets of fixed surfaces and a movable vane. In some cases a battery of cells of known e. m. f. may be used to charge the fixed surfaces, and the e. m. f. to be measured may be applied between one fixed surface and the vane. Electrostatic voltmeters are generally used to measure high electromotive forces. Fig. 11 shows an electrostatic voltmeter of an old type, which shows

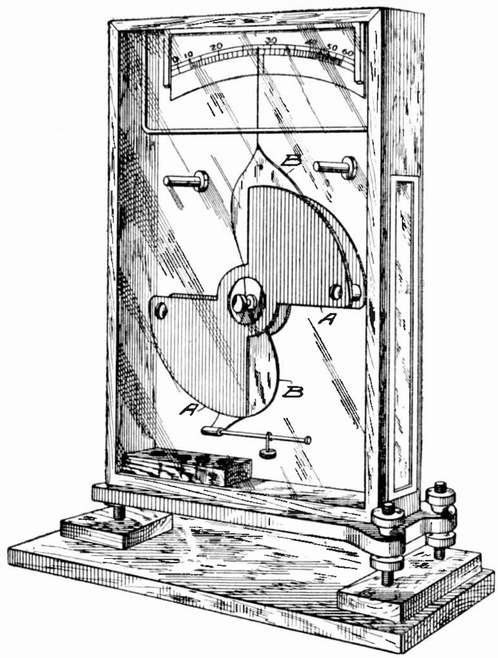


Fig. 11. Electrostatic Voltmeter.

the general scheme more clearly than better and more complicated electrometers.

Hot Wire Instruments. If current passes through a wire, a heating effect results and the wire lengthens because of its rise in temperature. If a pointer is held in a position of equilibrium between turning moments produced by two wires pulling on opposite arms of a lever, the heating of one of these wires by an electric current will produce a change in the position of equilibrium. It is evident that change in the temperature of the room affects both wires alike and produces no change in the zero position. The deflection of a hot wire instrument is dependent on the square of the current (as the heating is proportional to the square of the current). For this reason the hot wire instrument deflects in the same direction for currents in either direction and for alternating currents as well. As the effective value of an alternating current is equal to the square root of the mean square, it is evident that a hot wire instrument calibrated by direct currents, will give proper readings for alternating currents also. Hot wire instruments are made use of as ammeters (low resistance) and voltmeters (high resistance). As a rule hot wire instruments are used for alternating currents. They are usually less accurate than electrodynamometers of the best types.

Wattmeters. We have seen that an electrodynamometer has a turning moment proportional to the square of the current passing through it. If the current passing through the fixed coil is different from that passing through the movable coil, the turning moment will be proportional to the product of these currents. If the power delivered to a line is to be measured, the average product of the volts and amperes gives the result in watts. The current delivered from the line to the load may be passed through one coil (usually of low resistance) whose terminals are A and B, Fig. 12, and the e. m. f. may be applied at the terminals of the other coil (usually of high resistance) whose terminals are a and b, and produce a second current proportional to this e. m. f. In order to avoid measuring the effect of the pressure current it is led backward through coil F shown in dotted line, thus subtracting its effect. The instrument may be calibrated to read watts. As a rule it is easier to make the second coil of moderate resistance and to insert a non-inductively wound high resistance coil R in series. If the wattmeter is to be calibrated by the use of current and e. m. f. in separate circuits, the terminals *i* and *b* are used. The resistance of *S* is equal to that of *F*. The currents in both coils will reverse if the e. m. f. is reversed, but the deflection will be unchanged. The average power of a varying current equals the average product of current and e. m. f.; consequently a wattmeter calibrated with direct currents gives correct results for alternating currents. If the current and e. m. f. are alternating, the mean product will in general be less than the product of the effective values of current and e. m. f. (as measured by A. C. voltmeters and ammeters); consequently when dealing with alternating current and e. m. f. the product must be multiplied by a factor, called the *power factor*, which is usually less than unity, if the correct value is to be computed from ammeter and voltmeter readings. As a rule the power factor is found by dividing the watts as measured by a wattmeter by the product of volts and amperes.

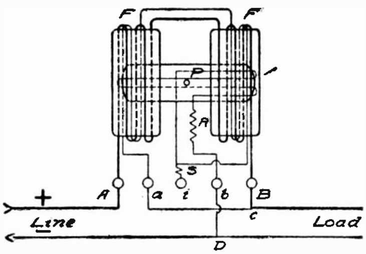


Fig. 12. Diagram of Wattmeter.

Recording Voltmeters and Ammeters. If any of the voltmeters or ammeters described above are arranged with a pen which traces a line on a disk or roll of paper drawn by clockwork past the pen, the instrument will record the variations of e. m. f. or current. There are several good types of recording voltmeters and ammeters on the market. A recording ammeter is shown in Fig. 13.

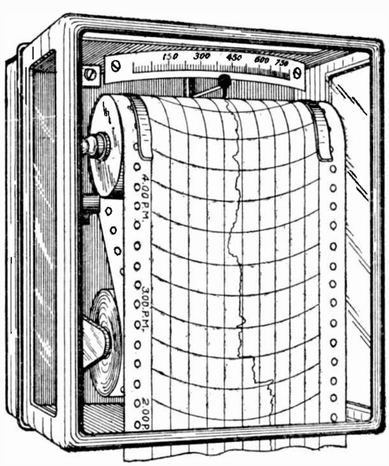


Fig. 13. Recording Ammeter.

Integrating Watt-Hour Meters. Integrating meters show the total consumption of the thing to be measured; for example, integrating gas meters show the consumption of gas in cubic feet. In the same way an integrating watt-hour meter (commonly, though inexactly, called an integrating wattmeter) shows the consumption of energy in watt-hours. Such an instrument is shown in Fig. 14. The instrument is essentially an electric motor geared to a train of wheels moving hands over dials. The speed of the motor is proportional to the power in watts, and the product of the average power and the time in hours (that is, watt-hours) is indicated by the change in the position of the hands on the dial since the last reading. To give correct readings the driving motor must be designed for the circuit on which it is used. The essential factors of the circuit are the e. m. f., maximum current, whether direct or alternating current is used, etc. In a three-wire system a single meter may be designed to measure the power of the two or three circuits involved.

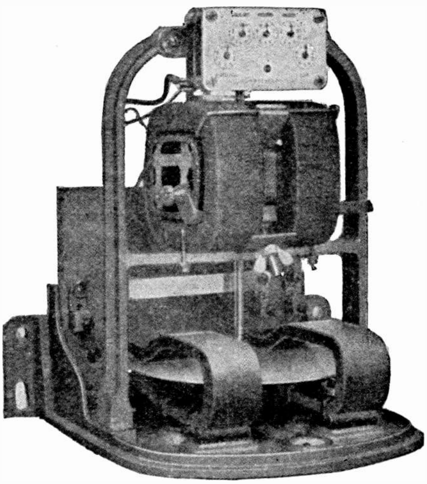


Fig. 14. Watt-Hour Meter.

Integrating Ampere-Hour Meters. An integrating ampere-hour meter (commonly called integrating ammeter) is similar to the watt-hour meter. It is used generally in connection with storage batteries to keep account of the charge and discharge. It is of little general use.

Rheostats and Resistance Coils. The word rheostat means an apparatus for stopping the current. In actual fact it does not wholly stop the current, but only reduces it to a desired extent. Every material interposes some resistance to the flow of an electric current. Substances interposing extremely high resistance are known as insulators, and those interposing relatively little resistance, as conductors. Metals, as a rule, are the best conductors. The metals most used commercially for electrical transmission are copper, aluminum, and iron (or steel). Alloys in general have much higher resistance than the metals of which they are composed. Carbon and solutions of various salts have much higher resistance than metals. Rheostats may be made of any of these materials, but those most generally used are steel wire or sheets, German silver wire or other alloys, carbon rods or plates, and solutions in tanks in which metal plates are immersed, the metal plates being connected to the terminals of the circuit. Such metal plates are known as electrodes. This last arrangement is usually called a *water rheostat*. Pure water has a very high resistance and is never used in water rheostats, but the resistance may be reduced as desired by dissolving salt in the water. The metal plates are usually arranged so that one electrode may be brought nearer the other when it is desired to increase the current. When the word rheostat is used, it is generally understood that the resistance is not exactly known. A rheostat is shown in Fig. 15.

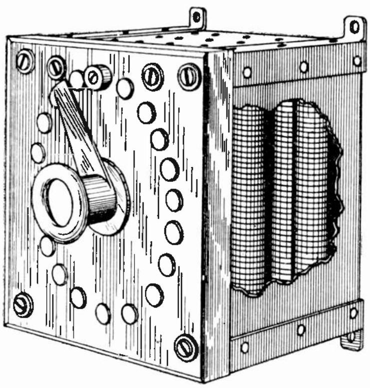


Fig. 15. Rheostat for Varying the Current in Any Circuit.

When it is desired that the resistance have a certain exact value, metals are the only practical materials to use. Coils of wire exactly adjusted are called *resistance coils*. They are adjusted to certain values in ohms. For very low resistances, *e. g.*, small fractions of an ohm, metal strips may be used. As most pure metals increase their resistance with increase of temperature by about 0.4% per degree centigrade, resistance coils are almost always made of certain alloys which change little in resistance with change in temperature. One alloy in particular, manganin, changes so little in resistance with change in temperature that it is usually chosen for standard *resistance* coils. Figs. 16 and 17 show standard resistances in the form of a coil and a strip. As mentioned above alloys have relatively high resistance and for this reason also the alloy manganin is preferable to any pure metal for resistances.

Lamp Rheostats. A very convenient form of carbon rheostat is a bank of incandescent lamps. The usual 16 c. p. lamp for a 110-volt circuit has a resistance when hot of about 220 ohms. Its resistance when cold is about twice as much. Carbon and solutions, unlike metals, are better conductors when hot than cold. It is evident that incandescent lamps, because of their change in resistance from cold to hot, are not suitable for standard resistances. If two lamps are arranged in series, *i. e.*, if the current is made to pass through one after the other, the resistance of the combination is twice that of a single lamp. On the other hand if the lamps are connected in parallel, *i. e.*, if the current divides between them, the resistance of the combination is only half of that of a single lamp. This result is evident as the same e.m.f. produces twice as much current in two lamps as in a single one. In the same way ten lamps in parallel have a combined resistance only one-tenth as much as a single lamp.

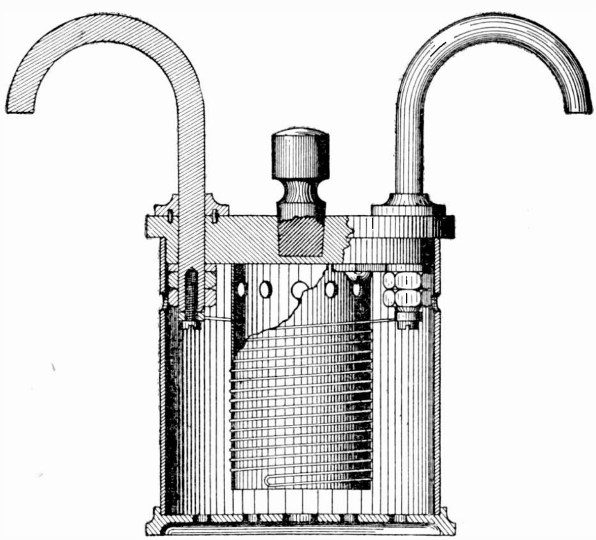


Fig. 16. A Standard Resistance Coil.

Multiplying Power of Shunts. The word shunt is the British name for a side track (or as we would call it, switch) on a railway. Any electrical side path is called a shunt. If the current has two or more paths in parallel offered to it, the current divides in inverse proportion to the resistance or, as more simply expressed, in direct proportion to the conductivity of the various paths. Thus if a galvanometer has a shunt across its terminals whose resistance is one-ninth of that of the galvanometer, nine times as much current will go through the shunt as through the galvanometer and consequently only one-tenth of the current will go through the latter. The total current is then ten times the current through the galvanometer and we

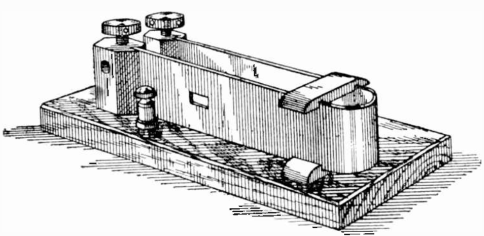


Fig. 17. A Standard Resistance Strip.

say that the multiplying power of the shunt is ten. If the galvanometer has a shunt of one ninety-ninth of the former's resistance, one one-hundredth of the current will pass through the galvanometer and the multiplying power of the shunt will be one hundred. In general, if the resistance of the shunt is $\frac{1}{m-1}$ of that of the galvanometer, the multiplying power of the shunt will be m. The evident effect of the shunt is to reduce the resistance of the galvanometer circuit to $\frac{1}{m}$ of its former value, *i. e.*, to $\frac{1}{m}$ of the resistance of the galvanometer itself; the resulting fall of potential over the galvanometer and shunt is, therefore, only $\frac{1}{m}$ as much as if the shunt were not there. Galvanometers are provided by their makers, if desired, with shunts having a multiplying power of 10, 100, and 1,000, marked to go with the particular galvanometer. It is evident that the usual shunt cannot be used with other galvanometers without recalculation of its multiplying power, which under such circumstances would probably be some inconvenient number.

Professor Ayrton has devised a form of shunt box with extra resistance which is automatically connected in series in proper amount to keep the total resistance constant but allowing only $\frac{1}{10}$, $\frac{1}{100}$, or $\frac{1}{1000}$ of the current to pass through the galvanometer.

OHM'S LAW

In 1827, Dr. G. S. Ohm of Berlin published a treatise, now famous, entitled *The Galvanic Circuit Investigated Mathematically*, in which he announced the fundamental law of electric circuits now known as Ohm's law. This is usually stated in the algebraic formula:

$$I = \frac{E}{R}$$

In words, the current (in amperes) equals the e. m. f. (in volts) divided by the resistance (in ohms). It is truly a surprising fact that the resistance of an electric circuit is a constant not dependent on the current passing. Many experimenters have tried in vain to find any inaccuracy in Ohm's law. If any two of the three quantities involved are known, the third may be found by solving the equation. Thus,

$$I = \frac{E}{R},\ R = \frac{E}{I},\ \text{and}\ E = I\,R$$

As will be seen later, one of the most convenient methods of measuring low resistances, as of a dynamo armature, is a simple application of Ohm's law.

MEASUREMENT OF RESISTANCE

Resistance Boxes. Measurement of resistance is made by comparison with certain standards of known resistance, the different methods of measurement varying to a great degree. The standard resistance coils are made of such alloys as manganin—an alloy of manganese copper and nickel—which has a high specific resistance and changes its resistance with rise in temperature to a much less extent than other metals. It is of course desirable that this change should be as small as possible. The size and length of the coils are such that they have resistances of a definite number of ohms at a certain temperature. The coils are insulated with silk or paraffined cotton and are very carefully wound. Each wire is doubled on itself before being coiled up, and then wound as shown at A and B in Fig. 18; or, as is sometimes preferred, the wire may be wound single in layers, the direction of winding being reversed for alternate layers. Inductance and capacity effects are by these means reduced to a minimum. The ends of the coils are soldered to brass pieces as C, D, E. Removable conical plugs F and G of brass are made to fit accurately between the brass pieces. When these are inserted as shown, the coils will be short circuited and a current will pass directly through C, F, D, G, and E without going through the coils. If F is withdrawn the coil A will then be inserted in the circuit; if G is also withdrawn then coils A and B will both be inserted, as the current cannot pass from C to E without going through the coils.

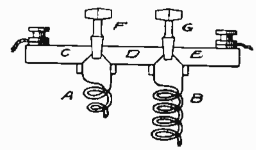


Fig. 18. Resistance Box Coils Showing Non-inductive Winding.

Resistance boxes are constructed consisting of a large number of resistance coils, and of such resistances that by withdrawing plugs varying resistances may be built up. A common form of resistance box has coils of the following ohms resistance: 1, 2, 2, 5, 10, 20, 20, 50, 100, 200, 200, 500, 1,000, 2,000. A resistance of 497 ohms could be made up by withdrawing plugs corresponding to the coils 200 + 200 + 50 + 20 + 20 + 5 + 2 = 497, or 768 by coils 500 + 200 + 50 + 10 + 5 + 2 + 1 = 768.

Resistance by Substitution. By Ohm's law the greater the resistance inserted in a circuit the less becomes the current, provided the e. m. f. remains constant. This gives us a simple although not very accurate method of measuring electrical resistance. If a battery of constant e. m. f., the unknown resistance, and a simple galvanometer are connected in series, the strength of the current passing will be indicated by the latter. Suppose the unknown resistance to be replaced by known resistances, enough resistance coils being inserted so that the deflection of the galvanometer needle is the same as when the unknown resistance was in circuit. The current will then be the same, and as the e. m. f. remains unchanged, the resistances must be equal in each case. The sum of the known resistance coils inserted will then be equal to the unknown resistance.

The advantages of this method are that it is rapid, and that only crude apparatus is required, as the galvanometer and resistance box can be very simple in form. The resistance of the battery and galvanometer should be but a few ohms, otherwise small resistances cannot be measured closely. Only small currents should be used so that the error from heating may be negligible.

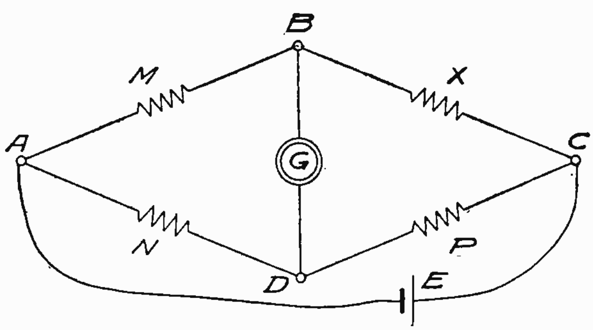


Fig. 19. Theoretical Diagram of a Wheatstone's Bridge.

Wheatstone's Bridge. All ordinary measurements of resistance are usually made by use of a Wheatstone's bridge.

The principles of this instrument will be understood from Fig. 19. There are four arms to the bridge with the resistances M, N, X, and P. From the points of junction A and C, wires connect with a battery E. A galvanometer G is connected between the junction points B and D. The current from the battery divides at A and passes through the resistances M and X, and N and P, uniting again at C. The fall of potential between A and C must of course be the same in amount through the resistances M and X as through N and P. If no current passes through the galvanometer then the points B and D will be at the same potential, and there will be the same fall of potential in the resistances M and N, and in the resistances X and P. Under these circumstances the ratio of the resistances of M to N will be the same as X to P, or

$$\frac{M}{N} = \frac{X}{P}.$$

If M, N, and P are known resistances, the resistance of X is readily found by the formula,

$$X = \frac{M}{N} \times P$$

The method of using the bridge will be better understood from Fig. 20. The bridge arm M has coils of 1, 10, 100 ohms resistance, and arm N, coils 10, 100, 1,000. The series of coils P for obtaining a balance usually has resistances of 1, 2, 2, 5, 10, 20, 20, 50, 100, 200, 200, 500, 1,000, 2,000 ohms, but coils up to 100 only are shown. There is a key K in the galvanometer circuit and a key H in the battery circuit. The battery key H should always be closed *before* the galvanometer key K, and should be kept closed until after K is opened. This not only insures steadiness in all currents when the galvanometer circuit is closed, but also protects the galvanometer from self-induction currents which would occur if the battery circuit were closed after that of the galvanometer. A double successive contact key, Fig. 21, may with advantage be substituted for the two single keys, thus insuring that the battery and galvanometer branches will be closed and opened in the proper se-

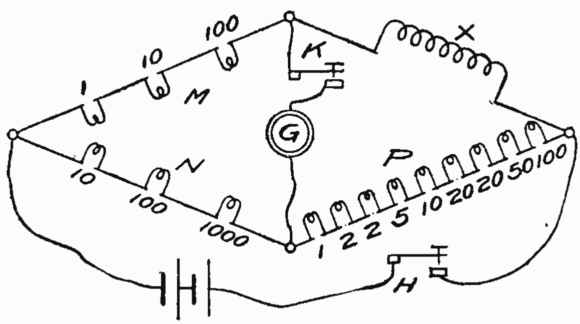


Fig. 20. Diagram Showing Method of Making Bridge Measurements.

quence. A reflecting galvanometer is used for accurate measurement

In making a measurement of an unknown resistance it is first necessary to gain a knowledge of its approximate resistance. For this purpose the 100-ohm plug is withdrawn from both arms *M* and *N*, the unknown resistance being connected at *X*. The ratios of *M* to *N* will then be unity, and hence for a balance the number of ohms required in the resistance coils *P* will be the same as the resistance *X*. The 1,000-ohm plug in *P* should first be drawn and the keys depressed in their proper order for an instant only. The galvanometer needle or mirror, as seen by the light reflected on the

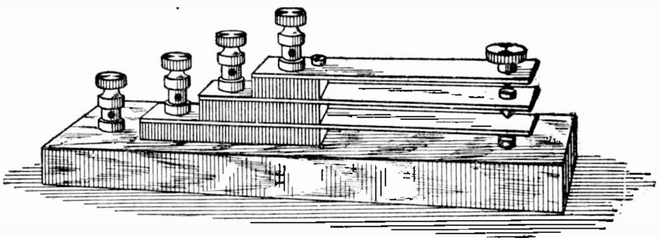


Fig. 24. 4-Point Contact Key.

scale, is deflected—say to the right, and the resistance is probably too large. The plug is replaced and the 1-ohm coil withdrawn. On depressing the keys suppose the spot of light is deflected to the left. Then the 1 ohm is too small and the 1,000 ohms too large; also in this case deflections to the right mean that the resistance inserted is too large, and to the left, that the resistance inserted is too small. The 1-ohm plug is now replaced, and 500, 200, etc., are successively tried until it is found that 12 ohms is too large and 11 ohms too small, that is, the unknown resistance is between 11 and 12 ohms.

Suppose that it is desired to find the correct value of the unknown resistance to the second place of decimals. The ratio of the arms *M* to *N* must then be changed so that the resistance coils *P* will have a value of between 1,100 and 1,200 ohms when a balance is obtained. The ratio of *X* to *P* will then be 11 to 1,100 approximately, or about 1 to 100. To obtain a balance the ratio of the arms *M* to *N* must also be 1 to 100. Hence the 100-ohm plugs first withdrawn are replaced and the 10-ohm plug withdrawn from *M* and the 1,000-ohm plug from *N* giving the required ratio. The same ratio could be obtained by withdrawing the 1-ohm plug in *M* and the 100-ohm plug in *N*.

The bridge is now arranged for the final measurement. As the resistance in P will now be over 1,100 ohms, the 1,000- and 100-ohm plugs are first removed. Suppose the 50-ohm plug to be also removed, and a deflection to the right shows that this is too great. The plug is replaced and 20 withdrawn, which proves to be too small. The next twenty plug is also withdrawn and a deflection to the left shows the resistance to be still too small. The 5-, 2-, and 2-ohm plugs are

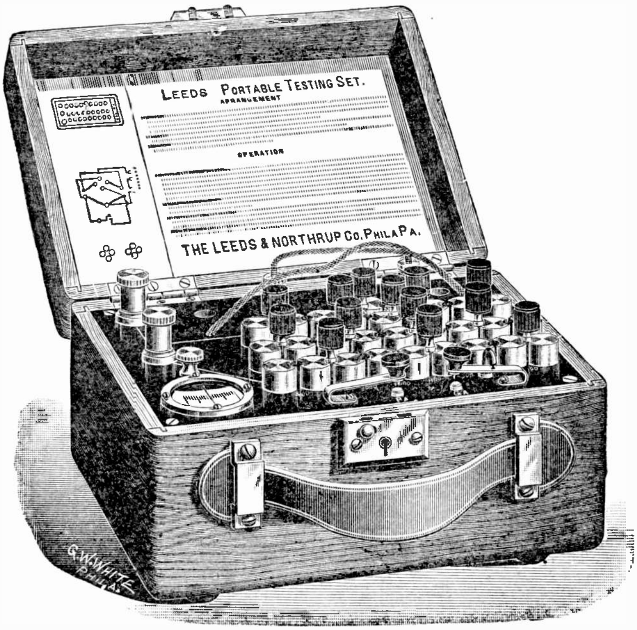


Fig. 22. Portable Testing Set.

successively withdrawn, the last two ohms proving to be too great. This is replaced and the 1-ohm plug withdrawn, and suppose no deflection is then obtained. The total number of ohms in P is now $1{,}000 + 100 + 20 + 20 + 5 + 2 + 1 = 1{,}148$. The value of X is therefore $\frac{10}{1000} \times 1{,}148 = 11.48$ ohms.

The above example illustrates the general method of using the bridge. Usually the resistance to be measured is known approximately and the required ratio between M and N can be determined without making a preliminary measurement. The possible changes in the ratio between M and N gives the bridge a great range of measurement. When M is 1 and N is 1,000 ohms, measurements of resistance as small as .001 ohm may be made. Bridges are usually arranged with a reversing key so that M and N may be interchanged, hence M could be 1,000 and N 1, and measurements of resistance as high as 4,110,000 ohms could be made with the bridge we have considered.

Portable Testing Set. There are many different varieties of bridges and their form always differs from that of the diagrams in Figs. 19 and 21. A portable testing set including Wheatstone's bridge, galvanometer, battery, and keys, is illustrated in Fig. 22. The rheostat of the bridge is made up of coils, 16 in number, of denominations 1, 2, 3, 4, 10, 20, 30, 40, 100, 200, 300, 400, 1,000, 2,000, 3,000, 4,000 ohms—11,110 ohms in all. Bridge coils are 1. 10, and 100 on one side and 10, 100, and 1,000 on the other. A reversing key admits of any ratio being obtained in either direction so that the range of the set is from .001 to 11,110,000 ohms. It is, however, impossible to construct a portable galvanometer of sufficient sensitiveness for these measurements, and the actual limits are from .001 ohm to 300,000 or 400,000 ohms.

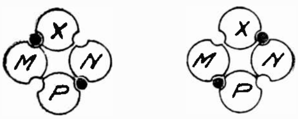


Fig. 23. Reversing Keys.

The reversing key, shown in Fig. 23, consists of the blocks M, N, P, and X and two plugs which must both lie on one diagonal or the other. The blocks are connected with the resistances indicated by their letters. In the left-hand figure M is connected with X and N with P, and the bridge arms have the relation

$$\frac{M}{N} = \frac{X}{P}, \text{ or } X = \frac{M}{N} \times P$$

In the right-hand figure M is connected with P and N with X, the bridge arms then having the relation

$$\frac{M}{N} = \frac{P}{X}, \text{ or } X = \frac{N}{M} \times P$$

The advantages of having a reversing key in the bridge arms are: the increase in range obtained, six coils being made to do the work of eight, and also that any error in the initial adjustment of the bridge arms can be detected by having the two arms equal, balancing and reversing. Unless the resistance of the coils inserted in M and N are exactly equal, the system will be unbalanced after reversing.

The galvanometer, the needle and scale of which are shown at the left in Fig. 22, is of the D'Arsonval type, and the coil is mounted in jewels. As this galvanometer is not affected by external magnetic fields or electric currents, it is suitable for dynamo or shop testing. The key for the galvanometer circuit is shown in front at the right.

The battery is made up of chloride of silver cells mounted in the bottom of the box. The cells will last a number of months even with daily use. Flexible connecting cords, running from the cells, have their terminal sockets combined with small binding posts so that connection may be made to an extra battery or other source of e. m. f. if desired. The left-hand key controls the battery circuit.

A plan of the connections of this testing set is shown in Fig. 24. The two lower rows of coils (marked 1 to 4,000) are connected beneath the top at the right by a heavy copper rod and constitute the rheostat arm, or what corresponds to P in the formula. By withdrawing the proper plugs in these rows any number of ohms from 1 to 11,110 may be obtained. The upper row of coils consists of the two bridge arms, M at the left and N at the right, with the reversing key between them. The two extremes of the upper row are joined by a heavy copper connection and correspond to the point A in Fig. 19. The upper block X of the reversing key is connected with the binding post B, the block P is joined to the left of the middle row of coils while the other end of the rheostat combination is connected with the binding post C. The resistance to be measured X is connected between the terminals B and C.

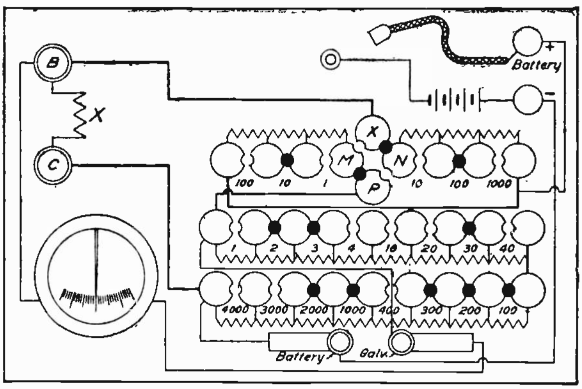


Fig. 24. Diagram of a Testing Set.

Example. Suppose a balance is obtained with an unknown resistance connected between B and C, when the plugs are withdrawn as shown in Fig. 24. What is the value of the unknown resistance?

Solution. The reversing key is arranged so that M is connected with P and N with X, hence

$$\frac{M}{N} = \frac{P}{X}, \text{ or } X = \frac{N}{M} \times P$$

In the figure $N = 100$, $M = 10$, and $P = 2{,}000 + 1{,}000 + 300 + 200 + 100 + 30 + 3 + 2 = 3{,}635$. Therefore

$$X = \frac{100}{10} \times 3{,}635 = 36{,}350 \text{ ohms}$$

Ans. 36,350 ohms.

Use and Care of Bridge. Before beginning a measurement it is essential that each plug be examined to see that it is firmly twisted into place, also in replacing a plug the same care should be used. A slight looseness will considerably increase the contact resistance and so introduce errors in the result. Moderate force only is needed in placing plugs. A strong person may damage the apparatus. For the same reason the plug tapers should be kept clean and the top of the bridge should be free from dust and moisture. Special care should be taken with the surfaces between adjacent blocks. The plugs should be handled only by their vulcanite tops, and care should be taken not to touch the blocks.

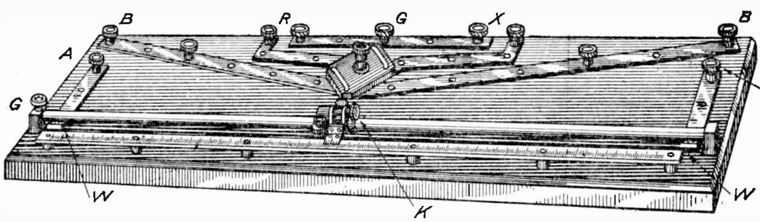


Fig. 25. Slide Wire Wheatstone's Bridge.

The plug tapers may be cleaned with a cloth moistened with alcohol and then rubbed with powdered chalk or whiting. The powder should be entirely removed with a clean cloth before the plugs are replaced. Sand paper or emery cloth should never be used to clean the plugs or bridge blocks. If there are no idle sockets for the reception of the plugs when they are withdrawn, they should be stood on end or placed on a clean surface.

Slide Wire Bridge. The simplest form of Wheatstone's bridge is the slide wire bridge. Fig. 25 illustrates the apparatus. The foundation of the bridge is a board well braced to avoid warping, which, after being well dried, is saturated with hot paraffin to make it a good insulator. The bridge wire is usually one meter long and stretched between substantial anchorages at the ends. Heavy straps of copper or brass serve as connections of negligible resistance to the other parts of the bridge. The known resistance is inserted at R and the unknown at X. Openings at A and A' are closed by heavy metal straps for the usual method of use, or in more complete methods by resistances which are, in effect, extensions of the bridge wire. The battery and its key are connected between B and B, and the galvanometer between G and G. The heavy rod back of and above the bridge wire is a support for the galvanometer key K and the index which is adjacent to the meter scale shown. The key and the index may be moved along the rod to find the balancing point. A commutator shown at the center of the apparatus serves to exchange the relative position of X and R in the arrangement. The commutator makes connection in four mercury cups. If the portion of the bridge wire to the left of the galvanometer key is a cm. long, the rest of the wire is 100-a long. If the commutator is arranged so that R is connected to the left end and X to the right end of the wire, when a balance is reached we have

$$\frac{R}{X} = \frac{a}{100 - a}, \text{ or } X = R\,\frac{100 - a}{a}$$

If the commutator is reversed and the new reading is a' we get

$$X = R\,\frac{a'}{100 - a'}$$

If the balancing point is near the end of the wire, it is evident that any small error in the reading and the assumption that the connections are of negligible resistance, will result in greater error in the final formula. For this reason it is well to treat the first balance as only approximate and after calculating X to take as known resistance a new value of R as nearly as possible equal to X. In this way the balancing point will be brought near the center of the wire.

For very exact comparison of two nearly equal resistances, we insert auxiliary resistances at A and A'. These are in effect extensions of the bridge wire. Call these resistances equal to A and A' cm. of the wire. When a balance is obtained at the points a and a' for the two positions of the commutator, we have

$$X = R\frac{A' + 100 - a}{A + a} \text{ and } X' = R\frac{A + a'}{A' + 100 - a'}$$

While it is still of advantage under these conditions to have a and a' somewhere near 50 cm. it is no longer necessary, for with the bridge wire extended by A and A' any point of the actual bridge wire is now near the center.

If R is materially larger or smaller than X, the balancing point may be beyond the end of the actual wire, *i. e.*, in one of the extensions, and no balance can be obtained. It is necessary then to adjust R until a balancing point is found on the wire. We may then proceed with the experiment.

A variation of this method, known as the *Carey-Foster method*, is used for the comparison of two standard resistances to discover small differences in adjustment.

Example. If with the openings A and A' closed with straps of negligible resistance and a resistance of 150 ohms for R, the mean balance point comes so that a = 68.4 cm. and b = 31.6 cm., what is the value of X? Ans. 69.3 ohms.

Example. If A and A' are equivalent to 500 cm. each, and R = 150 ohms, and the mean balance point makes a = 68.4 cm., and b= 31.6 cm., what is the value of X? Ans. 140.29 ohms.

Low Resistance Measurement. The bridge methods described above are not suitable to use in the measurement of small resistances, for the *lead* wires (*leading in* wires) used in connecting the unknown resistance to the *bridge* may have more resistance than the unknown. The *ammeter-voltmeter method* is that most generally used. The apparatus is connected as shown in Fig. 26. The current from the battery is led through the ammeter to the unknown low resistance R. An adjustable resistance r of a rheostat may be introduced into the circuit to control the current. The actual resistance r need not be known. The fall of potential V through R is measured by the voltmeter, and the current I by the ammeter. Ohm's law then gives

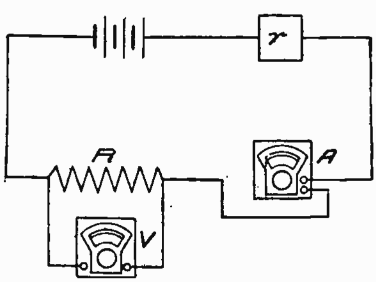


Fig. 26. Ammeter-Voltmeter Method of Low Resistance Measurement.

$$R = \frac{E}{I}$$

Ammeter-Voltmeter Method. It is evident that although the voltmeter is of very high resistance, a small current included in that measured by the ammeter passes through the voltmeter. In strictness this current, equal to $\frac{V}{\text{resistance of the voltmeter}}$, should be subtracted from the ammeter reading to get the value of I to be used in the formula. This correction is easily made, as all makers of voltmeters give the value of the resistance, usually marked on the voltmeter case; but the error resulting from neglecting the correction is generally immaterial. Instruments of suitable range should be used.

Example. The reading of the ammeter is 50 amperes, that of the voltmeter 1.5 volts; what is R? Ans. 0.03 ohm.

In the particular case chosen the ammeter had a range 0 to 75 amperes, and the voltmeter 0 to 3 volts. The resistance of the voltmeter was 300 ohms. The current through the voltmeter was 1.5 ÷ 300 = 0.005 amperes. It is evident that the correction is far smaller than the probable error of reading the ammeter, and any attempt at correction would be absurd.

This method may also be used to measure the resistance of a burning incandescent lamp. In such a case the bridge method is useless as the resistance of a cold lamp is probably double its resistance when hot.

Example. The voltmeter, 0 to 150 volts range and resistance 15,000 ohms, reads 110 volts; the ammeter, 0 to 1 amperes range, reads 0.5 ampere. What is the resistance R? Ans. 220 ohms.

High Resistance Measurement. *Direct Deflection Method.* An excellent method of measuring resistances of one megohm (one million ohms) or more, is the direct deflection method. The main instruments needed are a sensitive galvanometer, usually of high resistance and fitted with appropriate shunts; some standard resistances of 100,000 ohms (0.1 megohm) or more; and a battery of relatively low resistance and constant e. m. f. (a storage battery of many cells, if available). The resistance of the galvanometer both alone and combined with its shunts must be known. That of the battery and the connections is usually neglected. The connections are shown in

Fig. 27. The known resistance R is first connected in series with the galvanometer G and the testing battery B, through a key K. Care should be taken that the insulation of the apparatus be very high. The shunt S is adjusted to give a suitable deflection of the galvanometer and from this deflection what is known as the *constant* is calculated. The value of this constant is the resistance that must be inserted in the circuit to reduce the deflection to one scale division. The value of the constant is therefore equal to the product of the total resistance, assumed to be $R + \frac{G}{m}$, the scale deflection d, and the multiplying power of the shunt m. We thus get

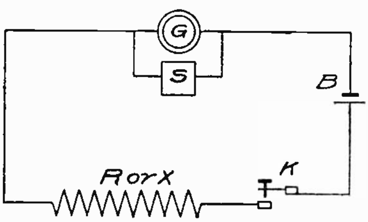


Fig. 27. Direct-Deflection Method of High Resistance Measurement.

$$\text{Constant} = \left(R + \frac{G}{m}\right) d\, m$$

As an illustration, suppose $R = 0.1$ megohm, $G = 20{,}000$ ohms $= 0.02$ megohm, $m = 1{,}000$, and $d = 200$ divisions; then

$$\text{Constant} = (0.1 + 0.00002) \times 200 \times 1{,}000$$
$$= 20{,}004 \text{ megohms}$$

This means that if the galvanometer were unshunted and the total resistance in the circuit were 20,004 megohms, a deflection of one division would result.

After the constant has been determined the known resistance R is replaced by the unknown resistance X. The galvanometer shunt is readjusted if necessary and the deflection obtained is again noted. The value of the total resistance is then found by dividing the value of the constant by the product of the deflection d_1 and the multiplying power m_1 of the shunt used. To continue our illustration suppose $d_1 = 50$ divisions, and $m_1 = 10$. The deflection, if the full current went through the galvanometer, would be $50 \times 10 = 500$ divisions. A deflection of one division is produced with a resistance of 20,004 megohms; hence a deflection of 500 divisions must correspond to $\frac{1}{500}$ of this, or 40.008 megohms. Subtracting the resistance of the shunted galvanometer $20{,}000 \div 10 = 2{,}000$ ohms, or 0.002 megohm, leaves the unknown resistance 40.006 megohms. The algebraic equation expressing this is

$$X = \frac{\left(R + \frac{G}{m}\right) d\, m}{d_1\, m_1} - \frac{G}{m_1} = 40.006 \text{ megohms}$$

Neglecting the resistance of the galvanometer in both cases, a simpler formula would give

$$X = \frac{R\, d\, m}{d_1\, m_1} = 40 \text{ megohms}$$

It may be noted that the difference between these results is an amount corresponding to a difference in deflection of 0.0075 of a single scale division, which is far smaller than the probable error which any observer would make. It is then clearly permissible to use the simpler formula,

$$X = \frac{R\, d\, m}{d_1\, m_1}$$

Example. In a high resistance measurement by the above method the known resistance was .2 megohms, and gave a deflection of 237 divisions, the multiplying power of the shunt being 100. With the unknown resistance inserted, the deflection was 178 divisions with the full current passing through the galvanometer. What was the value of this resistance? Ans. 26.6 megohms.

Voltmeter Method. Another method of measuring high resistance is that in which a sensitive high resistance voltmeter such as the Weston is used. This method, however, is not as accurate as the preceding and is not adapted to measurements of resistance greater than a few megohms. The voltmeter is connected in series with the unknown resistance and a source of constant e. m. f., as shown in Fig. 28. With such an arrangement the resistance X will be to the resistance of the voltmeter R, as the volts drop in X is to that in the voltmeter. The drop v in the voltmeter is given by its reading, and if the applied electromotive force V is known, the drop in X will be $V - v$. We therefore have the proportion,

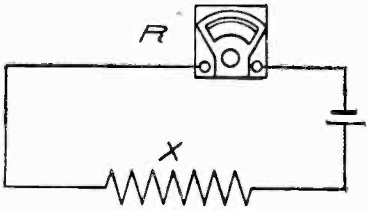


Fig. 28. Voltmeter Method of High Resistance Measurement.

$$X : R :: V - v : v, \text{ and}$$

$$X = \frac{V - v}{v} \times R$$

The voltage V, which should be at least 100, may be first determined by measurement with the voltmeter.

Example. A voltmeter having a resistance of 15,000 ohms, was connected in series with an unknown resistance. The e. m. f. applied to the circuit was 110 volts and the voltmeter indicated 6 volts. What was the value of the unknown resistance?

Solution. Applying the preceding formula

$$V = 110, v = 6, \text{ and } R = 15{,}000,$$

therefore

$$X = \frac{110-6}{6} \times 15{,}000 = 260{,}000 \text{ ohms, or } .26 \text{ megohms}$$

Ans. .26 megohms.

Insulation Resistance. The measurement of insulation resistance is performed by either of the two preceding methods of measuring high resistance. The voltmeter method is the simpler, but since it cannot be used to measure resistances greater than a few megohms, the direct deflection method proves to be the more valuable. The insulation of low potential circuits, however, need not exceed five megohms, and in testing such circuits the voltmeter method may be used. If little or no deflection is obtained it is then evident that the insulation is at least several megohms, which is all that is desired. As the insulation of high potential circuits must be greater than five or ten megohms, the direct deflection method should then be used.

The *connections* in testing the insulation of a circuit by these two methods are similar to those shown in Figs. 27 and 28, the resistance X being replaced by the insulation of the circuit. This is accomplished by connecting one wire to the line and the other to the ground such as, to a gas or water pipe. The insulation of the line from the earth is then included in the testing circuit; the current passing from the battery, or other source, through the voltmeter or galvanometer to the line, from the line through the insulation to the ground, and then to the battery.

The insulation of a dynamo, that is, the resistance between its conductors and its frame, is tested in a similar manner. This resistance should be at least one megohm for a 110-volt machine, but two megohms is to be preferred and is customary. This insulation is measured by connecting one wire to the frame and the other to the binding post, brushes, or commutator. The insulation is then included in the circuit. Insulation resistance decreases with increase of

THE POWER AND WIRE CHIEF'S ROOM OF THE EXCHANGE AT WEBB CITY, MISSOURI

temperature so that this test of a machine should be made after a full load run of several hours.

The e. m. f. used should be constant and of one to two hundred volts value. Secondary batteries are the best for this purpose but silver chloride testing cells are much used. The resistance of dielectrics increases by continued action of the current and this property is known as *electrification*. For this reason the deflection should not be read until after a certain period of electrification—usually one minute. This action is quicker in some materials than in others, and is also greater at low than at high temperatures.

Insulation Resistance of Cables. In the preceding cases of insulation resistance only a part of the insulation is under electric strain. In the case of submarine cables and lead covered cables used on land, the whole of the insulation is subjected to the electric strain. To test the resistance of a waterproof insulation, the insulated wire or cable may be immersed in a tank of water. Care should be taken to leave enough of the cable out of the water so that surface leakage near the ends may not interfere with the test. For short lengths of cable the resistance of the wire inside the insulating material may be ignored. The resistance between the wire and a metal plate immersed in the tank is practically the resistance of the insulation. Fig. 27 shows the arrangement of the apparatus. As a cable takes a certain charge as a condenser when subjected to an e. m. f., it is necessary to protect the galvanometer, by a short-circuiting switch between the galvanometer terminals, during the rush of current on first closing the circuit. The switch box *S*, Fig. 27, has such a short-circuiting switch. This is important as otherwise the galvanometer may be injured. If the insulation resistance is not too high the direct deflection method above described may be used. If the insulation is excellent the deflection produced by the leakage should be very small and some other method must be used.

Charge and Recharge Method. An excellent method in such cases is the charge and recharge method. In this method, Fig. 27, the cable is first charged for several minutes, care being taken to short-circuit the galvanometer. The circuit is then opened for, say, one minute and the circuit closed again, the short-circuiting switch of the galvanometer meanwhile having been opened. While the circuit was open, a certain part of the charge leaked out and this is now replaced by an equal added charge. The galvanometer makes a sudden throw due to this added charge and after many oscillations comes to rest. If the relation between the added charge and the galvanometer throw is known, the quantity added may be computed, and the leakage current is equal to the added charge (equal to that lost) divided by the time in seconds for which the circuit was open. If the steady leakage produces a measurable deflection, account should be taken of this in estimating that part of the sudden throw produced on closing the circuit again. This correction we here suppose to be negligible. To find the relation between charge and throw, a condenser of known capacity (farads) is charged by a known e. m. f. and then discharged through the galvanometer. The charge equals the product of capacity and e. m. f. used. The charge divided by the throw produced, gives the constant of the instrument as a ballistic galvanometer. As condensers are rated in microfarads (millionths of farads) care must be taken to use the value in farads if the value in ohms insulation resistance is required. If the value in microfarads is used, the final result will come out in megohms. If an e. m. f. E_1 volts and capacity C microfarads produces a ballistic throw d_1, and if an e. m. f. of E_2 volts produces a throw of d_2 on closing the circuit through the insulation under test after the circuit has been open for t seconds, ignoring the resistance of other parts of the circuit, the insulation resistance is

$$X = \frac{E_2 \times d_1 \times t}{E_1 \times d_2 \times C} \text{ megohms}$$

Example. If E_1 is 1.44 volts, C is 0.5 microfarad, d_1 is 28.8 cm., E_2 is 100 volts, d_2 is 20 cm., and t_1 is 60 seconds, what is X?

Ans. 12,000 megohms.

As a rule the insulation resistance per mile is required. The longer the cable the more surface is exposed to leakage; consequently it is evident that the insulation resistance per mile is found by multiplying the resistance of the sample by its length in fractions of a mile. That is, a mile of cable would have, say, one-quarter as much insulation resistance as a quarter of a mile of cable.

In the case of lead covered cables, no tank is required, as connection may be made with the lead covering instead of the immersed metal plate before mentioned.

Resistance of Lines. Telegraph, telephone, and power transmission lines may be measured in place to best advantage if one or more additional lines are available between the terminals. If only one wire is available both ends may be connected to ground and the resistance, which involves that of the connections to ground and that of the earth return, may be measured by one of the methods described above. Such a method though unsatisfactory may be the best available. The resistance of the earth return is generally low, but there is always much uncertainty as to the resistance to earth at the ends. Earth currents of electricity, due to many causes, may much complicate the problem. When a second line of resistance X_2 is available, that and the unknown resistance X_1 may be connected together at the distant end and the combined resistance R, which equals X_1+X_2, measured. Next, the distant junction may be grounded and the two wires connected as the proportional arms of a Wheatstone's bridge, as illustrated in Fig. 29. The resistances in the other proportional arms are R_1 and R_2. One terminal of the battery is grounded. When a balance is obtained the proportion of the whole resistance R in X is

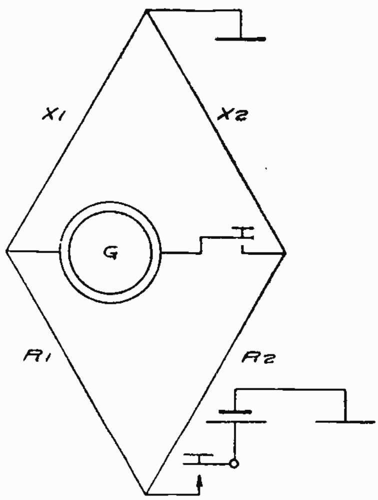


Fig. 29. Bridge Diagram for Line Resistance Measurement.

$$X_1 = R\frac{R_1}{R_1 + R_2}$$

In a similar way, $X_2 = R\dfrac{R_2}{R_1 + R_2}$

It is well to connect the battery in that branch of the bridge which includes the earth return as there may be a difference of potential due to earth currents, which does not disturb the *bridge* as it simply adds to or subtracts from the battery e. m. f. If a third line is available it may be used in the battery branch in place of the earth return. It will be noted that the resistance to earth at both ends is not in any of the four proportional arms and consequently does not affect the result.

Example. The two wires looped together have a resistance of 248 ohms. When a balance is obtained with them as arms of the bridge, $R_1 = 1{,}000$ ohms and $R_2 = 1{,}127$ ohms, the proportion being $R_1 : R_2 : : X_1 : X_2$. What are X_1 and X_2?

Ans. $X_1 = 116.6$ ohms; $X_2 = 131.4$ ohms.

Locating Grounds. In case a line wire is grounded at some unknown point, the above method may be used in locating the ground. The grounded wire and a second wire free from grounds may be looped together and their combined resistance measured. The loop, as before, is connected as two arms of a bridge, but the junction is left insulated. X_1 is now the resistance from the testing station to the point where the wire is grounded. X_2 is the combined resistance of the rest of that wire and the whole of the other wire. The resistance to the grounded point is then

$$X_1 = R\frac{R_1}{R_1 + R_2}$$

As a rule the resistance of every line is part of the office data, and therefore $R = X_1 + X_2$ is known in advance and need not be remeasured. As the resistance per mile is also usually part of the office data, the actual distance corresponding to X_1 may be computed and a lineman sent to the point to make the repair. If in a severe storm several grounds occur on the same wire, this method, of course, cannot be used to locate the trouble. In the case of ocean cables this method is used with excellent results. The cable repair steamer can be sent to the point of trouble where the cable is raised and repaired.

Locating Faults. This method may be used in the care of a broken submarine cable if both ends are exposed to the water, but it cannot be used for broken land-lines because the ends, even if both on the ground, are too imperfectly grounded. If the conductor of a submarine cable is broken but the insulation left intact, this method cannot be used. A method, however, in which the distributed capacity of the cable is measured in microfarads (see Capacity Measurements later) can be used to determine the location of the break. This latter method may also be used for a broken land-line where the end of the wire hangs free of the ground.

MEASUREMENT OF BATTERY RESISTANCE

Voltmeter Method. The following voltmeter method may be used to measure battery resistance. The battery of one or more cells is connected in circuit through a key K, with a known resistance R. The voltmeter of appropriate range is connected, as shown in Fig. 30, to the terminals of the battery. With the key K open, V_1—the e. m. f. of the battery—is measured. The key K is then closed and V_2 —the reading of the voltmeter— is observed. By Ohm's law the current is $\frac{V_2}{R}$. A part of the battery's e. m. f., equal to $V_1 - V_2$, is now lost inside the battery because of the resistance X of the battery. We then have the relation,

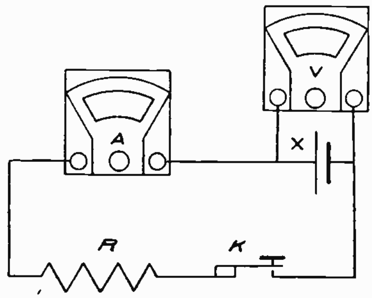


Fig. 30. Voltmeter Method of Measuring Battery Resistance.

$$V_1 - V_2 = X\frac{V_2}{R}, \quad \text{and}$$

$$X = R\frac{V_1 - V_2}{V_2}$$

If the resistance R is not known, an ammeter may be introduced into the circuit in series with R, and the current I measured directly. Then

$$XI = V_1 - V_2, \quad \text{and}$$

$$X = \frac{V_1 - V_2}{I}$$

It will be noticed that it is tacitly assumed that when the key K is open, not enough current will pass through the voltmeter to introduce any error. If the battery resistance is large this error is not negligible and a sensitive high resistance galvanometer with considerable additional resistance, perhaps 100,000 ohms besides, may be substituted for the voltmeter. If the deflections of the galvanometer in the two cases (open and closed) are d_1 and d_2, we then have

$$X = R\frac{d_1 - d_2}{d_2}$$

As the battery when furnishing a current begins at once to fall off in e. m. f., that is, *polarize*, a small error due to polarization makes the battery resistance appear too high. Such a value of the resistance R should be chosen as to make the deflections materially different. Otherwise a slight error in V_1 and V_2 or d_1 and d_2 will make their difference $V_1 - V_2$ or $d_1 - d_2$ many per cent in error.

Example. A cell has an e. m. f., $V_1 = 1.47$ volts when S is open and 1.12 when S is closed. R is 5 ohms. What is X?

Ans. $X = 1.56$ ohms.

Mance's Method. Another method is Mance's method, in which the battery, whose resistance X is to be determined, forms one arm of a Wheatstone's bridge, as indicated in Fig. 31. No key is placed in the galvanometer branch and no additional resistance, in the branch which includes the key S. The resistance in R_3 is adjusted until the galvanometer does not change its deflection on closing the key S. It is usually necessary to put considerable additional resistance R in the galvanometer arm to keep the deflection small. If the deflection does not change on closing the key S, it is evident that the decrease in the potential difference at the terminals of the cell due to its increased current when S is closed, must exactly equal the decrease in the potential difference between the terminals of R_3 due to this path being robbed of a part of its current because of the new path. Otherwise the potential difference at the galvanometer terminals, which is the difference of the potential differences over the two arms, would change and the deflection change. Similar reasoning applies to R_1 and R_2, only here the difference over R_2 increases by just the amount that that over R_1 falls, thus keeping the total amount constant for the combination of R_1 and R_2. The arrows show the direction of the currents in the various arms. If no change in the galvanometer current occurs, the changes in R_1 and R_3 must be equal and so also the changes in R_2 and X. It follows then if the galvanometer deflection remains constant whether S is open or closed, that

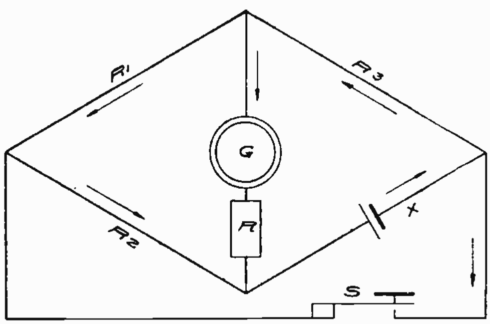


Fig. 31. Bridge Diagram for Mance's Method.

$$R_1 : R_2 :: R_3 : X, \text{ or}$$
$$X = \frac{R_2 \times R_3}{R_1}$$

Should the battery polarization change on closing the key S, the galvanometer deflection will change. For this reason the key S should be closed for an instant only.

Besides these methods there are excellent methods in which alternating currents are used, but they are too advanced to be described in this course. Such alternating-current methods should be used in measurement of the resistance of solutions (so called electrolytes) which are decomposed by a direct current.

MEASUREMENT OF ELECTROMOTIVE FORCE

Voltmeter Method. The simplest method of measuring an electromotive force is by the use of a voltmeter which indicates directly

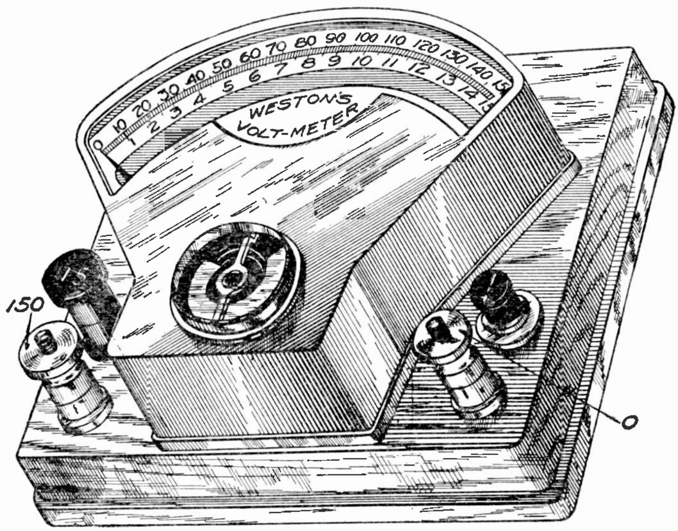


Fig. 32. Commercial Portable Voltmeter.

the number of volts. A voltmeter of the proper range should be chosen. For very small e. m. f 's the millivoltmeter, usual range 1 to 300 millivolts, *i.e.*, 1 to 0.3 volt, may be used. For higher e. m. f.'s, voltmeters reading to 1.5, 15, 150, and 300 volts respectively, are made by the Weston Electrical Instrument Co. and others. A voltmeter is simply a galvanometer calibrated to be read in volts. It is evident that if an additional resistance equal to that of the voltmeter is placed in series with the latter, twice the voltage will be required to produce the same deflection as before. In general, any resistance in series which makes the total resistance n times that of the voltmeter alone, may be used as a multiplier; and the reading of the voltmeter must be multiplied by n to get the value of the e. m. f. Such a multiplier may be bought with a voltmeter in order to make its effective range greater. For example, if the resistance of a voltmeter of range 0 to 150 volts, is 15,000 ohms, a multiplier having a resistance of 60,000 ohms will bring the total up to 75,000 ohms, and the constant n of the multiplier is 5. With this multiplier in the circuit the upper limit of the voltmeter is extended to 750 volts. If the multiplier is mounted inside the voltmeter, and if on using the binding posts marked 0 and 15 the range is 0 to 15 volts, and using the binding posts marked 0 and 150 the range is 0 to 150 volts, the multiplier evidently must have nine times the resistance of the main part. Such a voltmeter, shown in Fig. 32, is said to be a two-scale voltmeter, and it may be used equally well on either range. As the extra expense of providing the multiplier and extra binding post is slight, a two-scale voltmeter is a very inexpensive substitute for two voltmeters. It is also evident that a low range voltmeter may be used in connection with any resistance box as a multiplier. The Weston voltmeters have approximately 100 ohms resistance per volt of range and, therefore, take a maximum of about 0.01 amperes when used on an e. m. f. which is the maximum of the range. As a rule the current taken by a voltmeter is negligible in comparison with the current in the rest of the circuit.

The voltmeter method may be used equally well with both direct and alternating electromotive forces.

Potentiometer Method. For the comparison of e. m. f.'s, the potentiometer is the most accurate apparatus. When a balance is reached the e. m. f.'s to be compared are not allowed to furnish any current, and consequently no polarization results in their source. The effect of internal resistance is absolutely *nil* also. The arrangement of apparatus is shown in Fig. 33.

Two resistance boxes M and N, each of 10,000 ohms capacity, are arranged to have plugs withdrawn to a total of 10,000 ohms, and are connected in series with a battery B. To avoid injuring B, plugs corresponding to 10,000 ohms should be withdrawn before connecting it in circuit. The circuit has a high resistance and the effect of polarization of the battery *B* quickly reaches its limit and a steady current *I* flows through the circuit. If the resistance in box *M* is *R* ohms, that in box *N* is (10,000 − R) ohms; and the fall of potential over *M* is *R I* volts, and over the box *N* is (10,000 − R) *I* volts. One of the cells to be compared, a standard cell of e. m. f. *S*, is connected in series with some high resistance *A*, a sensitive galvanometer *G*, and a key *K*. In general, on closing the key *K* the galvanometer will deflect; but if the resistances in *M* and *N* are adjusted until the potential difference over *M* is exactly equal to the e. m. f. of the cell *S*, the latter is in perfect balance and can neither supply current to the general circuit supplied by *B* nor can current be forced backward through the cell *S*. In that case the e. m. f. of *S* equals the fall of potential through *M*, and, calling R_1 the resistance in *M*,

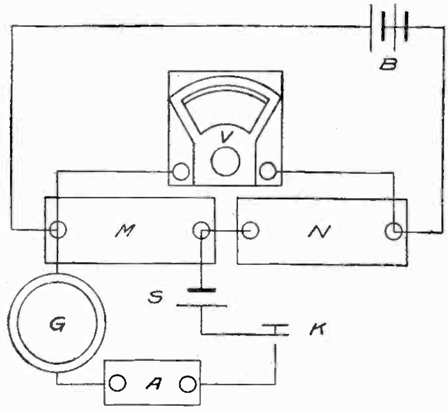


Fig. 33. Potentiometer Method of Measurement of E. M. F.

$$S = I R_1$$

If now a second cell of unknown e. m. f. *X* is substitued for *S*, and the resistances in *M* and *N* readjusted—but their sum kept 10,000—until on closing the key *K* no deflection results, calling the new value of the resistance in *M*, R_2, we have the relation

$$X = I R_2$$

It follows that

$$X = S \frac{R_2}{R_1}$$

If *S* is known, *X* may be computed. It is well to repeat the balance with *S* to be quite sure that no change has meanwhile occurred in the main battery *B*. Precaution should be taken in setting up the apparatus that *B* is greater than either *S* or *X* and that they are connected into the circuit so that they are in opposition to *B*. If these conditions are not obeyed, it is evident that no balance can be obtained. If no exact balance can be obtained, but a change of one ohm changes the galvanometer deflection from up to down the scale, the fraction of an ohm needed for an exact balance can be obtained by interpolation. In the next article on the calibration of a voltmeter such an interpolation is made.

Example. With a total resistance in M and N of 10,000 ohms of which the resistance in M was $R_1 = 5{,}267$ ohms, when the standard Clark cell of 1.433 volts was in the galvanometer circuit, and the resistance was $R_2 = 5{,}470$ ohms when the Leclanché cell was in the galvanometer circuit, what is the e. m. f. X of the Leclanché cell?

Ans. $X = 1.4882$ volts.

Calibration of a Voltmeter. If during the previous experiment, a voltmeter had been connected for the whole time between the extreme terminals of M and N, the potential difference V between the terminals of the voltmeter would have been

$$V = 10{,}000\, I = 10{,}000 \frac{S}{R_1}$$

This gives a convenient method of calibrating a voltmeter by means of a standard cell of known e. m. f. S. The calibration may be extended to various points of the voltmeter by changing the e. m. f. of the main battery B. In such cases the resistance in M, to obtain a balance, will change in the inverse ratio. It is evident that the calibration cannot by this method be extended to points below the e. m. f. of the standard cell. In the case of high e. m. f.'s, it is desirable to increase the total resistance in M and N beyond 10,000 ohms. For example, if the e. m. f. produced by B at the terminals of the voltmeter is 150 volts, a total resistance of 100,000 ohms would be about right. In this case over 99,000 ohms would be in N and less than 1,000 in M. If several standard cells are available, they may be connected in series in the galvanometer branch, thus increasing the resistance for a balance in the box M. As most boxes have one ohm for their smallest resistance, a greater per cent of accuracy is obtained if the resistance in M is large. If an exact balance cannot be obtained and the nearest smaller resistance produces a deflection d_1 one way, and the nearest larger resistance produces a deflection d_2 in the opposite direction, the fraction of an ohm which would have produced a balance is evidently

$$\frac{d_1}{d_1 + d_2}$$

Example. With a total resistance of 100,000 ohms in M and N, and 987 ohms in M producing a deflection of 5 divisions down the scale, and 988 ohms producing a deflection of 15 divisions up the scale, and a standard Clark cell of 1.433 volts e. m. f. in the galvanometer circuit, what is the correction to be added to the voltmeter reading which was 144.9 volts? Ans. Correction = + 0.25 volt.

Suggestion of Solution. The change in deflection by change of one ohm is 5 + 15 scale divisions; therefore, 987 is 0.25 ohm too small and 988 is 0.75 ohm too large. The e. m. f. figures out 145.15 volts; therefore, 0.25 volt will be added to the voltmeter reading to give the correct result.

This method, as will be seen later under the head of "Measurement of Current," can be used with a standard cell to measure a current.

Condenser Method. If a condenser of capacity C is connected by means of a charge and discharge key K, which has an upper and a lower contact, as shown in Fig. 34, alternately to a standard cell of e. m. f. B, and a ballistic galvanometer G, the throw d of the galvanometer will be a measure of the charge of the condenser equal to $B \times C$. If, now, a cell of unknown e. m. f. X is substituted for B, the deflection d_2 will be a measure of the charge of the condenser now equal to $X \times C$. It follows that

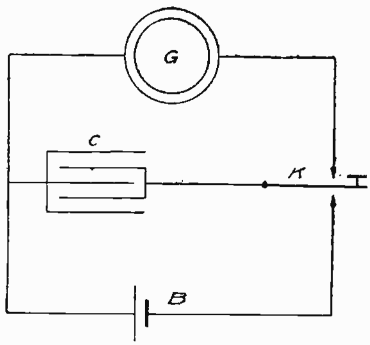


Fig. 34. Condenser Method of Measurement of E. M. F.

$$X = B\frac{d_2}{d_1}$$

This method is free from difficulties due to polarization and internal resistance of the cells; because the very small charge taken by the condenser produces no measurable polarization, and the effect of internal resistance is only to lengthen the time of charging of the condenser, but not to change the total quantity.

The accuracy of the method, however, is limited to that of the reading of the deflections d_1 and d_2, and it is difficult to get results much closer than, say, $\frac{1}{5}$ of 1%. The potentiometer method will give results easily to $\frac{1}{1000}$ of 1% if the resistances used are accurate; and in general the accuracy of the potentiometer method is limited only by the accuracy of the resistances. For accurate comparisons the potentiometer method is always used.

VOLTAIC CELLS AND BATTERIES

A *voltaic cell* is usually composed of a pair of electrodes immersed in a liquid or in two liquids separated from one another by a porous partition. The liquid, or liquids, must be what is known as an *electrolyte;* and must undergo a chemical breaking up, called *electrolysis,* with chemical action on one or both electrodes when the circuit is closed and a current flows through the cell.

Some cells fall rapidly in e. m. f. when the circuit is kept closed. This phenomenon is known as *polarization,* and it frequently is due in large part to the deposit of a film of hydrogen gas on the surface of one of the electrodes (the cathode). This gas is one of the products of the electrolysis of the liquid. If the cathode, for example a copper plate, as in the case of the gravity cell, is surrounded by a solution of copper sulphate, the hydrogen does not reach the copper plate but is intercepted by the copper sulphate solution, and copper instead of hydrogen is deposited. Naturally, the deposit of copper on a copper plate produces no polarization. The copper sulphate solution is called a *depolarizer.* The other electrode of the gravity cell is zinc and is immersed in a dilute solution of either zinc sulphate or sulphuric acid.

In the *Grove* and the *Bunsen* cells, the depolarizer is nitric acid in a porous cup in which the cathode is immersed. The nitric acid is rich in oxygen which it gives up to oxidize the hydrogen gas, thus forming water (H_2O) which makes the solution more dilute but causes no polarization. Cells with liquid depolarizers cannot be left on open circuit as the liquids diffuse into one another and the cell is spoiled. Cells for open circuit use must have either a solid or a paste for a depolarizer. The Leclanché cell has manganese dioxide (a solid) packed in a porous cup about its cathode of carbon. The data of various cells can be found in books on cells.

Standard Cells. There have been various cells used as standards of e. m. f. of which the *Clark* and the *Weston* have received most attention. A *standard cell* must be composed of materials which, while the cell is in use, do not change; that is, no new substance may be formed by the action of the cell; the cell should have little or no polarization when used by zero methods like the potentiometer method described above; the cell also must not deteriorate when left on open circuit.

Both the Clark and the Weston cells fulfill these requirements. At the International Electrical Congress, held in Chicago, 1893, the normal Clark cell was recommended for international legalization and its e. m. f. at 15° C. was voted to be considered for practical purposes as 1.434 volts; and a committee, consisting of Professors von Helmholtz, Ayrton, and Carhart, was charged with the duty of drawing up specifications for the precise form of the cell. Von Helmholtz died soon afterward and the other members of the committee could not agree on the specifications, with the result that the principal countries (in electrical matters) have never agreed on a form for the cell.

It has now been displaced by the Weston cell, which, in 1908, was recommended by an International Conference in London as an international standard. It is now known that the Clark cell has an e. m. f. slightly below 1.433 volts, instead of 1.434 volts as thought in 1893. The normal Clark cell uses as materials zinc amalgam in a saturated aqueous solution of zinc sulphate, with an excess of zinc sulphate crystals present, and pure mercury in the presence of mercurous sulphate in the form of a paste which acts as the depolarizer. The action of the cell is to form more zinc sulphate and reduce some of the mercurous sulphate to mercury, or *vice versâ*, when the current flows in the direction of the e. m. f. or is driven in the opposite direction by a greater outside e. m. f. The principal objection to the normal Clark cell is that its e. m. f. changes by a considerable amount with change in temperature, falling about 0.08% for every Centigrade degree rise in temperature.

The Weston normal cell is similar to the Clark cell except that cadmium replaces the zinc, and cadmium sulphate the zinc sulphate The Weston normal cell has a much lower temperature coefficient than the Clark cell, its e. m. f. falling about 0.00406% for each Centigrade degree rise above 20° C. and *vice versâ*. The e. m. f. of the

Weston normal cell at 20° C. was recommended by the London conference of 1908 to be taken provisionally as 1.0184 volts.

Storage Cells. Many voltaic cells when exhausted, may be recharged by forcing current through the cell in the reverse direction by the application of an outside e. m. f. greater than the e. m. f. of the cell. Such cells are called *storage cells*. In general only such cells as form no *new* kind of material when discharging are reversible, and evidently a cell to be charged and discharged repeatedly must be reversible.

All standard cells must be reversible. Reversibility, however, is not the only requirement of storage cells to be used commercially. Other qualities required are low internal resistance, large capacity for charge measured in ampere hours in comparison with size and weight, long life under service, ability to stand without harm in open circuit, moderate cost, etc.

The storage cell most used commercially has both plates of lead with dilute sulphuric acid as electrolyte and lead peroxide as the depolarizer. The lead peroxide is a solid or paste which adheres to the positive pole of the battery. The e. m. f. of a lead cell is about 2.2 volts when fully charged and may safely be discharged until its e. m. f. is reduced to 1.8 volts. When the cell is charged one plate has a deposit of lead peroxide, and the other has a spongy texture, due to its reduction from an oxide or a sulphate of lead in its previous history. When the battery is discharged, the sulphuric acid is electrolyzed; the hydrogen formed reduces some of the lead peroxide of the positive, and the sulphion forms some insoluble lead sulphate from the negative. The sulphuric acid becomes more dilute. On recharging the cell the lead sulphate is reduced to spongy lead at the negative, some additional lead peroxide is formed on the positive, and the density of the sulphuric acid increases. For details as to the manufacture of the various varieties of lead cells and other storage cells, the reader is referred to works on storage cells.

To increase the capacity of a cell the negative consists generally of a number of plates connected together both electrically and mechanically, and the positive consists of one plate less in number and connected together in the same manner. The positive plates are interlarded between the negative plates.

Storage cells are also called *secondary cells* or *accumulators* by some writers.

Batteries. The word battery is technically used to mean a group of cells. In common parlance the word is used sometimes to mean a single cell; but this use is not to be recommended.

MEASUREMENT OF CURRENT

Electrodynamometers. In the choice of a unit of current, it was decided that a unit of current in a straight conductor at right angles to a unit magnetic field, should exert a force (at right angles to both the directions of current and field) of one dyne per unit length of the conductor. As mentioned earlier, this unit of current was thought to be inconveniently large by the committee of the British Association for the Advancement of Science, which had the matter of electrical units in charge, and as a consequence for practical purposes they recommended that one-tenth of this theoretical unit should be taken as the practical unit. The latter unit is called the *ampere*. As the magnetic field due to the flow of an electric current in coils, may be computed from the data of the coils and the current, it is evident that absolute electrodynamometers may be made to measure current without the intervention of other electrical measuring apparatus. These absolute electrodynamometers may take various forms, including that of current balance. By means of an absolute electrodynamometer and a standard resistance, the e. m. f. of standard cells may be determined with a high degree of accuracy according to the principle of Ohm's law.

By comparison either directly with the standard electrodynamometer or indirectly by means of standard resistances and standard cells, other forms of electrodynamometers and all forms of ammeters may be adjusted so as to read amperes. It is evident from the above that as more improved absolute electrodynamometers are constructed, we may expect greater exactness in the determination of the e. m. f. of the Weston normal cell, which for the present is taken as 1.0184 volts at 20° C.

Ammeters. An ammeter is a galvanometer graduated so that it reads current directly in amperes. This graduation is obtained directly by comparison with either an absolute electrodynamometer or indirectly by means of a standard cell and standard resistances.

Ammeters for any desired range of current are on the market, and the accuracy of their readings is in proportion to the care with which they have been constructed and calibrated. Even the best are moderate in price and the poorest should not be one per cent in error.

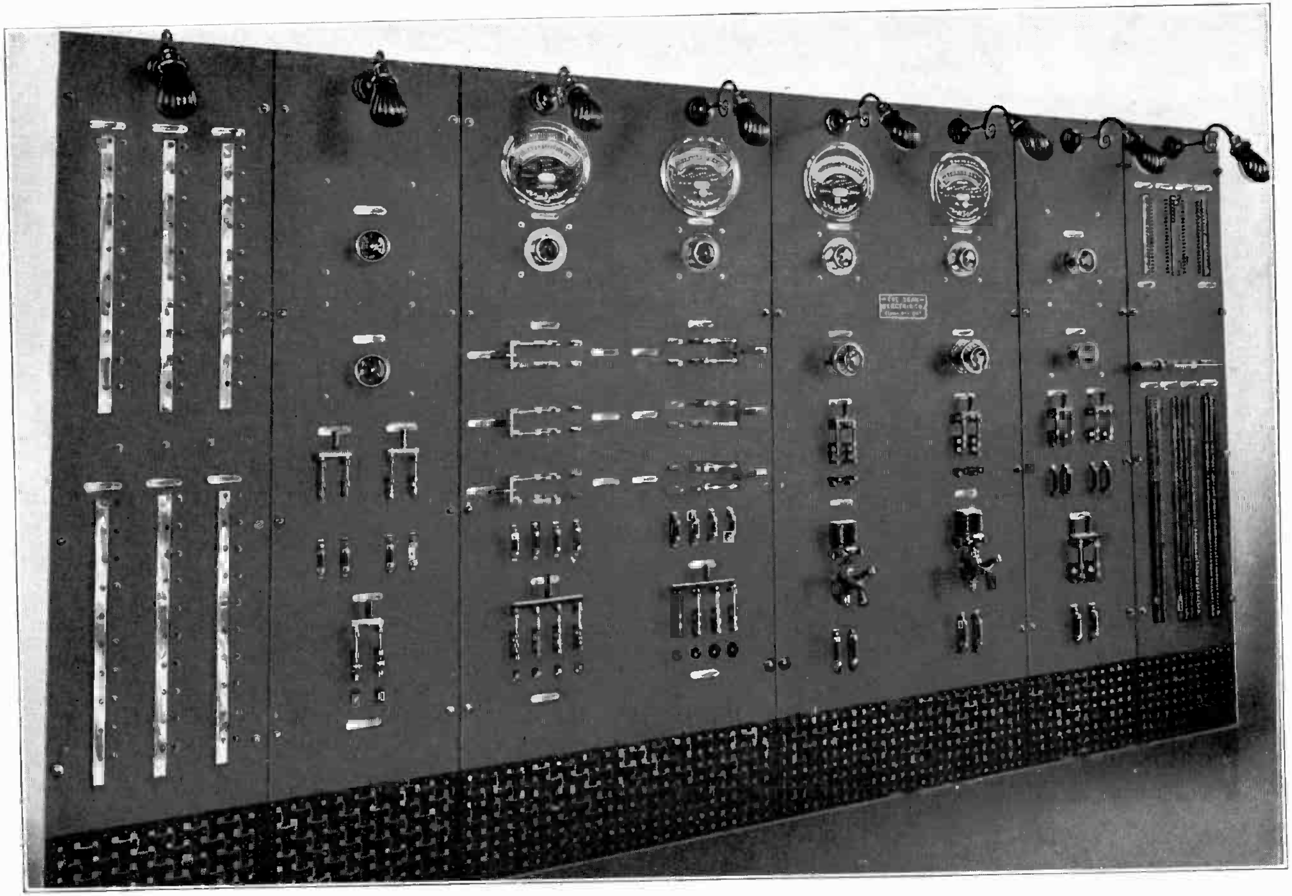
Ammeters to measure large currents carry the main portion of the current through shunts which differ theoretically in no respect from the shunts used with other forms of galvanometer.

To measure current by means of an ammeter involves introducing the instrument into the circuit, care being taken to connect the terminal marked + to the positive terminal of the source of e. m. f. The exact position of the ammeter in an undivided circuit is not important, as the current is the same throughout the circuit. Care should be taken that the ammeter has a range which the current does not exceed; otherwise the pointer may be bent or even the ammeter may be burned out by the action of excessive current. An ammeter has an exceedingly small resistance, and to connect an ammeter without additional resistance between the terminals of a dynamo or a battery is to produce a short circuit practically. Excessive current will flow through the ammeter and it probably will be destroyed.

Ammeters designed for direct-current circuits cannot be used on alternating-current circuits. Some forms of A. C. ammeters may be used on D. C. circuits; but as a rule ammeters should be used on the type of circuit for which they are designed.

Calibration of Ammeters. An ammeter may be compared directly with another in the same circuit by putting them in series and observing their readings with various values of the current. The current may be varied by changing the resistance in the circuit or the e. m. f. The potentiometer method may be used to calibrate an ammeter.

Potentiometer Method. The most exact method of measuring a current, assuming that the e. m. f. of a standard cell and the resistance of standard coils are known, is the potentiometer method. This is not an *absolute* method. The arrangement of the apparatus is somewhat complicated; but if it is compared with the potentiometer method as used for the comparison of e. m. f.'s (page 41) it will be seen that the commutator C, Fig. 35, is used to insert in the galvanometer branch either the standard cell of known e. m. f. S or a potential difference over a known resistance R due to the



FRONT OF LONG-DISTANCE POWER BOARD
U. S. Telephone Company, Cleveland, Ohio.
The Dean Electric Co.

current to be measured I. The current I may be passed also through an ammeter A in circuit with R, a rheostat and an auxiliary battery B_2 which causes the current I to flow through the circuit. In the lower part of the diagram the galvanometer G and, if desired, a high resistance to protect the galvanometer, are connected between the left end of the commutator and one terminal of the resistance box L; the right end of the commutator is connected to the other terminal of L. The auxiliary battery B_1 serves to send a constant current through L and M, whose combined resistance is kept constant at, say, 10,000 ohms. In setting up the apparatus, 10,000 ohms should be inserted in L and M before connecting the battery B_1; otherwise the battery will become badly polarized due to an excessive current. This precaution is very important. When a balance is obtained no current passes through the galvanometer on closing the key K.

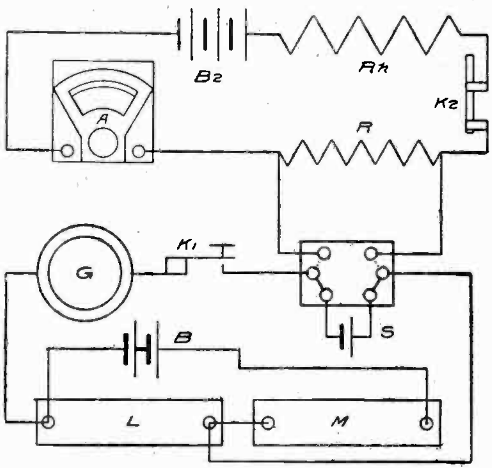


Fig. 35. Potentiometer Method of Current Measurement.

The order of procedure is as follows: first, connect S in circuit by means of the commutator C and shift resistance from L to M, or *vice versâ* until, on closing the key K a balance is reached, as indicated by a zero deflection of the galvanometer. The fall of potential through L, which under these conditions is exactly equal to the e. m. f. of the standard cell S, is then equal to its resistance R_1 multiplied by the current I from the battery B_1, or $S = R_1 I_1$; second, close the upper circuit by K_2, reverse the commutator to the position shown in the figure by dotted lines, which throws the p. d. over R into the galvanometer circuit. Adjust L and M until no current flows through the galvanometer on closing the key K_1. The total resistance in L and M is still kept 10,000 ohms. The resistance in L now has a value R_2, and the potential difference over L is now $R_2 I_1$ and is also in the galvanometer circuit. If no current flows through the galvanometer, $R_2 I_1$ must exactly equal and oppose the fall of potential $R I$ over the resistance R. We then have

$$S = R_1 I_1, \quad \text{and } R I = R_2 I_1,$$

or, combining these equations,

$$I = \frac{R_2 \times S}{R \times R_1}$$

By adjusting the rheostat in the upper, or the battery B_2 circuit, the current to be measured I, and consequently the point at which the calibration of the ammeter is desired, may be changed at will. The only limitation is that the battery B_1 must have a higher e. m. f. than the standard cell's e. m. f., and also higher than the largest p. d. over the resistance R.

As the e. m. f. of B_1 may be increased, if necessary, by introducing additional cells into B_1, there is no limit to the current I (in the upper circuit) which may be measured. In the case of very large currents the standard resistance R should be of relatively low resistance. If too much heat is developed in R its temperature may rise with consequent change of resistance.

Standard resistances are made of manganin which will carry any reasonable current without undue heating or change of resistance. These standards are arranged so that the wire may be immersed in an oil bath (pure petroleum) which may be kept stirred so that the heat may be carried away. A thermometer in the oil bath may be used to measure the temperature. Allowance thus may be made for any change in resistance due to change in temperature.

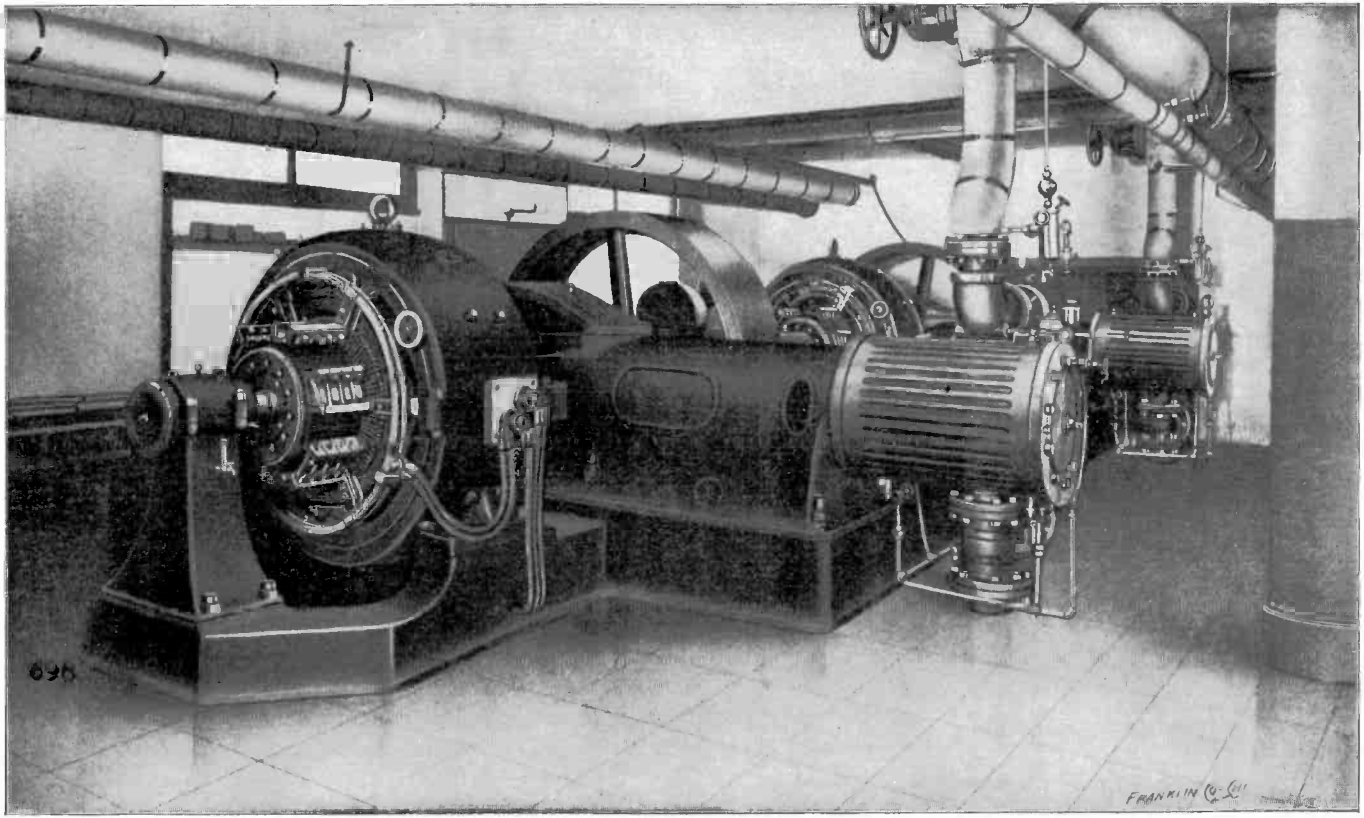
Such standards are made by the best manufacturers for 100, 10, 1, 0.1, 0.01, and 0.001 ohms resistance. Standard resistances calibrated by the Bureau of Standards at Washington are moderately expensive, but the cost is not higher than the cost of manufacture and testing at the Bureau would warrant. The certificate which accompanies each coil states the resistance at 20° C. and the change of resistance per degree change of temperature.

Silver Voltameter Method. If a current is passed through a solution of silver nitrate, each ampere deposits 0.001118 gram of silver from the solution each second. This is closely equal to 4 $\frac{1}{40}$ grams per hour. The silver voltameter is very difficult to handle with the degree of accuracy that is necessary for good results, so it is not recommended for general use.

To set up a voltameter, a platinum bowl is used as a cathode and a plate of pure silver as an anode. The electrolyte, 15 to 20 parts by weight of pure silver nitrate added to 100 parts of distilled water, is placed in the bowl, and the anode immersed in the solution. A current density of $\frac{1}{5}$ ampere or less per sq. cm. is allowed at the anode, and of $\frac{1}{50}$ ampere or less per sq. cm. at the cathode. Care is to be taken that no particles of silver mechanically detached from the anode shall reach the cathode. This may be accomplished by wrapping the anode in clean filter paper.

Before weighing the cathode to determine its increase in weight, any trace of the solution must be removed by careful working with distilled water and the cathode dried. This seems easy, but it is difficult, in fact.

The solution should be made anew for each experiment.



TWO 60 K. W. ENGINE TYPE GENERATORS DIRECT CONNECTED TO BALL ENGINES

Northern Electric Manufacturing Co.

ELECTRICAL MEASUREMENTS

PART II—ADVANCED

MEASUREMENT OF CAPACITY

Ballistic Galvanometer. In the measurement of the capacity of a condenser by the methods given in the subsequent pages, the charge of electricity from the condenser is allowed to flow as a momentary current through a galvanometer, giving the suspension a sudden *kick*. In order to calculate from this deflection the *quantity of electricity* in the condenser, it is necessary to assume that the galvanometer suspension is so heavy that it will not have moved very far before the charge has completely passed. This requisite, viz, a heavy suspension, is the distinguishing feature of the *ballistic* type of galvanometer. (See Fig. 7, Part I.)

As a rule the methods of measurement involve only a comparison of the deflections produced in the ballistic galvanometer by charged condensers of known and unknown capacity, so that, as long as the capacity of a standard condenser is known, the unknown factors, the galvanometer constant, etc., are unimportant. Nevertheless it may be instructive to know how these unknowns can be determined and the deflections can be made to give the actual quantity of electricity in the given condensers.

Because of the fact that the deflection of the galvanometer is not proportional to the current which produces the deflection, it is necessary to know the factor called the *constant* of the galvanometer before measurements can be taken. This constant is used in various forms but can be briefly stated as *the constant ratio between the current and the deflection produced by it.* When put in more definite form it can be given as follows:

$$K = \frac{2\,I\,D}{d}$$

in which I is the current flowing in the galvanometer, D is the distance from the galvanometer mirror to the scale, and d is the deflection produced on the scale.

With this in mind let us consider *how to find the quantity of electricity Q from the throw θ of the galvanometer, the galvanometer constant K, and the half period of the suspension.*

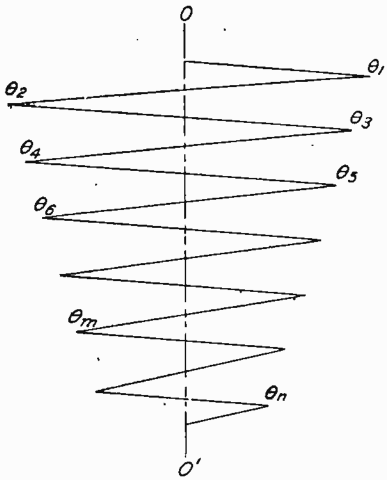


Fig. 36. Damping Diagram.

As has been stated above, while the quantity Q is passing through the galvanometer, short though it may be in duration, it constitutes a current and the magnetic effect of this current exerts a turning moment on the coil.

If I represents the mean value of this current, then the mean moment of force $\overline{Fh}$ acting on the coil while the current is flowing is

$$\overline{Fh} = I \text{ H } A$$

in which H is the strength of the field and A is the area of the galvanometer coil. If τ is the duration of the discharge, then the moment of force times the time can be given by

$$\overline{Fh}\tau = I\tau\text{H}A = Q\text{H}A$$

in which Q is the quantity of electricity, equal to $I\tau$.

If the moment of inertia M of the suspension and the angular velocity, which is given to it by this *kick*, are taken into consideration, the quantity of electricity Q may be obtained from the above equation as follows:

$$Q = K\omega \frac{M}{T_o}$$

in which ω is the angular velocity and T_o is the torsion constant of the suspension. By taking the half period of the suspension, which is easily obtained by counting the time of a given number of swings, and expressing ω in terms of the angle of throw θ, the expression for the quantity of electricity is given by the following equation:

$$Q = \frac{K\theta t}{\pi}$$

in which K is the galvanometer constant, θ the angle of throw (obtained by dividing the deflection d by twice the distance from mirror to scale D), t the half period of the suspension, and π 3.1416.

For accurate work θ must be multiplied by a damping factor $\sqrt{\rho}$, derived as follows: With the suspension swinging freely, Fig. 36, take a deflection θ_m, then after a given number of swings (n-m) take another deflection, θ_n; ρ is the (n-m) root of the ratio $\frac{\theta_m}{\theta_n}$.

Condensers. A condenser consists in its simplest form of two metal sheets separated by a nonconducting material, Fig. 37. If an e. m .f. is applied to the two metal sheets, they will take a static charge, one positive and the other negative. The nonconducting material is called a *dielectric,* as the electric force acts through it (*dia* meaning through). The capacity of such a condenser is proportional to the

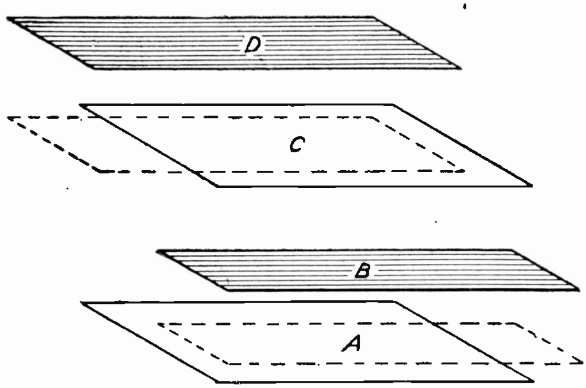


Fig. 37. Condenser Sheets.

area of the sheets and inversely proportional to the thickness of the dielectric. If the condenser is in the form of a glass jar coated outside and inside with tin foil, the arrangement is called a *Leyden jar.* A considerable portion of the surface near the edges of the jar should be free from the tin foil coating in order that the charge may not leak over the surface of the glass. The best condensers are made of many sheets of mica with sheets of tin foil interlarded, every alternate one being connected to one, and the others to the other terminal of the condenser, Fig. 38. By using many sheets of tin foil the capacity is increased in proportion to the total area. Mica is an excellent material for the dielectric as its resistance is extremely high, and very thin sheets have enough strength to withstand the mechanical stress due to the electric charges without breaking down. The mica and tin foil are clamped in place and the whole immersed in melted paraffin and then withdrawn, carrying out a coating of paraffin which protects the condenser from the effects of moisture. Several condensers of assorted capacities are frequently mounted in one box, Fig. 39. A 1 m. f. box will frequently have condensers of 0.5, 0.2, 0.1, 0.1, 0.05

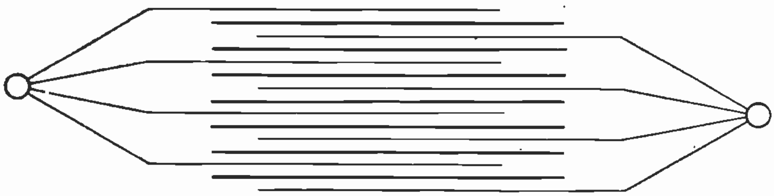


Fig. 38. Simple Condenser.

and 0.05 microfarad, Fig. 40. Cheaper condensers have paraffined paper or other materials in place of mica; but are usually poor since the dielectric, though it does not break down, is apt to yield gradually to the strain of the charge, producing an effect which is known as *absorption of the charge.* It seems as though some of the charge had been lost for when the condenser is discharged, less charge comes out than was put in. It is true that real leakage causes a loss of part of the charge, but we find also that a poor condenser, if set aside after being discharged, will, on a later test, show a small charge which has come from the gradual return of the dielectric to its original state. The Leyden jar (glass dielectric) absorbs a considerable portion of its charge. Standard condensers are sometimes made with massive plates of metal and with air, which has no absorption, as the dielectric. They are very expensive and have small capacity. For practical purposes

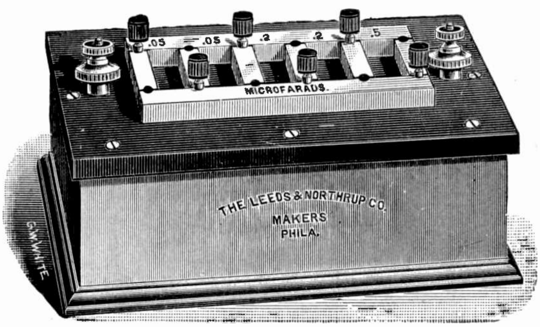


Fig. 39. Variable Condenser.

the best condensers have mica for the dielectric, for mica shows almost no absorption of the charge.

Single conductor submarine and land cables have the properties of condensers, the water acting as the second sheet in the case of the

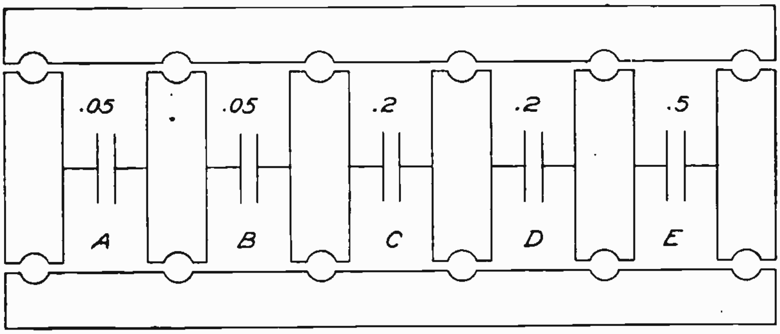


Fig. 40. Plan of Variable Condenser.

former, and the usual lead covering in the case of the latter. In telephone cables, each pair of wires and the insulation between make up a condenser. These cables almost always show considerable absorption of the charge.

Direct Deflection Method. Two condensers may be compared as to their capacity, if first one and then the other is charged by a cell B of known e. m. f., and then discharged through a ballistic galvanometer G, Fig. 41. If the deflection with the standard of capacity C is D_1, and that with the unknown of capacity X is d_2 then

$$X = C\frac{d_2}{d_1}$$

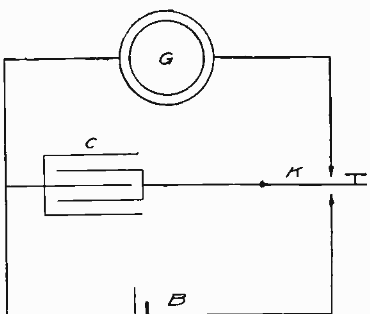


Fig. 41. Diagram for Direct Deflection Method.

A charge and discharge key K, Fig. 42, connects the condenser first to the battery and then to the galvanometer.

This method is convenient, but the accuracy of the results depends on the accuracy with which the throw of the galvanometer can be read. The accuracy is not much better than 1% even if neither condenser shows absorption of charge. If either condenser absorbs charge, the ratio of the deflections will depend on the time of charge and the slowness of clearing out of the charge. There are better methods.

Example. With a condenser of 0.5 microfarads in circuit, the deflection is 46 divisions; with the unknown capacity X in circuit, the deflection is 69 divisions. What is X?

Ans. $X = 0.75$ m. f.

Bridge Methods. The Wheatstone's bridge method of comparing resistances may be adapted to the comparison of two capacities. The apparatus may be arranged as shown in either Fig. 43 or Fig. 44. In the former a charge and discharge key is used to charge and discharge the condensers. If all the charge taken by C_1 passes through R_1 and all taken by C_2 passes through R_2, both in charging and discharging, then the galvanometer will not deflect; otherwise it will deflect in opposite directions for the charge and discharge. As the current divides in parallel circuits in inverse proportion to the resistances; and as the charge, and therefore the current, taken by condensers in parallel is directly proportional to their capacities, it is evident that if no current passes through the galvanometer

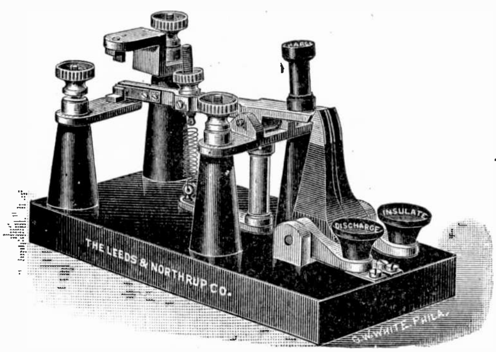


Fig. 42. Kempe Discharge Key.

$$C_1 : C_2 : : R_2 : R_1$$

therefore

$$C_1 = C_2 \frac{R_2}{R_1}$$

In Fig. 44 the battery circuit produces a current through R_1 and R_2, and they take potential differences between their terminals proportional to their resistances when the current becomes steady. The condensers will take a certain charge; and if the galvanometer is open, both condensers must take equal charges regardless of their capacities. If one has a smaller capacity than the other, the former will acquire a smaller potential difference than the latter, as the charge is equal to the product of the capacity and the potential difference. If C_1 and R_1 acquire equal potential differences, and C_2 and R_2 also equal potential differences, then on closing the galvanometer key no deflection will result. If on closing the galvanometer key a deflection results, it is evident that the above relation is not satisfied. If no deflection results

$$C_1 : C_2 : : R_2 : R_1,$$

and

$$C = C_2 \frac{R_2}{R_1}$$

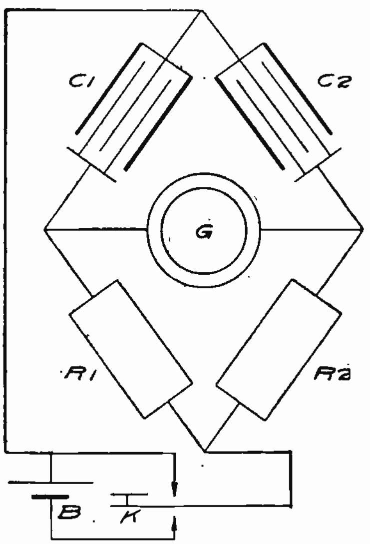


Fig. 43.

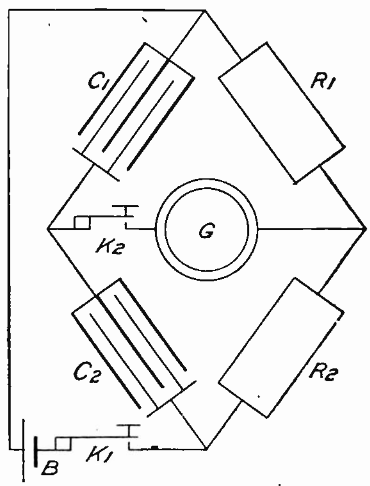


Fig. 44.

Diagrams for Bridge Methods for Measuring Capacities of Condensers.

The order of closing and opening keys is important. It should be as follows: First close K_1, then K_2 and note deflection if any; second, open K_2, then K_1, then close K_2 and note deflection (or discharge) which should be in opposite direction. Then open K_2. It is necessary to discharge the condensers before recharging them, otherwise they will take no new charge beyond what is necessary to make up for leakage or absorption of charge. If the condensers absorb charges it is impossible to get a perfect balance.

Method of Mixtures. In the method of mixtures the positive charge taken by one condenser is mixed with the negative charge of the other, and *vice versâ*, and the remaining difference of charges is discharged through the galvanometer. This method allows the time of charge and the time of mixing the charges to be varied at will, thus allowing the absorbed charge more or less time to make itself felt.

In Fig. 45, the Pohl's commutator P, by bringing the points e and c and f and d into contact as indicated, allows the condenser C_1 to charge until its potential difference is equal to that over R_1 (due to the current from the battery B), and also allows C_2 to charge until its potential difference equals that over R_2. The commutator is then reversed, bringing e into contact with a, and f into contact with d. The points a and b are permanently connected together. The + charge on C_2 can mix with the – charge on C_1, and the other charges on C_1 and C_2—which were previously so-called *bound charges*—now become free and can mix also. The remaining charges are divided between the two condensers in proportion to their capacities. If now the key K is closed, these remaining charges are discharged through the galvanometer. If no deflection occurs the charge remaining must be *nil*. As the charge taken by a condenser is equal to the product of its capacity multiplied by its potential difference, and as the potential differences to which C_1 and C_2 were charged were proportional to R_1 and R_2, then, by Ohm's law, when the charges on C_1 and C_2 are equal we must have the relation that

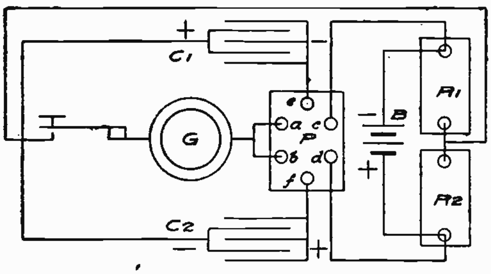


Fig. 45. Diagram for Method of Mixtures.

$$C_1 R_1 = C_2 R_2,$$

or

$$C_1 = C_2 \frac{R_2}{R_1}$$

If condenser C_1 absorbs part of its charge, its total charge will increase on charging for a longer time. If the charges are allowed to mix for a longer time there is more opportunity for the absorbed charge to be given up. It follows that if the time of charging is short, the capacity of the C_1 will appear to be smaller than if a longer time of charging were allowed. With good mica condensers little effect of absorption will be found. With most other dielectrics the absorption is quite marked.

Example. If in the bridge method or in the method of mixtures, $C_1 = 0.5$ microfarads, $R_1 = 2{,}340$ ohms, and $R_2 = 1{,}000$ ohms, what is C_2? Ans. $C_2 = 1.17$ microfarads.

Absolute Method. If a condenser is rapidly charged through a galvanometer and then discharged by short circuiting the condenser, the deflection of the galvanometer will be the same as though an equal charge had passed through the galvanometer in the form of a steady current during the same time. The difficulty with the method is that the galvanometer obstructs the complete charge of the condenser when the charges become very frequent. To get around this difficulty a second circuit to the galvanometer is arranged to carry a steady current equal in value but opposite in direction to the pulsating current due to the charge of the condenser. The result is that the galvanometer carries only the difference of these two currents, and when a balance is obtained, the resultant current is a small alternating current, alternately helped and hindered by the resistance and inductance of the galvanometer. The method then becomes somewhat like the Wheatstone's bridge method.

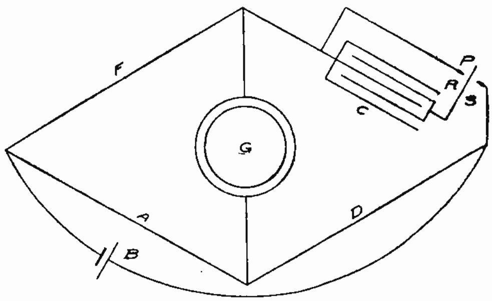


Fig. 46. Diagram for Absolute Method of Capacity Measurement.

To regulate the number of charges to a uniform number per second, a small motor running at a constant known speed or an electrically driven tuning fork of known frequency of vibration, may be used. The apparatus is arranged as in Fig. 46. If the condenser of capacity C is charged when the movable piece P makes contact with S, part of the charge will pass through the galvanometer of resistance G. The condenser is discharged when P makes contact with R. The battery B tends to send a steady current through the divided bridge circuit, part passing through F and G (both of fairly high resistance) and part through A (of low resistance). The resistance in the battery arm must be made very low in comparison with F, D, and G. Let us suppose D a fixed resistance, say, 1,000 ohms, and A, 1 ohm. In this case two proportional arms of a *postoffice* box may be used. Adjust F until a balance is obtained, with no deflection of the galvanometer. Let n be the number of charges of the condenser per second. We then have the closely approximate relation

$$C = \frac{A\ (F + G) \times 10^6}{n\, F\, (DG + DF + AG)}$$

The capacity C is in microfarads. If the factor 10^6 is omitted, the formula will give C in farads.

If the resistances in the battery branch and in A are not small, it is necessary to use a more complicated formula.

Example. When a balance is obtained $A = 1$ ohm, $F = 2{,}340$ ohms, $G = 10{,}000$ ohms, $D = 1{,}000$ ohms, and $n = 32$ periods per second. What is the capacity of C? Ans. $C = 0.01334$ microfarad.

Alternating-Current Method. If a circuit through which an alternating current is flowing includes a condenser, the charge and discharge of the condenser is repeated with every alternation of the current. The quantity of each charge is equal to the capacity multiplied by the p. d. to which the condenser is charged. The rate of charge or discharge is the value of the current at any particular instant. It is proved in treatises on alternating currents that the effective value of a current or an e. m. f. is the square root of the average square of its instantaneous values. Alternating-current ammeters and voltmeters such as those shown in Figs. 47, 52, and 53, calibrated with direct currents, show the effective values of A. C. currents and electromotive forces. The theory of alternating currents shows that the current passing in and out of a condenser, if the e. m. f. follows a sine law, is

$$I = \frac{2\,\pi\, n\, C\, E}{1{,}000{,}000}$$

From this it follows that

$$C = \frac{1{,}000{,}000\ I}{6.2832\ n\ E} = 159{,}155\ \frac{I}{n\,E},$$

when I is the effective value of the current in amperes, E the effective value of the e. m. f. in volts, n the number of cycles per second of the e. m. f. (and consequently of the current too), and C the capacity of the condenser in microfarads. If the capacity is rated in farads, omit the factor 1,000,000. In Fig. 48 the current I flows through the ammeter A, and the condenser of capacity C in series. A high resistance voltmeter V measures the potential difference E at the terminals of the condenser.

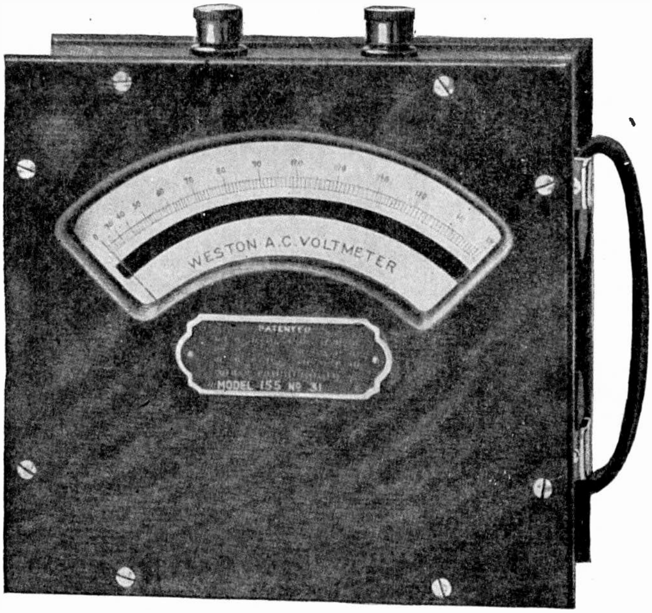


Fig. 47. Commercial Form of Portable A. C. Voltmeter.

Example. The ammeter reads 1 ampere, the voltmeter 220 volts, the frequency n is 60 cycles per second. What is the capacity of the condenser?

Ans. $C = 12.06$ microfarads.

If the voltmeter takes much current in proportion to the whole, a correction must be made for it. From the theory of alternating currents a condenser takes a current one-quarter of a period in phase *ahead* of its potential difference. A circuit in which there is both resistance and inductance takes a current lagging *behind* the potential difference. As voltmeters have some inductance, which should be small in comparison with the resistance, it will be seen that the current in the voltmeter lags a little over a quarter period in phase behind the condenser current. The relation of the currents with apparatus set up as in the previous figure is shown in Fig. 49, in which I_a, I_c, and I_v, are the currents in the ammeter, condenser, and voltmeter respectively. I_a and I_c are practically of equal length. The directions of the arrows show the phase relations.

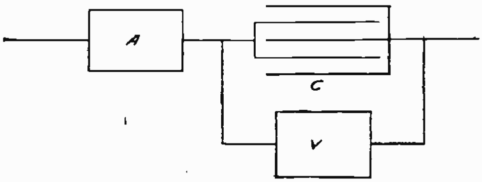


Fig. 48. Diagram for A. C. Method of Capacity Measurement.

If the condenser current is small and the voltmeter current large relatively, it will be seen from Fig. 50 that I_a may be materially larger than I_c, and that the ammeter reading must be corrected. It may be shown by trigonometry that if the voltmeter current lags by an angle a behind its potential difference, we will have

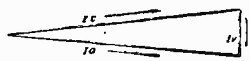


Fig. 49.

$$I_c = I_v \sin a + \sqrt{I_a^2 - (I_v \cos a)^2}$$

By the theory of alternating currents $\tan a = \frac{2 \pi n L}{R}$, where n is the frequency of the system, L the self-inductance, and R the resistance of the part of the circuit considered. If n, L, and R are known, a may be found.

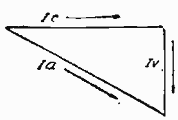


Fig. 50

Example. What correction, if any, should be made in the previous example, $I_a = 1$ amp., $E = 220$ volts, $n = 60$ cycles per second, if the voltmeter takes a current 0.06 amp. lagging 1° behind its potential difference?

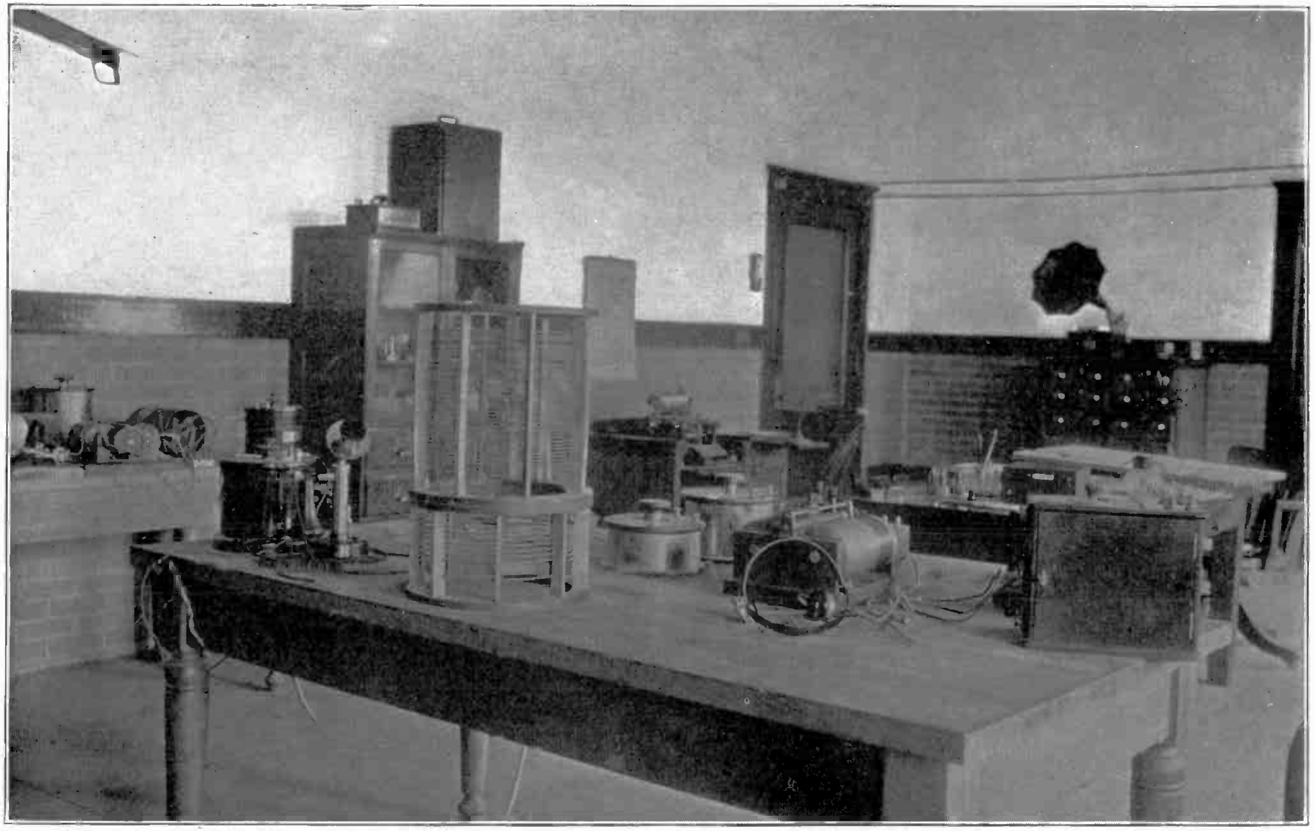
Solution.

$$\sin 1° = 0.01745, \cos 1° = 0.99985$$

$$I_c = 0.00105 + \sqrt{0.9964012} = 0.00105 + 0.99820$$
$$= 0.99925 \text{ amp.}$$

As the correction of the current is far below the accuracy with which the ammeter may be read, no correction in the computed capacity of the condenser should be made.

Example. If the current observed was 0.1 amp., the other data



RESEARCH LABORATORY OF THE SIGNAL CORPS OF THE U. S. ARMY
Where Major Squier carried on the Experiments whereby he evolved his Multiplex Telephony.

remaining the same as in the previous example, what correction, if any, should be made?

Solution.

$$I_c = 0.00105 + \sqrt{0.0064012}$$
$$= 0.00105 + 0.08001 = 0.08106 \text{ amp.}$$

The uncorrected formula gives C = 1.206 microfarads
The corrected formula gives C = 0.978 "
The difference is 0.228 "
which is 19%, a difference much too large to be ignored.

MEASUREMENT OF SELF-INDUCTANCE

Most methods of measuring inductance are too difficult for the readers of this book. The difficulty is due to the fact that a coil of wire which has inductance, has resistance also. During the increase of a current the inductance acts as a false resistance which makes the resistance appear too high. During the current's decrease, however, the inductance acts as a negative resistance, which makes the resistance appear too low. In the case of an alternating current the effect is to make the apparent resistance, called the *impedance*, higher than the real resistance. Algebraically expressed we have

$$\text{Impedance} = \sqrt{R^2 + 4\,\pi^2\,n^2\,L^2} = \frac{E}{I},$$

in which R is the real resistance in ohms, $\pi = 3.1416$, n the frequency in cycles per second, L the inductance in henrys, E the e. m. f. in volts, and I the current in amperes. The impedance of a coil is therefore not a constant quantity if R and L are constant, but depends on the frequency n. For commercial lighting n is usually 60, and for power circuits 25 cycles per second. Coils which have an iron core do not have a constant self-inductance, for the latter, with increase of current, rises slightly to a maximum and then falls off greatly for large values of the current.

Alternating-Current Method. If in a circuit, Fig. 51, the current through a coil of known resistance R and unknown inductance L, is measured by means of an ammeter A (two views of a well-known commercial instrument are shown in Figs. 52 and 53), and the potential difference E over the coil is measured by a voltmeter V, we have the following relation

$$2 \pi n L = \sqrt{\frac{E^2}{I^2} - R^2},$$

or

$$L = \frac{1}{2 \pi n} \sqrt{\frac{E^2}{I^2} - R^2}$$

Example. In a circuit for which the frequency $n = 60$ cycles per second, $R = 0.1$ ohm, $E = 110$ volts, and $I = 10$ amperes, what is the value of the inductance L?

Ans. $L = 0.0292$ henry.

If the resistance or inductance is very high, so that the total current is small, a correction must be made for the portion of the current passing through the voltmeter. The corrected formula is very complicated when expressed directly in terms of L, l, R, r, the inductances and resistances of the coil and the voltmeter respectively, n the frequency, E the potential difference, and I_a the current through the ammeter. If the tangents of the lag of the current in the two branches of the circuit are for the coil

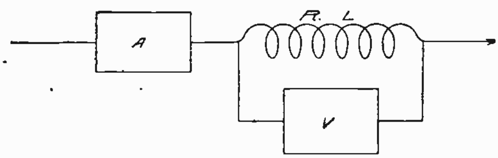


Fig. 51. Diagram for A. C. Method of Self-Inductance Measurement.

$$\tan b = \frac{2 \pi n L}{R},$$

and for the voltmeter circuit

$$\tan a = \frac{2 \pi n l}{r},$$

we get the equation for the cosine of the difference between a and b

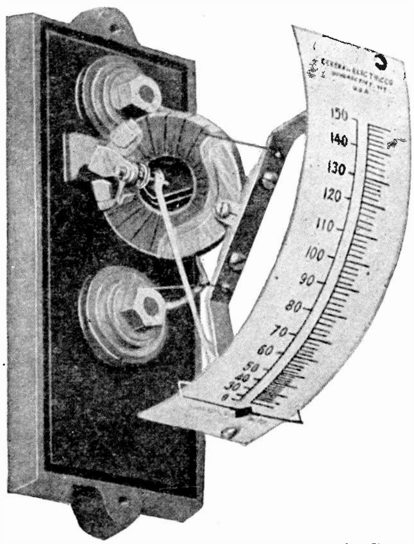


Fig. 52. Thomson Inclined Coil A. C. Ammeter.

$$\cos\left(\pm(a-b)\right) = \frac{rR}{2}\left(\frac{I_a^2}{E^2} - \frac{1}{r^2} - \frac{1}{R^2}\right)$$

Usually b is greater than a, so we write the formula

$$\cos(b-a) = \frac{rR}{2}\left(\frac{I_a^2}{E^2} - \frac{1}{r^2} - \frac{1}{R^2}\right)$$

As the constants of the voltmeter are supposed to be known, the angle a is known; therefore b may be determined and we finally get

$$L = \frac{R \tan b}{2 \pi n}$$

If b is so small that the difference between a and b is not greater than

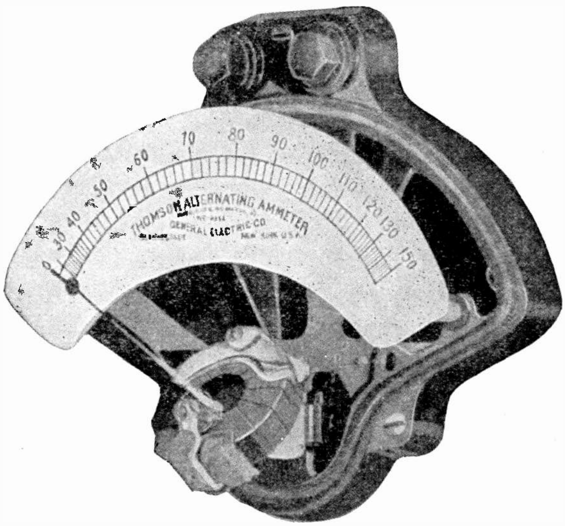


Fig. 53. Thomson Inclined Coil A. C. Ammeter.

a, there is always the possibility that the previous formula is the cosine of $(a - b)$. To determine which result to take, it is necessary to repeat the experiment with additional resistance in one of the two branches, and to take the value of L that equals one of the previous solutions. As a rule, however, the difference between a and b will be greater than a, and the incorrect result will lead to a negative value for b. As b must be positive, the negative result is rejected as impossible.

Bridge Method. Two self-inductances may be compared by a modification of the Wheatstone's bridge method. In the simplest of many bridge methods the coil of unknown inductance X is one arm of the bridge; a double coil, Fig. 54, whose inductance L may be varied by rotating one part to various positions inside the other part, and whose inductance is known for each position and marked by a pointer on a circular scale for each position, is inserted in an adjacent arm. The other arms are non-inductive resistances R_1 and R_2. The arrangement is shown in Fig. 55. The inductive branches have certain resistances R_3 and R_4. A regular Wheatstone's bridge balance is obtained by adjusting the resistances R_1 and R_2, care being taken to close the key K_2 in the galvanometer branch several seconds after closing the key K_1 in the battery branch. This precaution is necessary to insure that the currents are steady when the galvanometer key is closed, as inductive effects are produced only when the current is changing in value. When a balance is obtained $R_1 : R_2 :: R_3 : R_4$. If now the galvanometer key K_2 is closed first, the false resistance due to inductance, will cause the galvanometer to deflect when the battery circuit is closed. After oscillating a number of times the galvanometer finally comes to rest at its zero position. On opening the battery circuit the first deflection is in the opposite direction. If, now, the variable inductance is adjusted until there is no deflection on closing the battery circuit, the galvanometer circuit having been closed in advance, the false resistances due to inductance must increase the apparent resistances in both inductive branches in proportion to their real resistances, from which it follows that

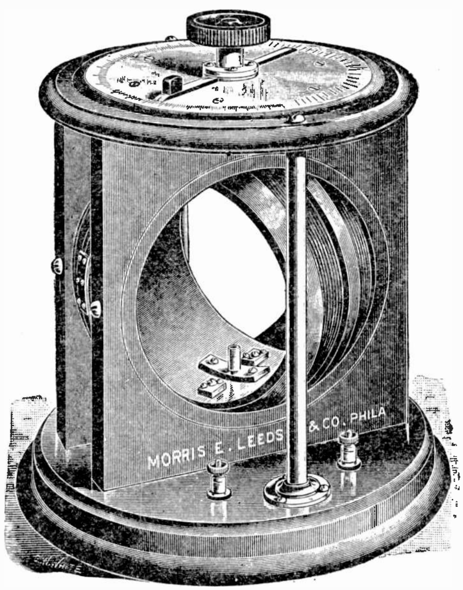


Fig. 54. Variable Self-Inductance.

$$X : L :: R_3 : R_4 :: R_1 : R_2,$$

and we get the relation

$$X = L\frac{R_1}{R_2}$$

If no variable standard of inductance is available, there are various modifications of the bridge method which may be used. These methods are as a rule very complicated and consequently beyond the scope of this course.

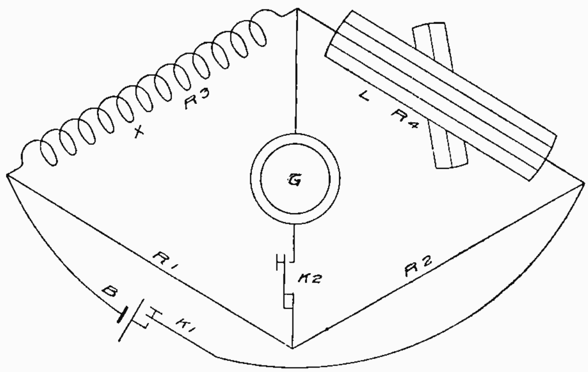


Fig. 55. Diagram of Bridge Method of Self-Inductance Measurement.

Condenser Method. The self-inductance of a coil may be compared with the capacity of a condenser. The bridge is set up as indicated in Fig. 56. The condenser of capacity C is in parallel with M which is one part of a constant resistance R_1. $R_1 = M + N$. R_2 and R_3 are resistances, one or both of which may be varied at will. The coil of resistance R_4, whose inductance L is to be measured, is in the fourth arm of the bridge. The galvanometer G, battery B, and keys K_1 and K_2 are as usual. The resistances are adjusted in R_2 and R_3 until a balance is reached, when K_2 is closed several seconds after closing K_1.

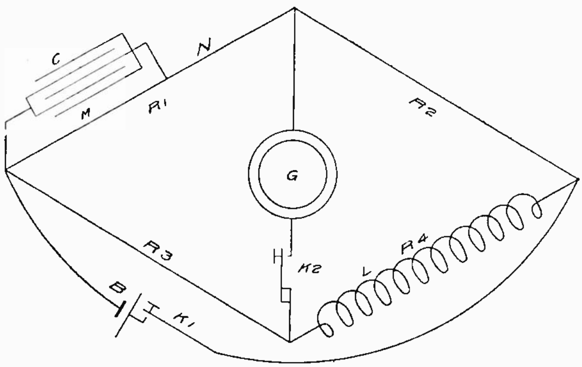


Fig. 56. Diagram of Bridge Method of Self-Inductance Measurement.

Then $R_1 : R_2 :: R_3 : R_4$, the usual Wheatstone's bridge relation. The galvanometer key K_2 is next kept closed and resistance shifted between M and N, care being taken to keep $M + N = R_1$ constant, until no deflection is produced at the instant of closing K_1. The explanation of the method is quite complicated, but leads to the simple result,

$$L = \frac{C\ R_2\ R_3\ M^2}{R_1^2\ 10^6} \text{ henries.}$$

C is in microfarads, R_1, R_2, R_3, and M in ohms, and the result for L in henries.

Example. The resistance R_1 was kept constant at 1,000 ohms, part of which M, when a balance was reached, was 516 ohms. R_2 = 1,000 ohms, R_3 = 1,260 ohms, and C = 1 m. f., makes up the balance of the data. What was L?

Ans. L = 0.3355 henry.

MEASUREMENT OF MUTUAL INDUCTANCE

If two electric circuits are in the neighborhood of one another, the increase or decrease of the current of one will produce a change in the magnetic field which will act to produce an e. m. f., and consequently a current in the second circuit if it is closed. If the current in one circuit varies at the rate of one ampere increase or decrease per second and an e. m. f. of one volt is produced in the second circuit, we say the mutual inductance is one henry. If the mutual inductance is constant, the e. m. f. produced in the second circuit is proportional to the rate of change of current in the first; also larger inductances produce proportionately larger e. m. f.'s in the second circuit with equal rates of change of current in the first. Algebraically expressed, if I_1 and I_2 represent any two values of the current, supposed to be increasing at a uniform rate, and t is the interval of time between these values of the current, and if E is the e. m. f. produced in the second coil whose mutual inductance with respect to the first is M, then

$$M \frac{I_2 - I_1}{t} = E$$

The inductance between the coils is called *mutual* because a certain increase of current in either will produce the same e. m. f. in the other regardless of which circuit has the original current. The relation is therefore *mutual.* If the circuit has an iron core the mutual inductance is not strictly constant, but with increasing current increases to a maximum and then falls again. As it is very difficult, if not impossible, to control the precise rate of change of the current so that it will increase at a uniform rate, either of two methods may be used to obtain the value of M without keeping the rate of change of I constant.

Ballistic Galvanometer Method. In this method the second circuit, called the *secondary* circuit, is of known resistance R_2, and includes a ballistic galvanometer G and sufficient extra non-inductive resistance T_2 to control the deflection within reasonable bounds. The other circuit, called the *primary* circuit, includes a key K, an adjustable resistance r_1, a battery B, and an ammeter A. The arrangement is shown in Fig. 57. The primary coil is P and the secondary S.

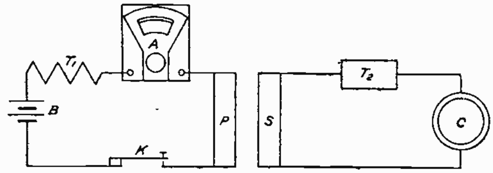


Fig. 57. Diagram of Ballistic Method of Mutual Inductance Measurement.

On closing the key K the current in P begins to increase and the galvanometer G begins to deflect. If we make no allowance for the false resistance due to the self-inductance of the secondary circuit, the current I_2 in the secondary is $I_2 = \frac{E}{R_2}$. As the current I_1 in the primary requires a considerable part of a second nearly to reach its maximum or steady value, it is evident that the secondary current I_2 will require at least an equal time to rise from zero to its maximum and to fall nearly to zero again. Theoretically it takes an infinite time for this to happen, but if the total resistance R_1 in the primary and R_2 in the secondary are reasonably large in comparison with their self-inductance, the time practically necessary is a second or so. The current I_2 in the secondary will, therefore, during the times that it flows, cause a certain quantity Q of electricity to pass through the galvanometer. If the ballistic galvanometer has a long period of swing—a condition required of ballistic galvanometers—practically the whole of the quantity Q will pass before the galvanometer gets far from its zero position. As the e. m. f. of the secondary is proportional to the rate of increase of the primary current I_1, it is evident that the *total* quantity flowing in the secondary will depend on the *total* rise of current in the primary in precisely the same way as the current *at any instant* in the secondary depends on the *rate of increase* of the current in the primary. As before mentioned, we have ignored the false resistance due to the self-inductance of the secondary. We have learned, however, in the chapter on self-inductance, that during the rise of a current the self-inductance increases the apparent resistance, but during its fall the opposite effect is produced. Therefore, during the rise and fall of the current in the secondary, no appreciable error is caused by ignoring the self-inductance of the secondary. The final result is $M I_1 = Q R_2$, or

$$M = \frac{Q R_2}{I_1}$$

To get the value of Q we must know the relation between the throw d_2 of the ballistic galvanometer to the quantity of electricity producing the throw. This may be found by charging a standard condenser of known capacity C by a standard cell of known e. m. f. E_s, and noting the deflection d on discharging the condenser through the ballistic galvanometer. As the charge of the condenser is $E_s C$, we obtain the result

$$Q : d_2 : : E_s C : d,$$

or

$$Q = \frac{d_2 E_s C}{d}$$

Substituting in the earlier equation the value of Q and expressing the capacity of the condenser in microfarads,

$$M = \frac{d_2 E_s C R_2}{d I_1 \times 10^6}$$

Example. The current I_1 in the primary coil rises on closing the circuit to 1 ampere. The total resistance in the secondary circuit is 10,000 ohms. The deflection produced is 21.3 cm. With a Weston normal cell of 1.0184 volts and a condenser of 0.2 microfarads, a deflection of 23.0 cm. was produced on discharging the condenser through the galvanometer. What is the mutual inductance M?

Ans. $M = 0.001886$ henry.

Alternating-Current Method. The previous method may be varied by putting in the secondary an alternating-current voltmeter of high resistance, and in the primary an A. C. ammeter, an e. m. f. source of sine form, and whatever resistance is needed to control the current. From the theory of alternating currents, the e. m. f. produced in the secondary is

$$E_2 = 2 \pi n M I_1,$$

or

$$M = \frac{E_2}{2 \pi n I_1},$$

when n is the frequency in cycles per second, M the mutual inductance, and I_1 the primary current. This relation assumes that the current in the secondary is too small to affect the flux of magnetic lines crossing over from primary to secondary. If the resistance of the secondary coil is small in comparison with that of the voltmeter, the voltmeter reading E_v is taken as E_2. If the coil is of too high resistance to make the last assumption allowable, the reading must be multiplied by $\frac{R_2}{R_v}$, when R_2 is the total resistance of the secondary and R_v the resistance of the voltmeter. We then get

$$E_2 = \frac{R_2}{R_v} E_v = 2 \pi n M I_1,$$

or

$$M = \frac{R_2 E_v}{2 \pi n R_v I_1}$$

If the secondary current I_2 is too large for its magnetic effect to be ignored, or if the current in the primary does not follow a simple sine law, the problem becomes too complex for easy solution.

Example. The current I_1 in the primary is 1.1 amperes, the frequency n is 60 cycles per second, the resistance of the secondary coil is negligible. The reading of the voltmeter E_v is 110 volts. What is the mutual inductance M? Ans. $M = 0.2653$.

Carey-Foster Method. Let a battery of constant e.m.f. be connected in series with one of the two coils P whose mutual inductance is to be determined, a known resistance R_1, and a key K, Fig. 58. Let the ballistic galvanometer G and another resistance R_2 be connected in series with the other coil S. Then if I be the steady current produced by the battery B through P, and M be the mutual inductance, and r be the resistance of the circuit through S, R_2, and the galvanometer, then the quantity of electricity Q, passing through the galvanometer on closing or opening the circuit will be

$$Q_1 = \frac{MI}{r}$$

Next, if the galvanometer be removed from this circuit and put in series with a condenser whose capacity is C, which is connected as a *shunt* to the resistance R_1, on opening or closing the battery circuit the quantity of electricity

$$Q_2 = IR_2C$$

By combining these two equations it is possible to find the relative values of C and M. In practice it is much more desirable to combine

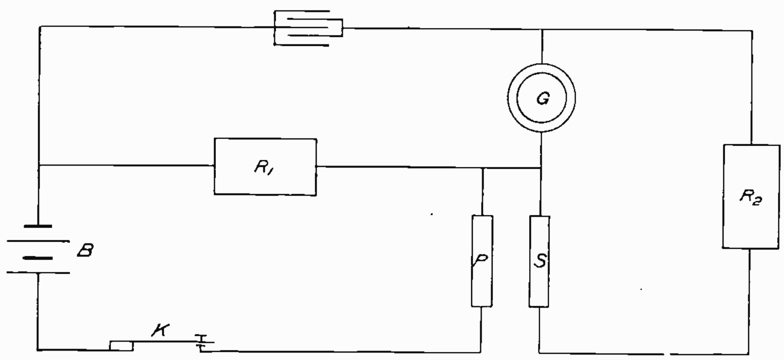


Fig. 58. Diagram of Carey-Foster Method of Measuring Mutual Inductance.

these two circuits, as shown above, so that the charge and discharge of the condenser and the currents produced at the same time in S by mutual induction are in the same direction through C, R_2, and S. Then if the resistance R_1 and R_2 and the capacity C are adjusted until no deflection of the galvanometer is produced, the following may be written:

$$Q_1r = MI, \text{ but } Q_1 = IR_1C; \text{ hence } M = CR_1r$$

Attention is called to the fact that in order that the galvanometer current may be 0 at every instant during the establishment of the steady current, it is essential that the coefficient of self induction of the coil S should be equal to the coefficient of mutual induction. Under this condition it is possible to replace the galvanometer by a telephone.

Example. Small Induction Coil, no iron core. Resistance of secondary, 194 ohms. Capacity of condenser, 4.9.26 microfarads

The secondary coil could slide endways remaining coaxial with the primary. The following are the results with the centers of the two coils as nearly coincident as possible:

R_1	r	R_1r (C. G. S. UNITS)	R_1	r	R_1r (C. G. S. UNITS)
15	194 + 217	6165×10^{18}	10	194 + 423	6170×10^{18}
14	+ 247	6174	9	+ 490	6156
13	+ 282	6188	8	+ 576	6160
12	+ 322	6192	7	+ 688	6174
11	+ 367	6171	6	+ 835	6174

$$\text{Mean value of } \frac{M}{C} = 6172.4 \times 10^{18}$$

Hence

$$M = 4.926 \times 10^{-15} \times 6172 \times 10^{18} = 3.04 \times 10^{7} \text{ or } .0304 \text{ henrys.}$$

MAGNETIC MEASUREMENTS

Certain materials, notably iron (or steel), nickel, and cobalt, have a property known as *magnetism*. These materials when magnetized have the property of attracting soft iron. The modern view of magnetism is that it is a property of the individual molecules of a body. A body which seems to be unmagnetized probably has its molecules arranged in more or less irregularly formed closed chains, Fig. 59, which produce no outside effect. To magnetize a body, it is, according to this theory, necessary to break the chains and to rearrange the connections of the molecules so that the ends of the chains of molecules come out at points on the surface where so-called magnetic charges appear, Fig. 60. The centers of action of these chain ends are called *poles*. In the simplest magnets there are two poles, and if the magnet is free to turn in a horizontal plane, one of the poles is turned toward the north and the other toward the south approximately. In general, the magnetic meridian, determined by the line joining the poles when at equilibrium in the horizontal plane, does not agree exactly with the geographical meridian. The line of no

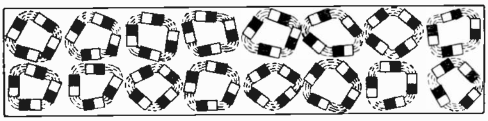


Fig. 59. Supposed Molecular Condition of a Piece of Unmagnetized Steel.

variation at present is located near the eastern shore of Lake Michigan and is moving westward. A century ago it was near the eastern end of Lake Erie. For points to the east of the line of no variation, the magnetic compass points west of north; and for points west of this line of no variation, it points east of north. The north seeking pole of a magnet is commonly called the *north pole* and the other the *south pole* of the magnet. If the magnet is free to turn in all directions, the north pole will dip downward and the south pole rise upward for points in the northern hemisphere and *vice versâ* for points in the southern hemisphere. The dip in Chicago is in the neighborhood of 70°.

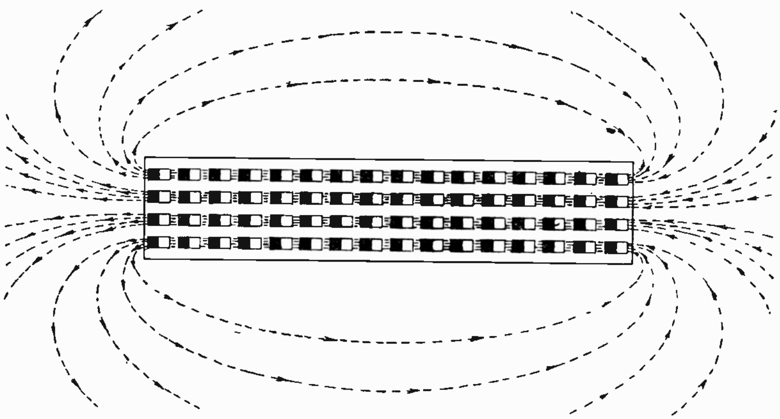


Fig. 60. Supposed Molecular Condition of a Magnetized Piece of Steel.

From the above it appears that the earth has a magnetic field, meaning by magnetic field an extent of space where magnetic forces are to be found. If a magnet with poles 1 cm. apart and of unit strength is in a unit magnetic field, it will act on each pole with a force of one dyne; and if the poles are turned so that the directions of the forces are at right angles to the line connecting the poles, a unit turning moment, or torque, is exerted on the magnet. In the first chapter of this book, unit magnetic pole was defined as a pole which, at a distance of one centimeter in air from a like pole, produces a repulsion of one dyne of force. It appears then that a magnetic field has both direction and magnitude, and is what is called a *vector* quantity. To define a vector quantity both magnitude and direction must be known.

Methods of Magnetizing. Besides natural magnets, composed of the magnetic oxide of iron and known as *loadstones,* artificial magnets may be made by subjecting hard steel to a magnetic field. The magnetic field used may be due to a loadstone, or an artificial magnet previously made, or a magnetic field due to an electric current in a coil of wire. Before 1819, when Oersted discovered the magnetic field produced by a current, the source of all artificial magnets was directly or indirectly the loadstone. Permanent magnets nowadays are practically all magnetized by means of electric currents.

Lines of Force and Permeability. To Michael Faraday we owe the notion of lines of force to express the vector quantity defining the magnetization. The direction of the lines is used to indicate the direction of magnetization, and the number of lines per square centimeter indicates the magnitude of the magnetization. The numbers of lines per square centimeter is commonly called the *flux density* or *flux of force* per square centimeter. The unit value occurs when there is one line per square centimeter, and is called the *gauss.* The symbol B is used to express this quantity algebraically. As different materials when put in equal fields take different degrees of magnetization, the relation of field strength to flux, known as the *permeability,* must be known. If H indicates the field strength, B the flux per sq. cm., and μ the permeability, we have the relation

$$B = \mu H$$

When the section considered has an area A sq. cms. and the average flux intensity is B, the total flux designated by Φ is algebraically expressed as

$$\Phi = B A = \mu H A$$

The unit in which Φ is measured is the Maxwell and is equal to one line of force.

If the lines of force pass from one material into another of different permeability μ, the lines representing B and Φ will usually suddenly change direction at the surface of separation between the materials, commonly called *media,* except in the case that the lines are normal to the surface. If the permeabilities of two media are μ_1 and

μ_2, and the angles between the normal and the lines in the two media are a_1 and a_2, we have the relation

$$\frac{\tan a_1}{\tan a_2} = \frac{\mu_1}{\mu_2}$$

Lines of force follow by preference paths of high permeability, though, other things being equal, they tend to follow the shorter paths. Consequently it rarely happens that the lines are straight, as they converge toward spaces filled with bodies of high permeability and there diverge again in spaces of low permeability. In general the total flux Φ distributes itself so that, length of path and permeability considered, it takes the easiest course. A line of force never ends, but always returns on itself. Many writers carelessly confuse and use the same unit (the gauss) for measuring **B** and **H**, for both are vector quantities and may be represented by lines. To avoid confusion we shall not represent **H** by lines. For highly magnetic materials, **B** is much greater than **H**. In the case of iron the ratio may be as high as $\mu = 3{,}000$ for moderate values of **B**. The value of μ is not constant for the same material for different values of **B**. In the case of soft iron the permeability for low values of **B** may be about $\mu = 120$, rising to $\mu = 2{,}000$, or in good samples $\mu = 3{,}000$, when **B** reaches a value between **B** = 5,000 to **B** = 8,500. For nickel and cobalt the highest value of the permeability is about $\mu = 200$. As a standard of comparison the permeability of air is taken as $\mu = 1$ and is believed to remain sensibly constant for all values of **B**. It follows that in air **H** = **B** (numerically). Materials more magnetic than air, for which $\mu > 1$, are called *paramagnetic*. Materials less magnetic than air, for which $\mu < 1$, are called *diamagnetic*. No magnetic material is without permeability, that is $\mu = 0$; in fact, even the most diamagnetic material, bismuth, is within a fraction of one per cent as permeable as air. Magnetic insulation is therefore impossible and to avoid magnetic leakage of lines of force from a prearranged path, it is necessary to distribute the *magnetomotive force* over the whole path.

Magnetomotive Force. By analogy with electric circuits, where the potential difference over each unit length of the circuit is found by multiplying the current by the resistance of that unit length, or dividing the current by the conductivity (the reciprocal of resistance) for the unit length, we see that in a part of a magnetic circuit, one centimeter long and one square centimeter in section, μ is analogous to the conductivity per cm. cube of an electric circuit. B is analogous to the current per sq. cm. of section of the conductor and H is analogous to the potential difference per centimeter length. H is called the magnetomotive force per unit length, and the total magnetomotive force is the average value of H multiplied by the length of the circuit l. It follows that the magnetomotive force (m. m. f.) is

$$\text{m. m. f.} = H\,l$$

If the magnetic field is produced by a current in a wire, the intensity of the field is greatest at the surface of the wire and falls in value to zero at the middle of the wire, and outside the wire falls in value according to the law of the reciprocal of the distance from the center. If, however, the wire is coiled into a long, straight coil of uniform section, called a *solenoid,* the magnetic field for the portion far from the ends is practically zero outside the solenoid and of uniform value inside the solenoid. If there are n turns of wire per centimeter and a current of I amperes, the inside magnetic field is

$$H = 0.4\,\pi\,n\,I = 1.2566\,n\,I$$

If the whole number of turns of wire is N, the magnetomotive force is

$$\text{m. m. f.} = 1.2566\,N\,I$$

The unit of m. m. f. is the *gilbert,* or that value of magnetic force which will establish one line or one maxwell per centimeter cube of air. Many practical authorities prefer to express the m. m. f. in *ampere turns* $N\,I$ omitting the factor 1.2566. This leads to some confusion if the fact is not made clear by stating that the m. m. f. is in ampere turns. If a long solenoid is bent into the form of a ring, it is called a *ring* solenoid. If the width of the ring is small in comparison with its diameter, it is assumed that the average value of H is equal to its value along the central line of the ring.

Reluctance. If a circuit is l centimeters long and averages A sq. cm. in section, the reluctance R of the whole circuit is

$$R = \frac{l}{A\,\mu}$$

The unit in which reluctance is measured is the *oersted.*

By analogy with Ohm's law the magnetic flux Φ is

$$\Phi = \frac{\text{m. m. f.}}{\text{reluctance}} = \frac{\text{m. m. f. } A\ \mu}{l} = \text{B } A = \mu \text{ H } A$$

Hysteresis. When iron or steel has been magnetized and the magnetizing force removed, a portion of the magnetization will still remain as more or less *permanent* magnetization. If next the magnetizing force is applied in the reverse direction, the magnetization will not be reversed until the m. m. f. has reached a certain value, *i. e.*, until H reaches a certain value. The residual value of B when the field is reduced to zero is called the *remanence* or *retentiveness* by some writers. The reverse field, m. m. f., necessary to reduce B to zero is called by the barbarous term (as Professor Mascart puts it) of *coercive force.* Further increase of the reverse m. m. f. will cause a rapid rise of B. With repeated cycles of change between positive and negative m. m. f.'s the values of H and B go through cycles. The tendency of B to lag behind H is called *magnetic lag* or *magnetic hysteresis*, hysteresis being the Greek word for lagging behind. A certain amount of energy is expended in the cycle and appears in the form of heat generated in the iron. This loss of energy per cycle is repeated *n* times per second, and the power used is known as the *hysteresis loss*, and is measured in watts per cubic centimeter. Sometimes the energy lost per cycle is measured in joules. One joule equals 10,000,000 ergs. The relation of H and B during the hysteresis cycle may be expressed in the form of a curve plotted in terms of H (horizontally) and B (vertically). The curve shown in Fig.

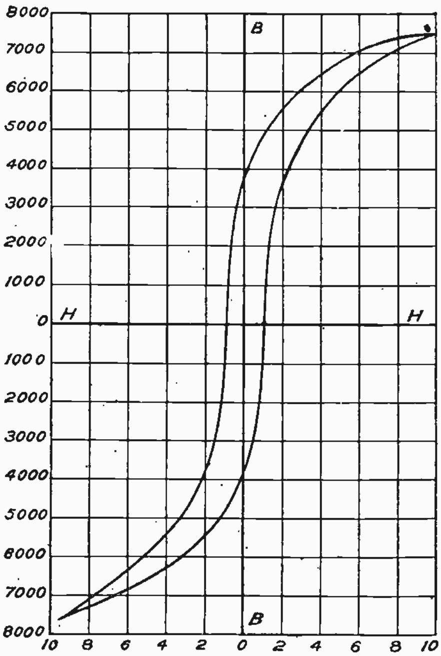
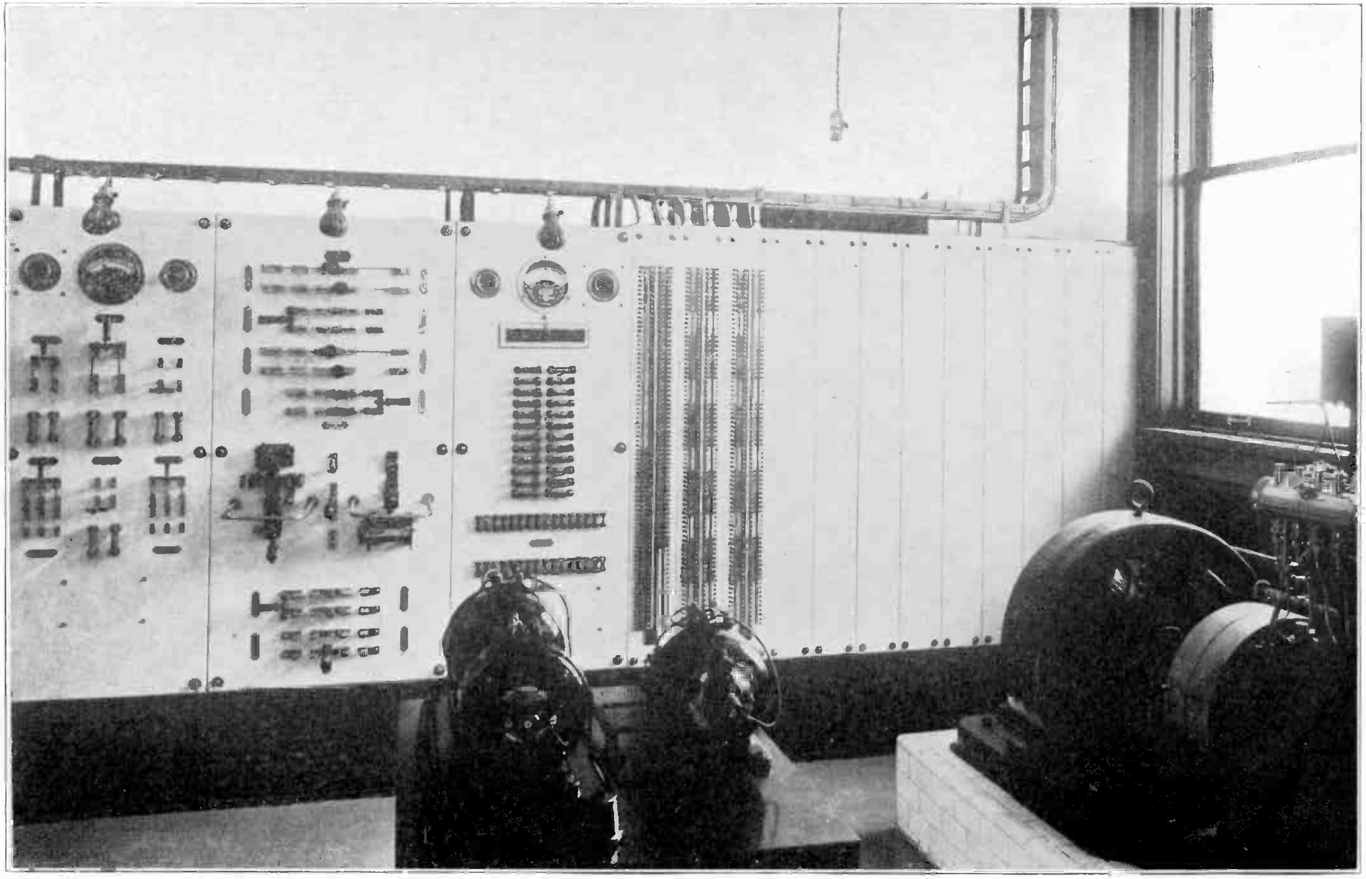


Fig. 61. Hysteresis Diagram.



POWER PLANT FOR AUTOMATIC SWITCHBOARD EQUIPMENT
Bay Cities Home Telephone Company, Berkeley, Cal.

61 is known as a *hysteresis curve*. If H and B are plotted to scale, the area of the curve divided by 40,000,000 π, or 125,660,000, gives the energy lost per cycle in joules. For measurements of hysteretic losses the sample may be made into the form of a ring with small difference between its largest and smallest radius. The ring may then be wound with a coil of wire in the form of a ring solenoid and the current and turns in the coil will determine the m. m. f. and consequently H in the core.

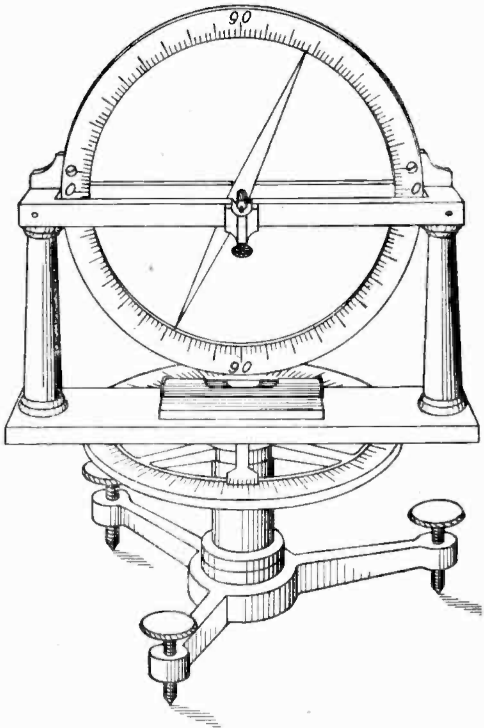


Fig. 62. Magnetic Dip Needle.

Magnetic Dip. *By Dip Needle.* If a long and slender magnetic needle, Fig. 62, with pointed ends is mounted on an axis passing precisely through its center of gravity, at the middle of an accurately graduated circle standing vertically in the magnetic meridian, the north pole of the needle will point downward from the horizontal by an angle equal to the magnetic dip. The angle of dip may then be read directly from the circle. As, however, it is difficult to magnetize the needle with exact uniformity, the bearing should be made reversible so that the needle may be turned over. Any irregularity of magnetization may be eliminated by taking the mean of the two readings of the magnet in the two positions. In case the bearing fails to pass exactly through the center of gravity, the error may be compensated by reversing the magnetization of the needle, care being taken to use the same magnetic field as before, and then repeat the observations of the dip with the magnet in both positions. The mean of the four readings will give the value of the dip. If the divided circle is not in the magnetic meridian, an error will be caused which is slight for slight deviations from the meridian. A compass needle mounted over the divided circle will locate the magnetic meridian well enough for practical purposes.

Earth Inductor Method. Another method is by use of the earth inductor which is a coil of wire mounted in a frame and which may be turned about an axis in the plane of the coil. No iron or other magnetic material should be used in the apparatus. The frame is carried on a support by which the axis of rotation may be made vertical or horizontal. The apparatus is shown in Fig. 63. All heavy parts are made of brass which is practically non-magnetic.

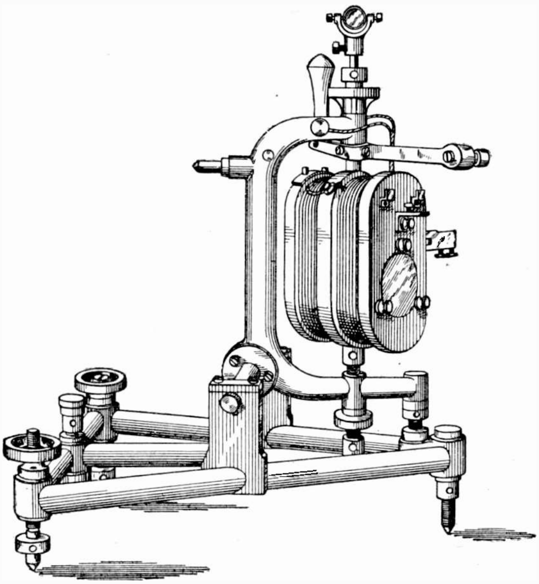


Fig. 63. Earth Inductor.

If the coil is turned about a vertical axis, as shown in the figure, from an east and west plane through 180° to the reverse position in the same plane, the number of lines = B A cos δ of the earth's magnetic field passing through the coil, will be cut by the coil, and if a ballistic galvanometer is in the circuit, its deflection d_1 will be proportional to the flux cut. If now the axis of rotation be made horizontal and the coil horizontal, a reversal in position will cut the number of lines = B A sin δ of the earth's magnetic field passing through the coil. The resulting deflection d_2 of the ballistic galvanometer is proportional to the flux cut. We then have the relation

$$\tan \delta = \frac{d_2}{d_1}$$

If the deflections are small they may be increased by reversing the position of the coil on the return swing of the galvanometer, and continuing until the amplitude of swing becomes constant. The deflections in two positions of the axis of the coil are proportional to the *horizontal* and the *vertical* components respectively of the magnetic field, and the ratio of the second to the first gives the tangent of the dip of the earth's field.

The angle of dip varies from + 90° at the earth's north magnetic pole to – 90° at the south magnetic pole. It is zero at the magnetic equator.

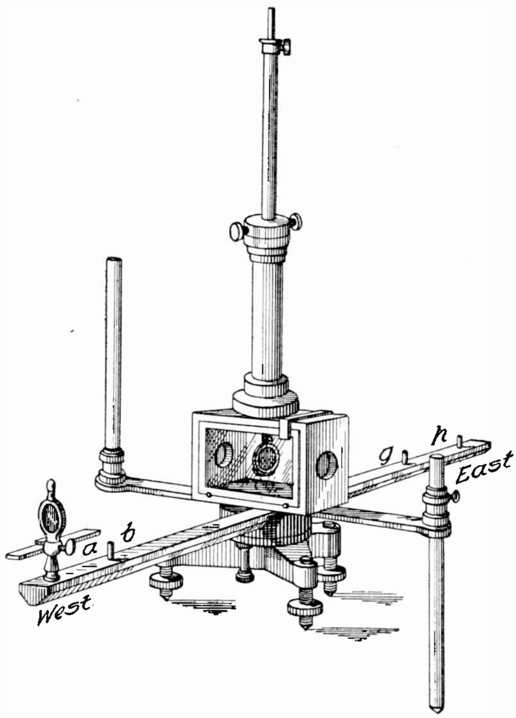


Fig. 64. Magnetometer.

The Earth's Magnetic Field. If in the previous method, the data of the earth inductor and of the ballistic galvanometer are known, the value of B may be determined. As the experiment is performed with air as the medium, the value of μ is 1, and H is numerically equal to B. The horizontal component of the earth's magnetic field is frequently spoken of as H, meaning thereby the *horizontal* component. In the same way V is the vertical component. The tangent of the angle of dip is the ratio

$$\frac{V}{H}$$

Magnetometer Method. The horizontal component may be measured by means of two magnets, one of which is of light weight and the other relatively large and heavy, both carrying mirrors. The little magnet and mirror may be suspended at the center of an instrument called a *magnetometer*, Fig. 64. The second magnet, of considerable size, is mounted on a support at its center at a fixed distance to the east of the little magnet and in an east and west position (point *g* of the figure). The small magnet takes up a position parallel to the resultant of the horizontal component of the earth's field and that of the large magnet. By means of a telescope and scale at a known distance, the angle of the deflection is measured. The other pole of the large magnet is now turned toward the small magnet by turning the large magnet end for end. The deflection measured by the telescope and scale should be as before, only in the opposite direction. The large magnet is now transferred to a support *b* at an equal distance to the west of the small magnet, and the observations repeated, obtaining two more deflections. All four deflections should be equal. If they differ slightly the mean is taken; if they differ much, something is wrong with the arrangement and the apparatus should be examined and the trouble corrected. The observations are now repeated at a larger distance (points *a* and *h*), and four more observations taken. From the data, assuming that the magnetic field falls off according to the inverse square of the distance from the poles of the magnet, a pair of equations may be formed from which the strength of the magnet's poles in terms of the horizontal component of the earth's field and their distance apart may be calculated. This distance apart of the poles will be found to be somewhat less than the length of the large magnet. The product of the pole strength and length between poles is called the *magnetic moment* of the magnet, represented by M. If r_2 = the larger distance, r_1 the smaller distance, and Φ_1 and Φ_2 the deflections, we get

$$M = \frac{H}{2} \frac{r_2^5 \tan \Phi_2 - r_1^5 \tan \Phi_1}{r_2^2 - r_1^2}$$

The large magnet is now hung up by a fine wire and set to vibrating. The period of vibration T_1 is determined by measuring with a stop watch the time of a considerable number of vibrations and finding the time of a single swing. If K_1 is the moment of inertia and θ the correction for the rigidity of the wire, we have

$$T_1 = \pi \sqrt{\frac{K_1}{M\,H(1 + \theta)}}$$

As there may be some difficulty in computing the moment of inertia

K_1, it is usual to add a brass ring of rectangular section and easily computed moment of inertia K_2. This ring must be placed on top of the magnet so that its center lies on the prolongation of the suspending wire. The moments of inertia are then added to get the total moment. There are reference marks on opposite ends of a diameter of the ring and corresponding marks on portions of a circle of the same radius of the ring marked on the top surface of the magnet to ensure precise centering. With the ring in position, the new time T_2 of vibration is determined.

$$T_2 = \pi \sqrt{\frac{K_1 + K_2}{MH(1 + \theta)}}$$

θ is determined by turning the torsion head, from which the magnet is hung by the wire, through a considerable angle and determining by the telescope and scale the angle through which the magnet follows. This enables one to compute how much effect the rigidity of the wire has on the restoring force which is due principally to the earth's field. If on turning the torsion head an angle α, the magnet follows an angle β, there is obtained, $\theta = \frac{\beta}{\alpha - \beta}$. Combining the earlier equations gives

$$MH = \frac{\pi^2 K_2}{(1+\theta)(T_2^2 - T_1^2)}$$

Substituting the value of M previously obtained we get on solving for H

$$H = \pi \sqrt{\frac{2 K_2 (r_2^2 - r_1^2)}{(1 + \theta)(T_2^2 - T_1^2)(r_2^5 \tan \Phi_2 - r_1^5 \tan \Phi_1)}}$$

The value of H in the southern part of Michigan is about 0.18 and the vertical component is about three times as strong or about 0.54. As the presence of masses of iron in the neighborhood has a considerable effect on the dip of the magnetic field and also on the value of the field, a measurement made in any place with iron masses near by, cannot be assumed as valid for even other parts of the same building. Laboratories for the study of the earth's magnetic field should have all iron excluded from the building materials and from the apparatus except the magnets.

If the angle of dip δ has been found by one of the previous methods, the total value of the earth's magnetic field F is

$$F = \frac{H}{\cos \delta}$$

The bars N and L shown in Fig. 51 are not used in this experiment.

Magnetic Flux and Permeability. There are a number of excellent methods of determining flux and permeability, of which the following will suffice for the purposes of this work.

Divided Bar Method. The divided bar method assumes that the material under test is in the form of two long iron bars or rods with the ends ground and polished into accurately plane surfaces. One bar, with the polished end upward, is mounted in a long solenoid, the polished end being at the middle of the solenoid. The other bar is placed on top of the first with the polished ends resting one on the other and accurately centered. The upper piece is attached to a spring balance which is used to measure the tension necessary to separate the bars. If the weight of the upper piece is subtracted, the remainder gives the pull. The bars and the solenoid must be long enough to have the magnetic field H at the surfaces in contact practically equal to what it would be in an infinitely long solenoid, for which I is the current in amperes and n the number of turns of wire per centimeter length, otherwise a correction must be made for the ends.

$$H = 0.4\,\pi\,n\,I = 1.2566\,n\,I$$

If the area of the ends of the bar is S sq. cm., and the force in grams (weight) F, the value of gravity g (= 980 about), we get for the flux density B,

$$B = \sqrt{\frac{8\,\pi\,g\,F}{S}} = 156.9\sqrt{\frac{F\ \text{(grams)}}{S\ \text{(sq.cm.)}}}$$

If the pull F is measured in pounds and the area S in square inches, we must allow for the ratio of the units. We then obtain

$$B = 1316\sqrt{\frac{F\ \text{(pounds)}}{S\ \text{(sq. in.)}}}$$

In using the method, the spring balance should be supported in guides and drawn upward gradually by means of a turn-buckle or analogous means. The last reading before the bars separate is the one to be taken. If the bars are rounded at the corners an error will be made because the value of B will be increased at the smaller section to a greater value than back in the rod, as the total flux Φ is spread over a smaller area. The pull will be increased because from the above formula it appears that the pull is proportional to the product SB^2. Therefore avoid rounding the edges. If the surfaces do not fit one another, the air where they do not touch will have a lower permeability and there will be a tendency for some of the flux to escape at the side, thus reducing B and consequently the pull.

To obtain the permeability μ divide B by H. As mentioned earlier the permeability increases as B increases, reaching a maximum for moderate values of B and then falls off rapidly for further increase of B.

A magnetization curve (B, H curve) or a permeability curve (B, μ curve) may be plotted from values obtained for different values of B, H, and μ. A bar of iron which has never previously been magnetized, will behave for small values of H differently from what it will again. For this reason the values of H used should increase gradually from lower to higher values. A bar once magnetized cannot be brought back to its original condition by any process except heating it to the temperature at which it becomes practically unmagnetic and then cooling it again, retempering it if necessary. If it is demagnetized by reversing the direction of the field and reducing the latter to lower values gradually on each reversal, most of the magnetism may be removed. This is supposed to reduce the magnetization of the bar to a set of concentric magnetizations in opposite directions in successive concentric layers. This is not quite equivalent to the irregular chains of molecules in a bar which has never been magnetized. A bar which has been demagnetized by a simple reversal of the field to a value apparently reducing B to zero, results in reversing the outer layer only, making the total flux zero *algebraically* as the sum of two *equal* and *opposite* fluxes in concentric layers.

Divided Ring Method. The divided ring method has the material in the form of a ring which has been cut in two and the opposite surfaces polished. The surfaces should be exactly in the same plane to insure a close fit when the ring is put together again. The pull necessary to separate the ring is twice as much as for one surface; so the total pull, after allowing for the weight of the upper part, should be divided by two before applying the previous formula. The ring is magnetized by a ring solenoid surrounding it. The solenoid is in two parts which separate with the parts of the ring.

Ballistic Method. If the material to be tested is in the form of a very long rod, say, 50 diameters in length, or better in the form of a ring, Fig. 65, with little difference between the outer and the inner radius, surrounded by a solenoid of n turns per cm. length through which the current I amp. passes, the field is H = 1.2566 n I. A secondary coil of a small number of turns (of which all or a part only may be used) is wound about the ring and is connected to a ballistic galvanometer whose throw for a known quantity passing is known. The ratio K of quantity to throw may be found by charging a condenser of known capacity C microfarads by a standard cell of e. m. f. E volts, and discharging it through a ballistic galvanometer, producing a deflection d. The constant K is then $K = \frac{E\,C}{d \times 10^6}$. Or the galvanometer constant may be determined by winding a solenoid of n_1 turns per cm. on a core of wood or other material of the same permeability as air, for which μ equals 1. H then equals B, and the flux passing through the core whose area is A_1, the current being I_1, is

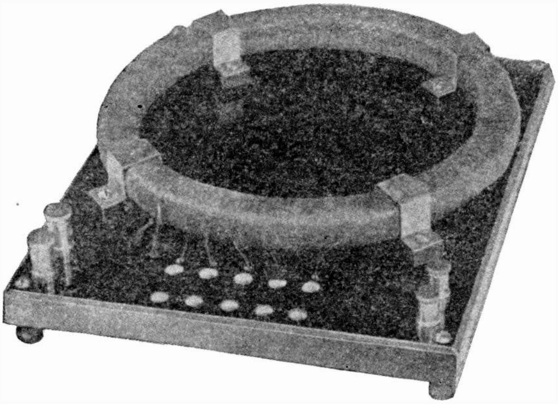


Fig. 65. Iron in Ring Form for Ballistic Measurement.

$$\Phi_1 = 1.2566\ n_1\ A_1\ I_1$$

The total quantity of electricity Q_1 passing through a ballistic galvanometer in series with a secondary circuit of m_1 turns and in a circuit of total resistance R_1, on making or breaking the primary circuit I_1, is

$$Q_1 = \frac{m_1\ \Phi_1}{R_1} = \frac{1.2566\ n_1\ m_1\ A_1\ I_1}{R_1}$$

If the deflection is d_1, the quantity per unit deflection is

$$\frac{Q}{d_1} = \frac{1.2566\ n_1\ m_1\ A_1\ I_1}{R\ d_1} = K$$

K is called the *constant* of the ballistic galvanometer.

If the primary circuit, the solenoid, has n turns per centimeter length, and the secondary circuit a total number m of turns, and the area of the section of the ring is A, and the resistance of the secondary circuit is R, and the deflection is D on reversing the primary circuit of I amperes, we have the flux

$$\Phi = \frac{R\ D\ K}{2\ m}$$

and

$$\mathrm{B} = \frac{\Phi}{A} = \frac{R\ D\ K}{2\ A\ m}$$

The current must be reversed suddenly, some form of commutator being used, otherwise the galvanometer may not feel the full effect. We had previously

$$\mathrm{H} = 1.2566\ n\ I$$

The value of the permeability for any value of **H** is

$$\mu = \frac{\mathrm{B}}{\mathrm{H}}$$

In using the method the current in the primary is *reversed* because otherwise the residual magnetism will produce a disturbance. If in the experiment the current starts at small values, the disturbing effects of previous magnetization is a minimum. We then insert a high resistance in the circuit at first and note the deflection of the galvanometer on reversing the current. Then increasing the current, the process is repeated. Several reversals should be made at each value of the current until enough observations have been made to ensure an accurate result. The deflection on the first reversal is apt to be different from those following. The **B**, **H** curve obtained by this method starts from the origin.

Hysteresis Curves. If instead of reversing the current it is simply changed by a sudden change in the resistance, the deflection will measure the change in **B**. Starting with no current in the primary and the ring unmagnetized, the circuit is suddenly closed with auxiliary resistance in circuit and the throw of the galvanometer noted as well as the current in the primary. The values of **B** and **H** are determined. Next the current is suddenly increased by cutting out part of the resistance and the deflection noted and the ammeter read. The deflection of the galvanometer measures the *increase* of **B**. The value of **B** is found by adding the *increase* to the previous value. The current is again increased and the deflection of the galvanometer will measure the increase of B. This is added to the previous total, and so on until the value of B is found for the highest value of H which is to be used. The current, and consequently H, is now reduced by steps, and the deflections of the galvanometer in the opposite direction will measure the decrease of B. To obtain the value of B, these decreases in B are subtracted from the previous value. When the zero value of the current, and consequently of H, is reached, the value of B will still be a considerable amount. The current is now reversed and built up by steps and the deflections will measure the continued decrease of B to zero and its reversal and building up in the reverse direction. This is continued until the maximum reverse value H is reached, equal, we will say, to its previous positive maximum. The current is reduced by steps to zero, reversed, and built up again in the first direction. The deflections measuring changes in B are noted and the total computed by the algebraic sum of all that precede. The sum of all the deflections corresponding to all the steps from the positive maximum to the negative maximum, should equal the sum in the reverse direction. The B, H curve will then make a closed curve for each cycle after the first quarter cycle. The curve for the first quarter cycle starts from the origin and never returns there again. As explained before, the magnetization lags behind the field H, producing the magnetization.

If the curve of B and H, as obtained by this method, is plotted, it is called a *hysteresis curve*, Fig. 61. The curve plotted to scale has an area to 4 π times the energy in ergs expended per cubic centimeter per cycle. Dividing the area by $4 \times \pi \times 10^7$ gives the energy in joules per cycle. If the cycle were run through n times per second, the power in watts would be equal to $\frac{\text{area of curve} \times n}{40{,}000{,}000\ \pi}$ watts expended in each cubic centimeter. This is what happens when an alternating current is used.

There are two sources of error which may cause trouble in this experiment and which have not been mentioned above. The first is the effect of the current in the primary producing eddy currents in the material of the ring, just as currents are produced in the secondary circuit. In fact, the material of the ring is in itself a secondary circuit of a single turn, and currents in the material of the ring will be parallel to the current in the secondary outside. These eddy currents produce a magnetic field in the ring which opposes the rise of H and B in the ring. Therefore, H in the ring rises slower than the current in the primary coil; and unless the period of the galvanometer is high, some of the effect of the increase of B, which may be slow in increasing, will come too late to be measured by the galvanometer deflection. The other trouble is that if there is any vibration the magnetization may change by small steps one for each shock. This causes the magnetization to creep up or down, depending on whether the field has last been increased or decreased. To avoid the first error it is well to have the material in the form of thin sheets which give little chance for eddy currents, and to avoid the second the ring should rest on a pad of felt or other material which will absorb the vibrations.

Hysteresis Tester. A method of comparing the hysteresis loss of different samples of iron is to compare their effect in dragging the magnetic field when samples are rotated in a constant magnetic field Suppose the sample takes the form of a disk between a pair of field magnet poles. If the disk is at rest the field will produce a flux density B in the disk parallel to H. If the disk is now rotated the residual magnetization will cause the flux to rotate with the disk until the tangential component arrests further rotation of the flux. H and B then make a small angle with one another for very soft iron in the disk, and a proportionately larger angle for harder iron which shows more hysteresis. The turning moment required to rotate the disk will be proportional to the energy expended per cycle. If the poles are free to turn, they will follow the disk. If the poles are kept from rotating by some counter moment due to springs or gravitational action, the displacement of the poles in the direction of rotation of the disk will measure the relative hysteresis loss. If with one sample disk the displacement is twice that produced by another sample, the hysteresis loss is about double. If the hysteresis loss is known for one disk that of the other may be computed.

As the relative twist of B with respect to H is the same for all moderate speeds of rotation, it is not necessary to be careful about the exact speed of rotation. Also it is not necessary that the sample be in the form of a disk. The same relation for samples in the form of bundles of equal size strips will be found to hold true. The absolute angles of twist will be different, but they will have a ratio of equal value.

Professor Ewing has devised a hysteresis tester in which the sample, in the form of a bundle of strips, is rotated by means of a crank and gear train between the poles of a permanent magnet which is mounted on knife edges at a point above its center of gravity. The magnet follows the rotating bundle until the gravitational force gives an equal torque in the opposite direction.

If the sample is in the form of a solid bar, eddy currents of considerable magnitude may be produced which will complicate the results and introduce more or less uncertainty. Moreover, the eddy currents will be greater at higher than at lower rates of rotation, thus introducing different corrections at different speeds. For these reasons the bundle must be well laminated to obtain reliable results.

STANDARD SYMBOLS FOR WIRING PLANS

AS ADOPTED AND RECOMMENDED BY

THE NATIONAL ELECTRICAL CONTRACTORS ASSOCIATION OF THE UNITED STATES and THE AMERICAN INSTITUTE OF ARCHITECTS,

Copies may be had on application to the Sec'y of The Nat. Elec Cont. Assoc'n, Utica, N. Y., and the Sec'y of The American Instit. of Architects, Washington, D. C.

Ceiling Outlet, Electric only Numeral in center indicates number of Standard 16 C. P. Incandescent Lamps

Ceiling Outlet, Combination. $\frac{4}{2}$ indicates 4-16 C. P Standard Incandescent Lamps and 2 Gas Burners. If gas only

Bracket Outlet; Electric only. Numeral in center indicates number of Standard 16 C. P. Incandescent Lamps.

Bracket Outlet, Combination. $\frac{4}{2}$ indicates 4-16 C. P Standard Incandescent Lamps and 2 Gas Burners. If gas only

Wall or Baseboard Receptacle Outlet. Numeral in center indicates number of Standard 16 C. P Incandescent Lamps.

Floor Outlet. Numeral in center indicates number of Standard 16 C. P Incandescent Lamps.

Outlet for Outdoor Standard or Pedestal, Electric only Numeral indicates number of Stand. 16 C. P Lamps.

Outlet for Outdoor Standard or Pedestal, Combination. $\frac{6}{6}$ indicates 6-16 C. P Stand. Incan. Lamps; 6 Gas Burners.

Drop Cord Outlet.

One Light Outlet, for Lamp Receptacle.

Arc Lamp Outlet.

Special Outlet, for Lighting, Heating and Power Current, as described in Specifications.

Ceiling Fan Outlet.

S^1 S. P Switch Outlet.

S^2 D. P Switch Outlet.

S^3 3-Way Switch Outlet.

S^4 4-Way Switch Outlet.

S^D Automatic Door Switch Outlet.

S^E Electrolier Switch Outlet.

Show as many Symbols as there are Switches. Or in case of a very large group of Switches, indicate number of Switches by a Roman numeral, thus: S^1 XII, meaning 12 Single Pole Switches.

Describe Type of Switch in Specifications, that is, Flush or Surface, Push Button or Snap.

Meter Outlet.

Distribution Panel.

Junction or Pull Box.

Motor Outlet, Numeral in center indicates Horse Power.

Motor Control Outlet.

Transformer

Main or Feeder run concealed under Floor

Main or Feeder run concealed under Floor above.

Main or Feeder run exposed.

Branch Circuit run concealed under Floor.

Branch Circuit run concealed under Floor above.

Branch Circuit run exposed.

Pole Line.

Riser.

Telephone Outlet, Private Service.

Telephone Outlet, Public Service.

Bell Outlet.

Buzzer Outlet.

Push Button Outlet; Numeral indicates number of Pushes.

Annunciator. Numeral indicates number of Points.

Speaking Tube.

Watchman Clock Outlet.

Watchman Station Outlet

Master Time Clock Outlet.

Secondary Time Clock Outlet.

Door Opener.

Special Outlet; for Signal Systems, as described in Specifications.

Battery Outlet.

Circuit for Clock, Telephone, Bell or other Service, run under Floor, concealed.
Kind of Service wanted ascertained by Symbol to which line connects.

Circuit for Clock, Telephone, Bell or other Service, run under Floor above, concealed.
Kind of Service wanted ascertained by Symbol to which line connects.

NOTE—If other than Standard 16 C. P. Incandescent lamps are desired, Specifications should describe capacity of Lamp to be used.

SUGGESTIONS IN CONNECTION WITH STANDARD SYMBOLS FOR WIRING PLANS

It is important that ample space be allowed for the installation of mains, feeders, branches and distribution panels

It is desirable that a key to the symbols used accompany all plans.

If mains, feeders, branches and distribution panels are shown on the plans, it is desirable that they be designated by letters or numbers.

Heights of Centre of Wall Outlets (unless otherwise specified)

Living Rooms	5′ 6″
Chambers	5′ 0″
Offices	6′ 0″
Corridors	6′ 3″

Height of Switches (unless otherwise specified) 4′ 0″

ELECTRIC WIRING

METHODS OF WIRING

The different methods of wiring which are now approved by the National Board of Fire Underwriters, may be classified under four general heads, as follows:

1. Wires Run Concealed in Conduits.
2. Wires Run in Moulding.
3. Concealed Knob and Tube Wiring.
4. Wires Run Exposed on Insulators.

WIRES RUN CONCEALED IN CONDUITS

Under this general head, will be included the following:

(*a*) Wires run in rigid conduits.
(*b*) Wires run in flexible metal conduits.
(*c*) Armored cable.

Wires Run in Rigid Conduit. The form of rigid metal conduit now used almost exclusively, consists of plain iron gaspipe the interior surface of which has been prepared by removing the scale and by removing the irregularities, and which is then coated with flexible enamel. The outside of the pipe is given a thin coat of enamel in some cases, and, in other cases, is galvanized. Fig. 1 shows one make of enameled (unlined) conduit.

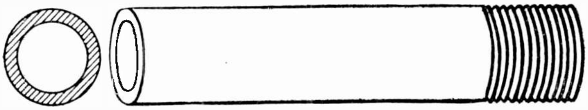


Fig. 1. Rigid Enameled Conduit, Unlined.
Courtesy of American Conduit Mfg. Co., Pittsburg, Pa.

Another form of rigid conduit is that known as the *armored conduit,* which consists of iron pipe with an interior lining of paper impregnated with asphaltum or similar compound. This latter form of conduit is now rapidly going out of use, owing to the unlined pipe being cheaper and easier to install, and owing also to improved methods of protecting the iron pipe from corrosion, and to the introduction of additional braid on the conductors, which partly compensates for the pipe being unlined. The introduction of improved devices—such as outlet insulators, for protecting the conductors from the sharp edges of the pipe, at outlets, cut-out cabinets, etc.—also decreases the necessity of the additional protection afforded by the interior paper lining.

Rigid conduits are made in gaspipe sizes, from one-half inch to three inches in diameter. The following table gives the various data relating to rigid, enameled (unlined) conduit:

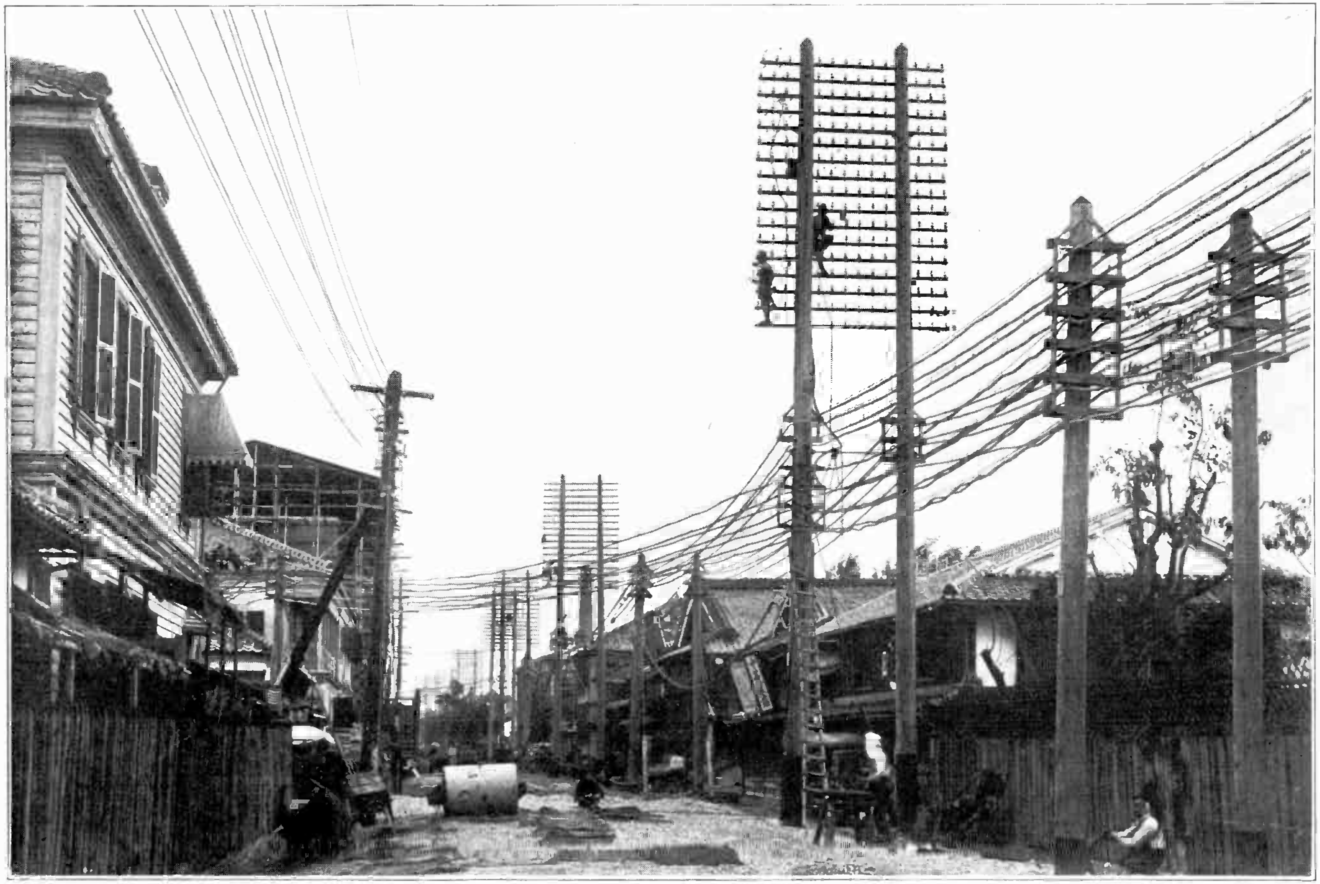
TABLE I
Rigid, Enameled Conduit—Sizes, Dimensions, Etc.

Standard Pipe Size	Thickness	Nominal Weight per 100 Feet	Number of Threads per Inch of Screw	Actual Outside Diameter. Inches	Nominal Inside Diameter. Inches
½	.109	84	14	.84	.62
¾	.113	112	14	1.05	.82
1	.134	167	11½	1.31	1.04
1¼	.140	224	11½	1.66	1.38
1½	.145	268	11½	1.90	1.61
2	.154	361	11½	2.37	2.06
2½	.204	574	8	2.87	2.46
3	.217	754	8	3.50	3.06

Tables II, III, and IV give the various sizes of conductors that may be installed in these conduits. Caution must be exercised in

TABLE II
Single Wire in Conduit

Size Wire, B. & S. G.	Loricated Conduit, Unlined; D. B. Wire
No. 14-4	½ inch
" 2	¾ "
" 1	¾ "
" 0	¾ inch or 1 "
" 00	1 "
" 000	1 "
" 0000	1 "
250,000 C. M.	1¼ "
300,000 C. M.	1¼ "
350,000 C. M.	1¼ "
400,000 C. M.	1¼ " or 1½ "
450,000 C. M.	1½ "
500,000 C. M.	1½ "
600,000 C. M.	1½ " or 2 "
700,000 C. M.	2 "
800,000 C. M.	2 "
900,000 C. M.	2 "
1,000,000 C. M.	2 " or 2½ "
1,500,000 C. M.	2½ "
1,700,000 C. M.	3 "
2,000,000 C. M.	3 "



AËRIAL TELEPHONE CONSTRUCTION IN JAPAN

TABLE III
Two Wires in One Conduit

Size Wire, B. & S. G.	Loricated Conduit, Unlined; D. B. Wire
No. 14	½ inch.
" 12	½ inch or ¾ "
" 10	¾ "
" 8	1 "
" 6	1 "
" 5	1 " or 1¼ "
" 4	1¼ "
" 3	1¼ "
" 2	1¼ " or 1½ "
" 1	1½ "
" 0	1½ "
" 00	1½ " or 2 "
" 000	2 "
" 0000	2 "
250,000 C. M.	2 " or 2½ "
300,000 C. M.	2½ "
350,000 C. M.	2½ "
400,000 C. M.	2½ " or 3 "
450,000 C. M.	3 "
500,000 C. M.	3 "
600,000 C. M.	3 "
700,000 C. M.	3 "

TABLE IV
Three Wires in One Conduit

Size Wire, B. & S. G.		Loricated Tube, Unlined; D. B. Wire
Outside	Center	
No. 14	No. 12	¾ inch
" 12	" 10	¾ "
" 10	" 8	1 "
" 8	" 6	1 "
" 6	" 4	1¼ "
" 5	" 2	1¼ "
" 4	" 1	1¼ inch or 1½ "
" 3	" 0	1½ "
" 2	" 2/0	1½ " or 2 "
" 1	" 3/0	2 "
" 0	" 4/0	2 "
" 2/0	250 M.	2 " or 2½ "
" 3/0	300 M.	2½ "
" 4/0	400 M.	2½ "
250 M.	450 M.	2½ " or 3 "
250 M.	500 M.	3 "
300 M.	600 M.	3 "
350 M.	700 M.	3 "
400 M.	800 M.	3 "
450 M.	900 M.	3 "

using these tables, for the reason that the sizes of conductors which may be safely installed in any run of conduit depend, of course, upon the length of and the number of bends in the run. The tables are based on average conditions where the run does not exceed 90 to 100 feet, without more than three or four bends, in the case of the smaller sizes of wires for a given size of conduit; and where the run does not exceed 40 to 50 feet, with not more than one or two bends, in the case of the larger sizes of wires, for the same sizes of conduit.

Unlined conduit can be bent without injury to the conduit, if the conduit is properly made and if proper means are used in making the bends. Care should be exercised to avoid flattening the tube as a result of making the bend over a sharp curve or angle.

In installing iron conduits, the conduits should cross sleepers or beams at right angles, so as to reduce the amount of cutting of the beams or sleepers to a minimum.

Where a number of conduits originate at a center of distribution, they should be run at right angles for a distance of two or three feet from the cut-out box, in order to obtain a symmetrical and workmanlike arrangement of the conduits, and so as to have them enter the cabinet in a neat manner. While it is usual to use red or white lead at the joints of conduits in order to make them water-tight, this is frequently unnecessary in the case of enameled conduit, as there is often sufficient enamel on the thread to make a water-tight joint.

When iron conduits are installed in ash concrete, in Keene cement, or, in general, where they are subject in any way to corrosive action, they should be coated with asphaltum or other similar protective paint to prevent such action.

While the cost of circuit work run in iron conduits is usually greater than any other method of wiring, it is the most permanent and durable, and is strongly recommended where the first cost is not the sole consideration. This method of wiring should always be used in fireproof buildings, and also in the better class of frame buildings. It is also to be recommended for exposed work where the work is liable to disturbance or mechanical damage.

Wires Run in Flexible Metal Conduit. This form of conduit, shown in Fig. 2, is described by the manufacturers as a conduit composed of "concave and convex metal strips wound spirally upon each other in such a manner as to interlock several concave surfaces and present their convex surfaces, both exterior and interior, thereby securing a smooth and comparatively frictionless surface inside and out."

The field for the use of this form of conduit is rapidly increasing. Owing to its flexibility, conduit of this type can be used in numerous cases where the rigid conduit could not possibly be employed. Its use is to be recommended above all the other forms of wiring, except that installed in rigid conduits. For new fireproof buildings, it is not so durable as the rigid conduit, because not so water-tight; and it is very difficult, if not impossible, to obtain as workmanlike a conduit system with the flexible as with the rigid type of conduit. For completed or old frame buildings, however, the use of the flexible conduit is superior to all other forms of wiring.

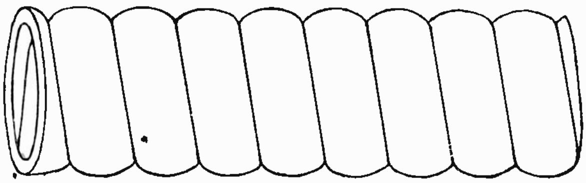


Fig. 2. Flexible Steel Conduit.
Courtesy of Sterling Electric Co., Troy, N. Y.

Table V gives the inside diameter of various sizes of flexible conduit, and the lengths of standard coils. inside diameter of this conduit is the same as that of the rigid conduit; and the table given for the maximum sizes of conductors which may be installed in the various sizes of conduits, may be used also for flexible steel conduits, except that a little more margin should be allowed for flexible steel conduits than for the rigid conduits, as the stiffness of the latter makes it possible to pull in slightly larger sized conductors.

TABLE V

Greenfield Flexible Steel Conduit

Inside Diameter	Approximate Feet in Coil
$\frac{5}{16}$ inch	200
$\frac{3}{8}$ "	200
$\frac{1}{2}$ "	100
$\frac{3}{4}$ "	50
1 "	50
$1\frac{1}{4}$ inches	50
$1\frac{1}{2}$ "	50
2 "	Random Lengths
$2\frac{1}{2}$ "	" "
3 "	" "

This conduit should, of course, be first installed without the conductors, in the same manner as the rigid conduit. Owing to the flexibility of this conduit, however, it is absolutely essential to fasten it securely at all elbows, bends, or offsets; for, if this is not done, considerable difficulty will be experienced in drawing the conductors in the conduit.

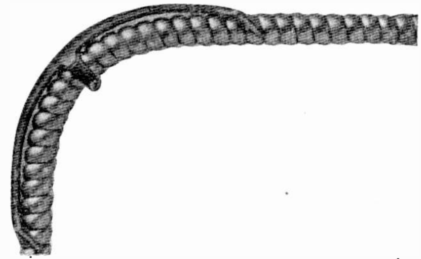


Fig. 3. Use of Elbow Clamp for Fastening Flexible Conduit in Place.

The rules governing the installation of this conduit are the same as those covering rigid conduits. Double-braided conductors are required, and the conduit should be grounded as required by the *Code Rules*. As already stated, the conduit should be securely fastened (in not less than three places) at all elbows; or else the special elbow clamp made for this purpose, shown in Fig. 3, should be used.

In order to cut flexible steel conduit properly, a fine hack saw should be employed. Outlet-boxes are required at all outlets, as well as bushing and wires to rigid conduit. Fig. 4 shows a coil of flexible steel conduit. Figs. 5, 6, and 7 show, respectively, an outlet box and cover, outlet plate, and bushing used for this conduit.

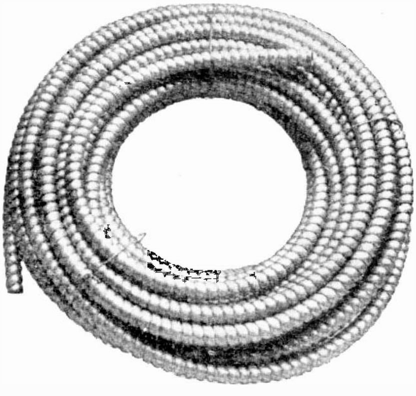


Fig. 4. A 100-Foot Coil of Flexible Steel Conduit.
Courtesy of Sprague Electric Co., New York, N. Y.

Armored Cable. There are many cases where it is impossible to install a conduit system. In such cases, probably the next best results may be obtained by the use of *steel armored cable.* The rules governing the installation of armored cable are given in the *National Electric Code*, under Section 24-A, and Section 48; also in 24-S. This cable is shown in Fig. 8.

Steel armored cable is made by winding formed steel strips over the insulated conductors. The steel strips are similar to those used for the steel conduit. Care is taken in forming the cable, to avoid crushing or abraiding the insulation on the conductors as the steel

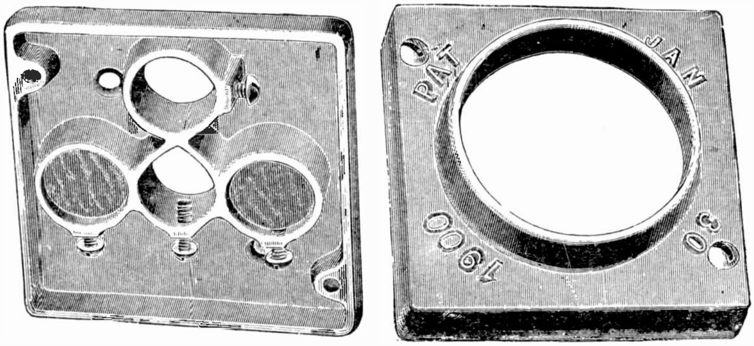


Fig. 5. Outlet Box for Flexible Steel Conduit.

strips are fed and formed over the same. In the process of manufacture, the spools of steel ribbon are of irregular length, and when a

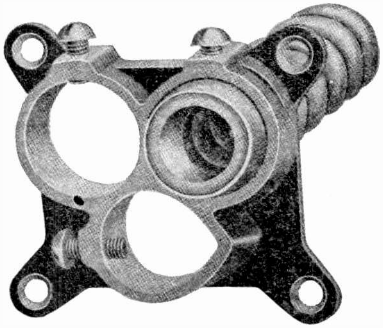


Fig. 6. Outlet Plate for Flexible Steel Conduit.

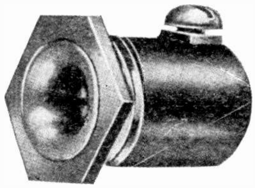


Fig. 7. Outlet Bushing.
Courtesy of Sprague Electric Co., New York, N. Y.

spool is empty, the machine is stopped, and the ribbon is started on the next spool, the process being continued. There is no reason why

Fig. 8. Flexible Armored Cable. Twin Conductors.
Courtesy of Sprague Electric Co., New York, N. Y.

the conduit cables could not be made of any length; but their actual lengths as made are determined by convenience in handling. Armored cable is made in *single conductors* from No. 1 to No. 10 B. & S. G.; in *twin conductors,* from No. 6 to No. 14 B. & S. G.; and *three-conductor* cable, from No. 10 to No. 14 B. & S. G. Table VI gives various data relating to armored conductors:

TABLE VI

Armored Conductors—Types, Dimensions, Etc.

Size B. & S Gauge	Type and Number of Conductors	Outside Diameter (Inches)
No. 14	BX twin conductor	.63
" 12	" " "	.685
" 10	" " "	.725
" 8	" " "	.875
" 6	" " "	1.3125
" 14	BM twin conductor (for marine work—ship wiring)	.725
" 12	" " "	.725
" 10	" " "	.73
" 14	BX3 three conductor	.71
" 12	" " "	.725
" 10	" " "	.73
" 14	BXL twin conductor, leaded	.725
" 12	" " " "	.725
" 10	" " " "	.87
" 14	BXL3 three conductor, leaded	.90
" 12	" " " "	.90
" 10	" " " "	.94
" 10	Type D single conductor, stranded	.550
" 8	" " " " "	.550
" 6	" " " " "	.575
" 4	" " " " "	.700
" 2	" " " " "	.900
" 1	" " " " "	.965
" 10	Type DL single conductor, stranded, leaded	.625
" 8	" " " " " "	.710
" 6	" " " " " "	.700
" 4	" " " " " "	.760
" 2	" " " " " "	.920
" 1	" " " " " "	.910
	Steel Armored Flexible Cord	
" 18	Type E twin conductor	.40
" 16	" " " "	.40
" 14	" " " "	.47
" 18	Type EM twin conductor, re-inforced	.575
" 16	" " " " "	.585
" 14	" " " " "	.595

In Table VI, Types D (single), BX (twin), and BX3 (3 conductors) are armored cable adapted for ordinary indoor work. Type BM (twin conductors) is adapted for marine wiring. Types DL (single), BXL (twin), and BXL 3 (3 conductors) have the conductors lead-encased, with the steel armor outside, and are especially adapted for damp places, such as breweries, stables, and similar places.

Type E is used for flexible-cord pendants, and is suitable for factories, mills, show windows, and other similar places. Type EM is the same as Type E; but the flexible cord is reinforced, and is suitable for marine work, for use in damp places, and in all cases where it will be subject to very rough handling.

While this form of wiring has not the advantage of the conduit system—namely, that the wires can be withdrawn and new wires inserted without disturbing the building in any way whatever—yet it has many of the advantages of the flexible steel conduit, and it has some additional advantages of its own. For example, in a building already erected, this cable can be fished between the floors and in the partition walls, where it would be impossible to install either rigid conduit or flexible steel conduit without disturbing the floors or walls to an extent that would be objectionable.

Armored conductors should be continuous from outlet to outlet, without being spliced and installed on the loop system. Outlet boxes should be installed at all outlets, although, where this is impossible, outlet plates may be used under certain conditions. Clamps should be provided at all outlets, switch-boxes, junction-boxes, etc., to hold the cable in place, and also to serve as a means of grounding the steel sheathing.

Armored cable is less expensive than the rigid conduit or the flexible steel conduit, but more expensive than cleat wiring or knob and tube wiring, and is strongly recommended in preference to the latter.

WIRES RUN IN MOULDING

Moulding is very extensively used for electric circuit work, in extending circuits in buildings which have already been wired, and also in wiring buildings which were not provided with electric circuit work at the time of their erection. The reason for the popularity of moulding is that it furnishes a convenient and fairly good-looking runway for the wires, and protects them from mechanical injury.

It seems almost unwise to place conductors carrying electric current, in wood casing; but this method is still permitted by the *National Electric Code,* although it is not allowed in damp places or in places where there is liability to dampness, such as on brick walls, in cellars, etc.

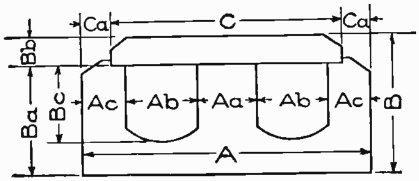


Fig. 9. Two-Wire Wood Moulding.

The dangers from the use of moulding are that if the wood becomes soaked with water, there will be a liability to leakage of current between the conductors run in the grooves of the moulding, and to fire being thereby started, which may not be immediately discovered. Furthermore, if the conductors are overloaded, and consequently overheated, the wood is likely to become charred and finally ignited. Moreover, the moulding itself is always a temptation as affording a good "round strip" in which to drive nails, hooks, etc. However, the convenience and popularity of moulding cannot be denied; and until some better substitute is found, or until its use is forbidden by the *Rules,* it will continue to be used to a very great extent for running circuits outside of the walls and on the ceilings of existing buildings. Figs. 9, 10, 11, and 12 show two- and three-wire moulding respectively; and Table VII gives complete data as to sizes of the moulding required for various sizes of conductors.

While the *Rules* recommend the use of hardwood moulding, as a matter of fact probably 90 per cent of the moulding used is of whitewood or other similar cheap, soft wood. Georgia pine or oak ordinarily

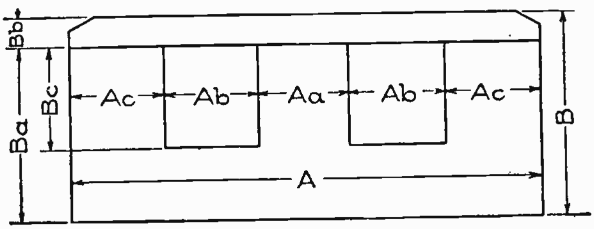


Fig. 10. Two-Wire Wood Moulding.

costs about twice as much as the soft wood. In designing moulding work, if appearance is of importance, the moulding circuits should be laid out so as to afford a symmetrical and complete design. For example, if an outlet is to be located in the center of the ceiling, the moulding should be continued from wall to wall, the portion beyond the outlet, of course, having no conductors inside of the moulding. If four outlets are to be placed on the ceiling, the rectangle of moulding should be completed on the fourth side, although, of course, no con-

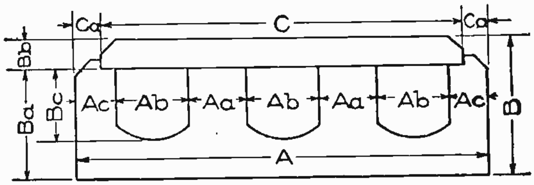


Fig. 11. Three-Wire Wood Moulding.

ductors need be placed in this portion of the moulding. Doing this increases the cost but little and adds greatly to the appearance.

Moulding is frequently used in combination with other methods of wiring, including armored cable, flexible steel tubing, and fibrous tubing. In many instances, it is possible to fish tubing between beams or studs running in a certain direction; but when the conductors are to run in another direction or at right angles to the beams or studs, exposed work is necessary. In such cases, a junction-box or outlet-box must be placed at the point of connection between the moulding and the armored cable or steel tubing.

Where circuits are run in moulding, and pass through the floor, additional protection must be provided, as required by the *Code Rules*,

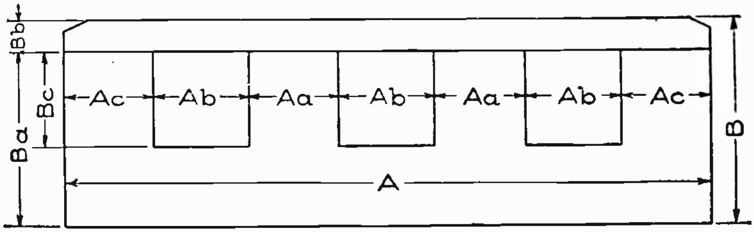


Fig. 12. Three-Wire Wood Moulding.

to protect the moulding. As a rule, it is better to use conduit for all portions of moulding within six feet of the floor, so as to avoid the possibility of injury to the circuits. Where a combination of iron conduit or flexible steel tubing is used with moulding, it is well to use double-braided conductors throughout, because, although only single-

TABLE VII

Sizes of Mouldings Required for Various Sizes of Conductors

Fig. No.	Type of Moulding	Number of Wires	Maximum Size of Wire B and S. Gauge		Dimensions in Inches									
			Solid	Stranded	A	Aa	Ab	Ac	B	Ba	Bb	Bc	C	Ca
9	A-2	2	12	14	1 1/2	1/2	1/4	1/4	27/32	5/8	7/32	1/4	1 1/8	3/16
9	A-4	2	8	10	1 11/16	1/2	5/16	9/32	29/32	11/16	7/32	5/16	1 5/16	3/16
9	A-6	2	4	5	2	1/2	7/16	5/16	1 1/16	13/16	1/4	7/16	1 9/16	7/32
9	A-8	2	1	2	2 3/8	1/2	9/16	3/8	1 3/16	15/16	1/4	9/16	1 13/16	9/32
9	A-9	2	—	3/0	3	5/8	3/4	7/16	1 13/32	1 1/8	9/32	3/4	2 7/16	9/32
10	A-10	2	—	250,000 C.M.	3 15/16	11/16	7/8	3/4	1 11/16	1 3/8	5/16	7/8	—	—
10	A-11	2	—	400,000 C.M.	4 7/8	15/16	1	31/32	2 3/16	1 7/8	5/16	1	—	—
11	B-2	3	12	14	2 3/16	7/16	1/4	9/32	27/32	5/8	7/32	1/4	1 13/16	3/16
11	B-4	3	8	10	2 1/2	15/32	5/16	5/16	29/32	11/16	7/32	5/16	2 1/8	3/16
11	B-6	3	4	5	2 7/8	13/32	7/16	3/8	1 1/16	13/16	1/4	7/16	2 3/8	1/4
11	B-8	3	1	2	3 5/8	19/32	9/16	3/8	1 3/16	15/16	1/4	9/16	3 1/16	9/32
11	B-9	3	—	3/0	4 5/16	9/16	3/4	15/32	1 13/32	1 1/8	9/32	3/4	3 3/4	9/32
12	B-10	3	—	250,000 C.M.	5 1/2	23/32	7/8	23/32	1 11/16	1 3/8	5/16	7/8	—	—
12	B-11	3	—	400,000 C.M.	6 3/4	15/16	1	15/16	2 3/16	1 7/8	5/16	1	—	—

braided conductors are required with moulding, double-braided conductors are required with unlined conduit, and if double-braided conductors were not used throughout, it would be necessary to make a joint at the outlet-box where the moulding stopped and the conduit work commenced. Where the conductors pass through floors, in moulding work, and where iron conduit is used, the inspection authorities, in order to protect the wire, usually require that a fibrous tubing be used as additional protection for the conductors inside of the iron pipe, although, if double-braided wire is used, this will not usually be required. Fig. 13 shows a fuseless cord rosette for use with moulding work. Fig. 14 shows a device for making a *tap* in moulding wiring.

Moulding work, under ordinary conditions, costs about one-half as much as circuit run in rigid conduit, and about 75 per cent, under ordinary conditions, of the cost of armored cable. Where the latter method of wiring or the conduit system can be employed, one or the other of these two methods should be used in preference to moulding,

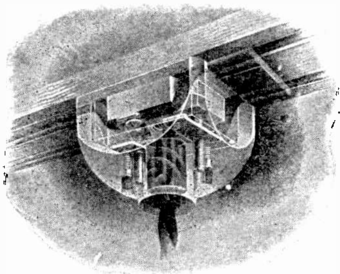


Fig. 13. Fuseless Cord Rosette.
Courtesy of Crouse-Hinds Co., Syracuse, N. Y.

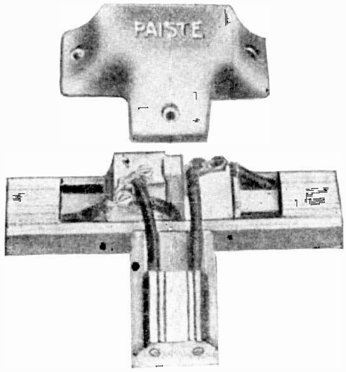


Fig. 14. Device for Making "Tap" in Moulding.
Courtesy of H. T. Paiste Co., Philadelphia, Pa.

as the work is not only more substantial, but also safer. Various forms of metal moulding have been introduced, but up to the present time have not met with the success which they deserve.

CONCEALED KNOB AND TUBE WIRING

This method of wiring is still allowed by the *National Electric Code*, although many vigorous attempts have been made to have it abolished. Each of these attempts has met with the strongest opposition from contractors and central stations, particularly in small towns and villages, the argument for this method being, that it is the cheapest method of wiring, and that if it were forbidden, many places which are wired according to this method would not be wired at all, and the use of electricity would therefore be much restricted, if not entirely done away with, in such communities. This argument, however, is only a temporary makeshift obstruction in the way of inevitable progress, and in a few years, undoubtedly, the concealed knob and tube method will be forbidden by the *National Electric Code*.

The cost of wiring according to this method is about one-third of the cost of circuits run in rigid conduit, and about one-half of the cost of circuits run in armored cable. The latter method of wiring is rapidly replacing knob and tube wiring, and justly so, wherever the additional price for the latter method of wiring can be obtained. As the name indicates, this method of wiring employs *porcelain knobs*

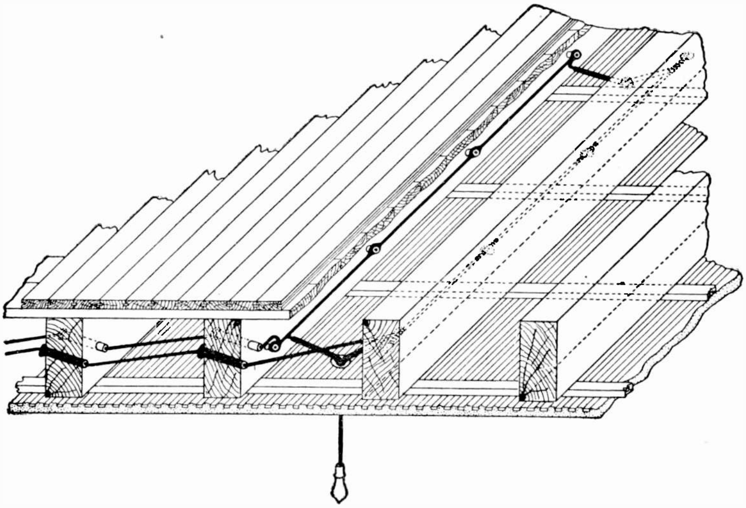


Fig. 15. Knob and Tube Wiring.

and tubes, the circuit work being run *concealed* between the floor beams and studs of a frame building. The knobs are used when the circuits run parallel to the floor beams; and the porcelain tubes are used when the circuits are run at right angles to the floor beams.

Fig. 15 shows an example of knob and tube wiring. In concealed knob and tube wiring, the wires must be separated at least ten inches from one another, and at least one inch from the surface wired over, that is, from the beams, flooring, etc., to which the insulator is fastened. Fig. 16 shows a good type of porcelain knob for this class of wiring. For knob and tube wiring, it will be noted that, owing to the fact that the wiring is concealed, the conductors must be kept further apart than in the case of exposed or open wiring on insulators, where, except in damp places, the wires may be run on cleats or on insulators only one-half inch from the surface wired over.

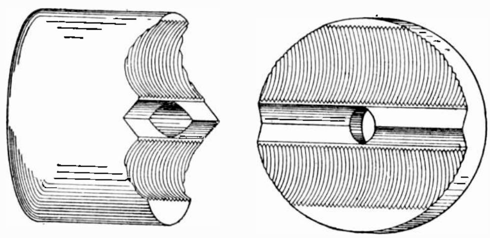


Fig. 16. Porcelain Knob.

Fibrous Tubing. Fibrous tubing is frequently used with knob and tube wiring, and the regulations governing its use are given in Rule 24, Section S, of the *National Electric Code.* This tubing, as stated in this *Rule,* may be used where it is impossible and impracticable to employ knobs and tubes, provided the difference in potential between the wires is not over 300 volts, and if the wires are not sub-

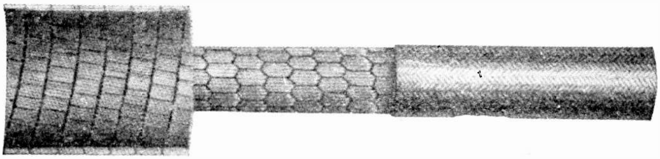


Fig. 17. Flexible Tubing, "Flexduct" Type.
Courtesy of National Metal Molding Co., Pittsburg, Pa.

ject to moisture. The cost of wiring in flexible fibrous tubing is approximately about the same as the cost of knob and tube wiring. Duplex conductors, or two wires together are not allowed in fibrous tubing.

Fibrous tubing is required at all outlets where conduit or armored cable is not used (as in knob and tube wiring); and, as required by the *Rules,* it must extend back from the last porcelain support to one inch beyond the outlet. Fig. 17 shows one make of fibrous tubing.

Table VIII gives the maximum sizes of conductors (double-braided) which may be installed in fibrous conduit.

TABLE VIII

Sizes of Conductors in Fibrous Conduit

OUTSIDE DIAMETER	INSIDE DIAMETER	ONE WIRE IN TUBE
$\frac{17}{32}$ inch	$\frac{1}{4}$ inch	No. 12
$\frac{21}{32}$ "	$\frac{3}{8}$ "	" 8
$\frac{25}{32}$ "	$\frac{1}{2}$ "	" 6
$\frac{15}{16}$ "	$\frac{5}{8}$ "	" 1
$1\frac{3}{32}$ "	$\frac{3}{4}$ "	" 2/0
$1\frac{5}{16}$ "	1 "	250,000 C. M.
$1\frac{9}{16}$ "	$1\frac{1}{4}$ "	400,000 C. M.
$1\frac{13}{16}$ "	$1\frac{1}{2}$ "	750,000 C. M.
$2\frac{1}{8}$ "	$1\frac{3}{4}$ "	1,000,000 C. M.
$2\frac{3}{8}$ "	2 "	1,500,000 C. M.
$2\frac{5}{8}$ "	$2\frac{1}{4}$ "	2,000,000 C. M.

WIRES RUN EXPOSED ON INSULATORS

This method of wiring has the advantages of cheapness, durability, and accessibility.

Cheapness. The relative cost of this method of wiring as compared with that of the concealed conduit system, is about fifty per cent of the latter if rubber-covered conductors are used, and about forty per cent of the latter if weatherproof slow-burning conductors are used. As the *Rules* of the Fire Underwriters allow the use of weatherproof slow-burning conductors in dry places, considerable saving may be effected by this method of wiring, provided there is no objection to it

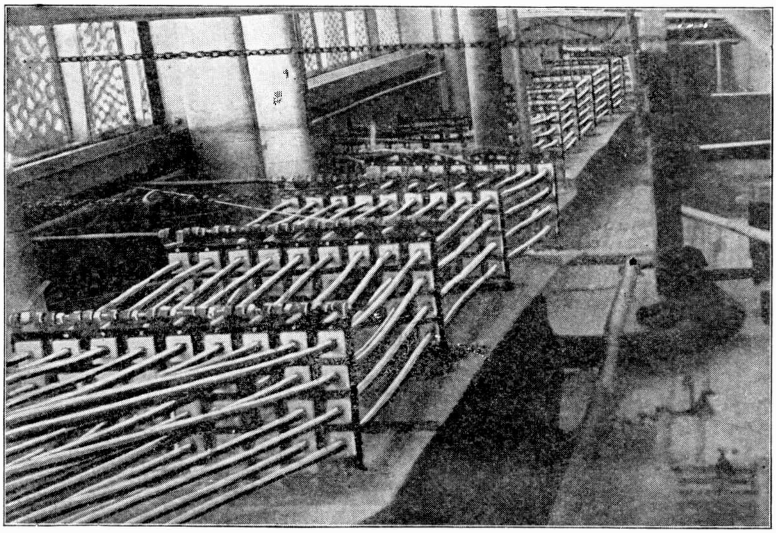


Fig. 18. Large Feeders Run Exposed on Insulators.

from the standpoint of appearance, and also provided that it is not liable to mechanical injury or disarrangement.

Durability. It is a well-known fact that rubber insulation has a relatively short life. Inasmuch as in this method of wiring, the insulation does not depend upon the insulation of the conductors, but on the insulators themselves, which are of glass or porcelain, this system is much more desirable than any of the other methods. Of course, if the conductors are mechanically injured, or the insulators broken, the insulation of the system is reduced; but there is no gradual deterioration as there is in the case of other methods of wiring, where rubber is depended upon for insulation. This is especially true in hot places, particularly where the temperature is 120° F. or above. For such cases, the weatherproof slow-burning conductors on porcelain or glass insulators are especially recommended.

Accessibility. The conductors being run exposed, they may be readily repaired or removed, or connections may be made to the same.

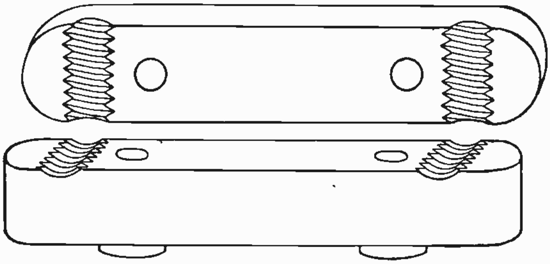


Fig. 19. Two-Wire Cleat.

This method of wiring is especially recommended for mills, factories, and for large or long feeder conductors. Fig. 18 shows examples of exposed large feeder conductors, installed in the New York Life Insurance Building, New York City. For small conductors, up to say No. 6 B. & S. Gauge each, porcelain cleats may be used to support one, two, or three conductors, provided the distance between the conduc-

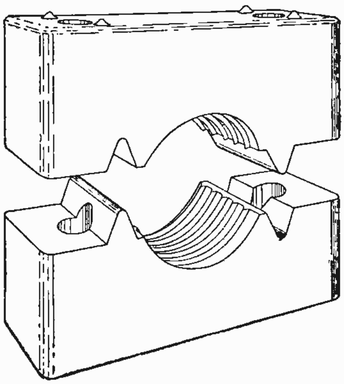


Fig. 20. One-Wire Cleat.

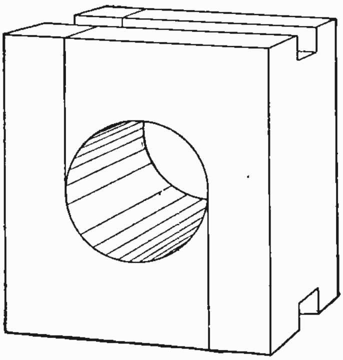


Fig. 21. Porcelain Insulator for Large Conductors.

tors is at least $2\frac{1}{2}$ inches in a two-wire system, and $2\frac{1}{2}$ inches between the two outside conductors in a three-wire system where the potential between the outside conductors is not over 300 volts. The cleat must hold the wire at least one-half inch from the surface to which the cleat is fastened; and in damp places the wire must be held at least one inch from the surface wired over. For larger conductors, from No. 6 to No. 4/0 B. & S. Gauge, it is usual to use single porcelain cleats or knobs. Figs. 19 and 20 show a good form of two-wire

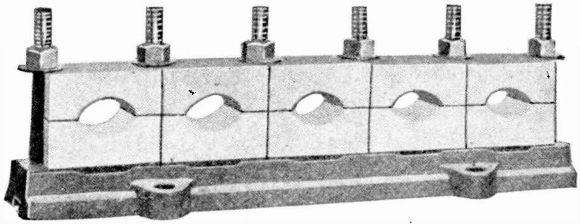


Fig. 22. Iron Rack and Insulators for Large Conductors.
Courtesy of General Electric Co., Schenectady, N. Y.

cleat and single-wire cleat, respectively.

For large feeder or main conductors from No. 4/0 B. & S. Gauge upward, a more substantial form of porcelain insulator should be used, such as shown in Fig. 21. These insulators are held in iron racks or angle-iron frames, of which two forms are shown in Figs. 22 and 23. The latter form of rack is particularly desirable for heavy conductors and where a number of conductors are run together. In this form of rack, any length of conductor can be removed without disturbing the other conductors.

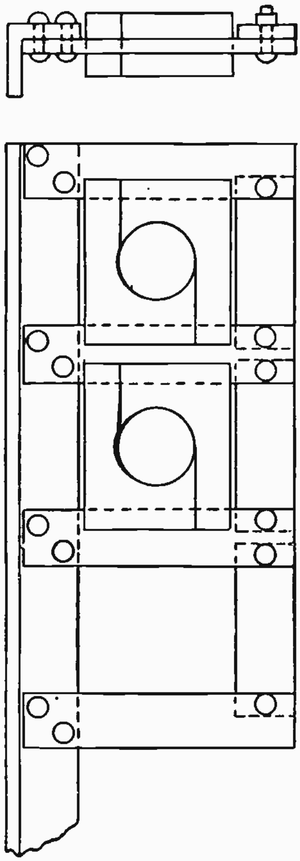
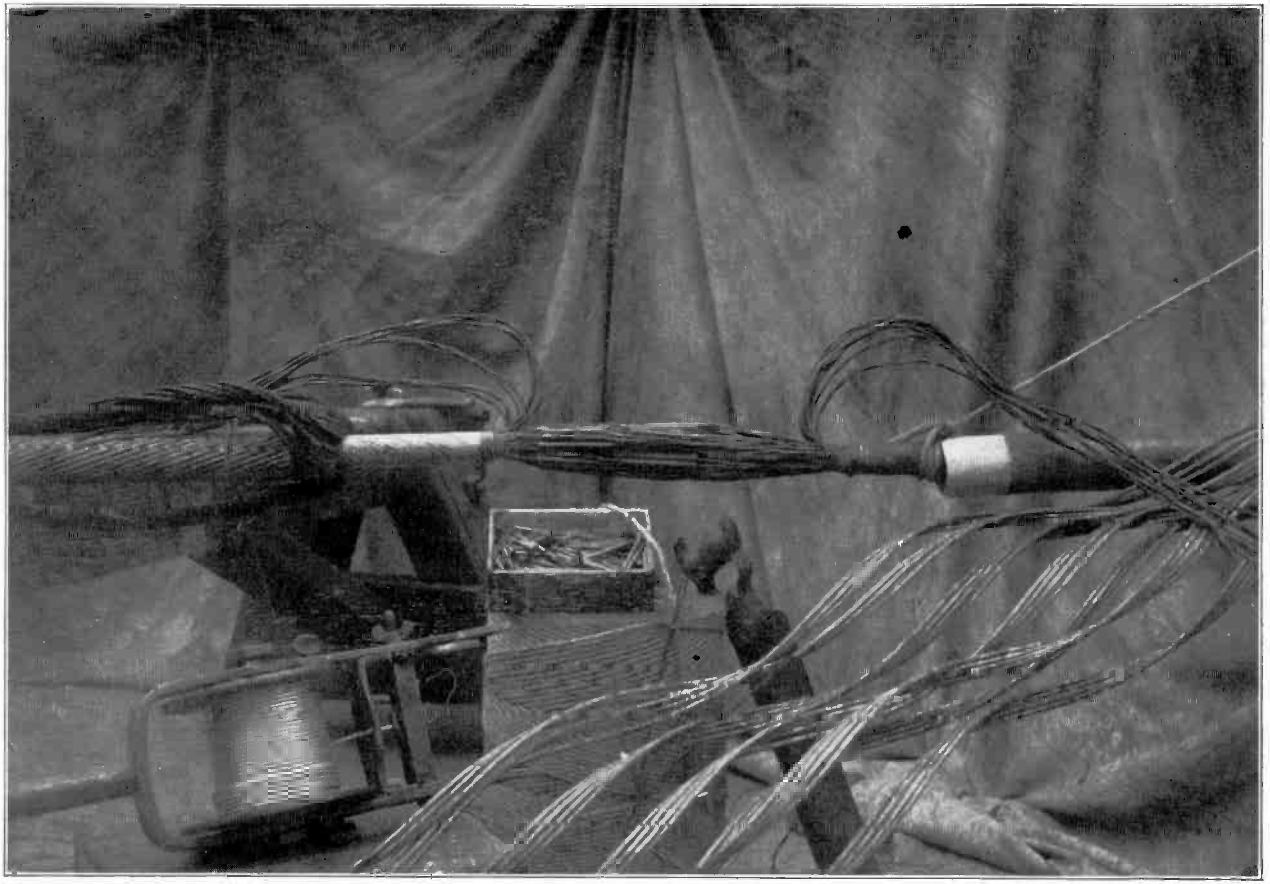


Fig. 23. Elevation and Plan of Insulators Held in Angle-Iron Frames.

As a rule, the porcelain insulators should be placed not more than $4\frac{1}{2}$ feet apart; and if the wires are liable to be disturbed, the distance between supports should be shortened, particularly for small conductors. If the beams are so far apart that supports cannot be obtained every $4\frac{1}{2}$ feet, it is necessary to provide a running board as shown in Fig. 24, to which the porcelain cleats and knobs can be fastened. Figs. 25 and 26 show two methods of supporting small conductors. For conductors of No. 8 B. & S.



SPLICING A 50-PAIR, PAPER-INSULATED, No. 19 B. & S., GAUGE-ARMORED SUBMARINE CABLE ACROSS SAN FRANCISCO BAY

Gauge, or over, it is not necessary to break around the beams, provided they are not liable to be disturbed; but the supports may be placed on each beam.

Where the distance between the supports, however, is greater than 4½ feet, it is usually necessary to provide intermediate supports, as shown in Fig. 27, or else to provide a running-board. Another method which may be used, where beams are further than 4½ feet apart, is to

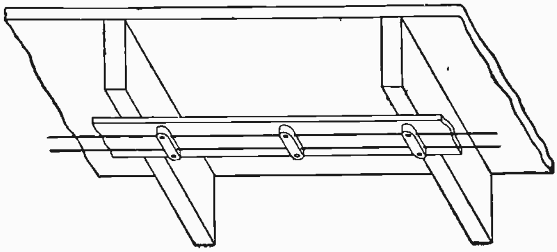


Fig. 24. Insulators Mounted on Running-Board across Wide-Spaced Beams.

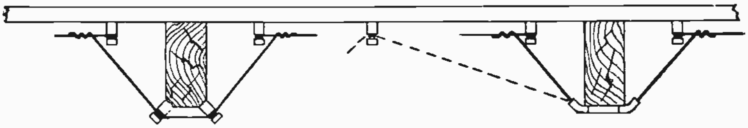


Fig. 25. Method of Supporting Small Conductors.

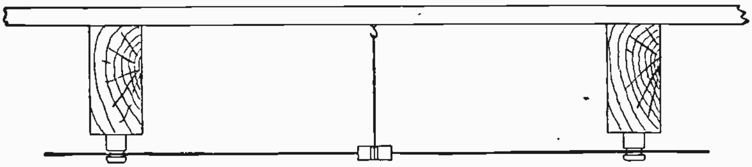


Fig. 27. Intermediate Support for Conductor between Wide-Spaced Beams.

run a main along the wall at right angles to the beams, and to have the individual circuits run between and parallel to the beams.

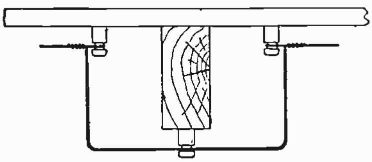


Fig. 26. Method of Supporting a Small Conductor.

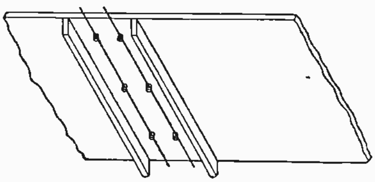


Fig. 28. Conductors Protected by Wooden Guard-Strips on Low Ceiling.

In low-ceiling rooms, where the conductors are liable to injury, it is usually required that a wooden guard strip be placed on each side of the conductors, as shown in Fig. 28.

Where the conductors pass through partitions or walls, they must be protected by porcelain tubes, or, if the conductors be of rubber, by means of fibrous tubing placed inside of iron conduits.

All conductors on the walls for a height of not less than six feet from the ground, either should be boxed in, or, if they be rubber-covered, should (preferably) be run in iron conduits; and in conductors having single braid only, additional protection should be provided by means of flexible tubing placed inside of the iron conduit.

Where conductors cross each other, or where they cross iron pipes, they should be protected by means of porcelain tubes fastened with tape or in some other substantial manner that will prevent the tubes from slipping out of place.

TWO-WIRE AND THREE-WIRE SYSTEMS

As both the two-wire and the three-wire system are extensively used in electric wiring, it will be well to give some consideration to the advantages and disadvantages of each system, and to explain them somewhat in detail.

Relative Advantages. The choice of either a two-wire or a three-wire system depends largely upon the source of supply. If, for example, the source of supply will always probably be a 120-volt, two-wire system, there would be no object in installing a three-wire system for the wiring. If, on the other hand, the source of supply is a 120-240-volt system, the wiring should, of course, be made three-wire. Furthermore, if at the outset the supply were two-wire, but with a possibility of a three-wire system being provided later, it would be well to adapt the electric wiring for the three-wire system, making the neutral conductor twice as large as either of the outside conductors, and combining the two outside conductors to make a single conductor until such time as the three-wire service is installed. Of course, there would be no saving of copper in this last-mentioned three-wire system, and in fact it would be slightly more expensive than a two-wire system, as will be shortly explained.

The object of the three-wire system is to reduce the amount of copper—and consequently the cost of wiring—necessary to transmit a given amount of electric power. As a rule, the proposition is usually one of lighting and not of power, for the reason that by means of the three-wire system we are able to increase the potential at which the current is transmitted, and at the same time to take advantage of the greater efficiency of the lower voltage lamp. If current for power (motors, etc.) only were to be transmitted, it would be a simple matter to wind the motors, etc., for a higher voltage, and thereby reduce the weight of copper. If, however, we increase the voltage of lamps, we find that they are not so efficient, nor is their life so long. With the standard carbon lamp, it has been found that the 240-volt lamp, with the same life, requires about 10 to 12 per cent more current than the corresponding 120-volt lamp. Furthermore, in the case of the more efficient lamps recently introduced (such as the Tantalum lamp, Tungsten lamp, etc.), it has been found impracticable, if not impossible, to make them for pressures above 125 volts. For this reason the three-wire system is employed, for by this method we can use 240 volts across the outside conductors, and by the use of a neutral conductor obtain 120 volts between the neutral and the outside conductor, and thereby be enabled to use 120-volt lamps. Furthermore, if a 240-volt lamp should ever be placed on the market that was as economical as the lower voltage lamp, the result would be that the 240-480-volt system would be introduced, and 240-volt lamps used. As a matter of fact, this has been tried in several cities—and particularly in Providence, Rhode Island. As a rule, however, the 120-volt lamp has been found so much more satisfactory as regards life, efficiency, etc., that it is nearly always employed.

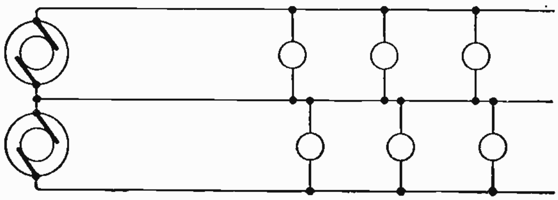


Fig. 29. Three-Wire System, with Neutral Conductor between the Two Outside Conductors.

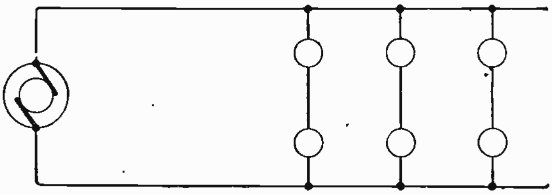


Fig. 30. Lamps Arranged in Pairs in Series, Dispensing with Necessity for Third or Neutral Conductor.

The two-wire system is so extremely simple that no explanation whatever is required concerning it.

The three-wire system, however, is somewhat confusing, and will now be considered.

Details of Three-Wire System. The three-wire system may be considered as a two-wire system with a third or neutral conductor placed between the two outside conductors, as shown in Fig. 29. This neutral conductor would not be required if we could always have the lamps arranged in pairs, as shown in Fig. 30. In this case, the two lamps would burn in series, and we could transmit the current at double the usual voltage, and thereby supply twice the number of lamps with one-quarter the weight of copper, allowing the same loss in pressure in the lamps. The reason for this is, that, having the lamps arranged in series of pairs, we reduce the current to one-half, and, as the pressure at which the current is transmitted is doubled, we can again reduce the copper one-half without increasing the loss in lamps. We therefore see that we have a double saving, as the current is reduced one-half, which reduces the weight of copper one-half, and we can again reduce the copper one-half by doubling the loss in volts without increasing the percentage loss. For example, if in one case we had a straight two-wire system transmitting current to 100 lamps at a potential of 100 volts, and this system were replaced by one in which the lamps were placed in series of pairs, as shown in Fig. 30, and the potential increased to 200 volts—100 lamps still being used—we should find, in the latter case, that we were carrying current really for only 50 lamps, as we would require only the same amount of current for two lamps now that we required for one lamp before. Furthermore, as the potential would now be 200 instead of 100 volts, we could allow twice as much loss as in the first case, because the loss would now be figured as a percentage of 200 volts instead of a percentage of 100 volts. From this, it will readily be seen that in the second case mentioned, we would require only one-quarter the weight of copper that would be required in the first case.

It will readily be seen, however, that a system such as that outlined in the second scheme having two lamps, would be impracticable for ordinary purposes, for the reason that it would always require the lamps to be burned in pairs. Now, it is for this very reason that the third or neutral conductor is required; and, if this conductor be added, it will no longer be necessary to burn the lamps in pairs. This, then, is the object of the three-wire system—to enable us to reduce the amount of copper required for transmitting current, without increasing the electric pressure employed for the lamps.

With regard to the size of the neutral conductor, one important point must be borne in mind; and that is, that the *Rules of the National Electric Code* require the neutral conductor in all interior wiring to be made at least as large as either of the two outside conductors. The reasons for this from a fire standpoint are obvious, because, if for any reason either of the outside conductors became disconnected, the neutral wire might be required to carry the same current as the outside conductors, and therefore it should be of the same capacity. Of course, the chances of such an event happening are slight; but, as the fire hazard is all-important, this rule must be complied with for interior wiring or in all cases where there would be a probability of fire. For outside or underground work, however, where the fire hazard would be relatively unimportant, the neutral conductor might be reduced in size; and, as a matter of fact, it is made smaller than the outside conductors.

The three-wire system is sometimes installed where it is desired to use the system as a two-wire, 125-volt system, or to have it arranged so that it may be used at any time also as a three-wire, 125-250-volt system. Of course, in order to do this, it is necessary to make the neutral conductor equal to the combined capacity of the outside conductors, the latter being then connected together to form one conductor, the neutral being the return conductor. This system is not recommended except in such instances, for example, as where an isolated plant of 125 volts is installed, and where there is a possibility of changing over at some future time to the three-wire, 125-250-volt system. In such a case as this, however, it would be better, where possible, to design the isolated plant for a three-wire, 125-250-volt system originally, and then to make the neutral conductor the same size as each of the two outside conductors.

The weight of copper required in a three-wire system where the neutral conductor is the same size as either of the two outside conductors, is $\frac{3}{8}$ of that required for a corresponding two-wire system using the same voltage of lamps.* It is obvious that this is true, because,

*NOTE.—If, in the two-wire system, we represent the weight of each of the two conductors by $\frac{1}{2}$, the weight of each of the outside conductors in a three-wire system would be represented by $\frac{1}{8}$; and if we had three conductors of the same size, we would have $\frac{1}{8}+\frac{1}{8}+\frac{1}{8}=\frac{3}{8}$ of the weight of copper required in a three-wire system, which would be required in a corresponding two-wire system having the same percentage of loss and using the same voltage of lamps.

If the neutral conductor were made $\frac{1}{2}$ of the size of each of the outside conductors, as is sometimes done in underground work, the total weight of copper required would be $\frac{1}{8}+\frac{1}{8}+\frac{1}{16}=\frac{5}{16}$ of that required in the corresponding two-wire system.

as the discussion proved concerning the arrangement shown in Fig. 30, where the lamps were placed in series of pairs, we found that the weight of copper for the two conductors was one-quarter the weight of the regular two-wire system. It is then of course true, that, if we had another conductor of the same size as each of the outside conductors, we increase theweight of copper one-half, or one-quarter plus one-half of one-quarter—that is, three-eighths.

In the three-wire system frequently used in isolated plants in which the two outside conductors are joined together and the neutral conductor made equal to their combined capacity, there is no saving of copper, for the reason that the same voltage of transmission is used, and, consequently, we have neither reduced the current nor increased the potential. Furthermore, though the weight of copper is the same, it is now divided into three conductors, instead of two, and naturally it costs relatively more to insulate and manufacture three conductors than to insulate and manufacture two conductors having the same total weight of copper. As a matter of fact, the three-wire system, having the neutral conductor equal to the combined capacity of the two outside ones, the latter being joined together, is about 8 to 10 per cent more expensive than the corresponding straight two-wire system.

In interior wiring, as a rule, where the three-wire system is used for the mains and feeders, the two-wire system is nearly always employed for the branch circuits. Of course, the two-wire branch circuits are then balanced on each side of the three-wire system, so as to obtain as far as possible at all times an equal balance on the two sides of the system. This is done so as to have the neutral conductor carry as little current as possible. From what has already been said, it is obvious that in case there is a perfect balance, the lamps are virtually in series of pairs, and the neutral conductor does not carry any current. Where there is an unbalanced condition, the neutral conductor carries the difference between the current on one side and the current on the other side of the system. For example, if we had five lamps on one side of the system and ten lamps on the other, the neutral conductor would carry the current corresponding to five lamps.

In calculating the three-wire system, the neutral conductor is disregarded, the outer wires being treated as a two-wire circuit, and the calculation is for one-half the total number of lamps, the percentage of loss being based on the potential across the two outside conductors.

The three-wire system is very generally employed in alternating-current secondary wiring, as nearly all transformers are built with three-wire connections.

While unbalancing will not affect the total loss in the outside conductors, yet it does affect the loss in the lamps, for the reason that the system is usually calculated on the basis of a perfect balance, and the loss is divided equally between the two lamps (the latter being considered in series of pairs). If, however, there is unbalancing to a great degree, the loss in lamps will be increased; and if the entire load is thrown over on one side, the loss in the lamps will be doubled on the remaining side, because the total loss in voltage will now occur in these lamps, whereas, in the case of perfect balance, it would be equally divided between the two groups of lamps.

CALCULATION OF SIZES OF CONDUCTORS

The formula for calculating the sizes of conductors for direct currents, where the length, load, and loss in volts are given, is as follows:

The size of conductor (in circular mils) is equal to the current *multiplied by* the distance (one way), *multiplied by* 21.6, *divided by* the loss in volts; or,

$$CM = \frac{C \times D \times 21.6}{V} \quad \text{. . . . .} \quad (1)$$

in which C = Current, in amperes;
D = Distance or length of the circuit (one way, in feet);
V = Loss in volts between the beginning and end of the circuit.

The constant (21.6) of this formula is derived from the resistance of a mil foot of wire of 98 per cent conductivity at 25° Centigrade or 77° Fahrenheit. The resistance of a conductor of one mil diameter and one foot long, is 10.8 at the temperature and conductivity named. We multiply this figure (10.8) by 2, as the length of a circuit is usually given as the distance one way, and in order to obtain the resistance of both conductors in a two-wire circuit, we must multiply by 2. The formula as above given, therefore, is for a two-wire circuit; and in calculating the size of conductors in a three-wire system, the calculation should be made on a two-wire basis, as explained hereinafter.

Formula **1** can be transformed so as to obtain the loss in a given circuit, or the current which may be carried a given distance with a stated loss, or to obtain the distance when the other factors are given, in the following manner:

Formula for Calculating Loss in Circuit when Size, Current, and Distance are Given

$$V = \frac{C \times D \times 21.6}{CM} \qquad \text{(2)}$$

Formula for Calculating Current which may be Carried by a Given Circuit of Specified Length, and with a Specified Loss

$$C = \frac{CM \times V}{D \times 21.6} \qquad \text{(3)}$$

Formula for Calculating Length of Circuit when Size, Loss, and Current to be Carried are Given

$$D = \frac{CM \times V}{C \times 21.6} \qquad \text{(4)}$$

Formulæ are frequently given for calculating sizes of conductors, etc., where the load, instead of being given in amperes, is stated in lamps or in horse-power. It is usually advisable, however, to reduce the load to amperes, as the efficiency of lamps and motors is a variable quantity, and the current varies correspondingly.

It is sometimes convenient, however, to make the calculation in terms of watts. It will readily be seen that we can obtain a formula expressed in watts from Formula **1**. To do this, it is advisable to express the loss in volts in percentage, instead of actual volts lost. It must be remembered that, in the above formulæ, V represents the volts lost in the circuit, or, in other words, the difference in potential between the beginning and the end of the circuit, and is not the applied E. M. F. The loss in percentage, in any circuit, is equal to the actual loss expressed in volts, *divided by* the line voltage, *multiplied by* 100; or,

$$P = \frac{V}{E} \times 100.$$

From this equation, we have:

$$V = \frac{P\,E}{100}.$$

If, for example, the calculation is to be made on a loss of 5 per cent, with an applied voltage of 250, using this last equation, we would have:

$$V = \frac{5 \times 250}{100} = 12.5 \text{ volts.}$$

Substituting the equation $V = \frac{P\,E}{100}$ in Formula **1**, we have:

$$C\,M = \frac{C \times D \times 21.6}{\frac{P\,E}{100}}$$

$$= \frac{C \times D \times 21.6 \times 100}{P\,E}$$

$$= \frac{C \times D \times 2{,}160}{P\,E}.$$

This equation, it should be remembered, is expressed in terms of applied voltage. Now, since the power in watts is equal to the applied voltage *multiplied by* the current ($W = EC$), it follows that

$$C = \frac{W}{E}.$$

By substituting this value of C in the equation given above $\left(C\,M = \frac{C \times D \times 2{,}160}{P\,E}\right)$, the formula is expressed in terms of watts instead of current, thus:

$$CM = \frac{W \times D \times 2{,}160}{E\,P\,E}, \qquad \textbf{(5)}$$

in which W = Power in watts transmitted;
D = Length of the circuit (one way)—that is, the length of one conductor;
P = Figure representing the percentage loss;
E*= Applied voltage.

All the above formulæ are for calculations of two-wire circuits. In making calculations for three-wire circuits, it is usual to make the calculation on the basis of the two outside conductors; and in three wire calculations, the above formulæ can be used with a slight modification, as will be shown.

In a three-wire circuit, it is usually assumed in making the calculation, that the load is equally balanced on the two sides of the neutral conductor; and, as the potential across the outside conductors is double that of the corresponding potential across a two-wire circuit, it is evident that for the same size of conductor the total loss in volts could be doubled without increasing the percentage of loss in lamps. Furthermore, as the load on one side of the neutral conductor, when the system is balanced, is virtually in series with the load on the third side, the current in amperes is usually one-half the sum of the current required by all the lamps. If C be still taken as the total

*NOTE. Remember that V in Formulæ 1 to 4 represents the volts lost, but that E in Formula 5 represents the applied voltage.

current in amperes (that is, the sum of the current required by all of the lamps) in Formula 1, we shall have to divide this current by 2, to use the formula for calculating the two outside conductors for a three-wire system. Furthermore, we shall have to multiply the voltage lost in the lamps by 2, to obtain the voltage lost in the two outside conductors, for the reason that the potential of the outside conductors is double the potential required by the lamps themselves. In other words, Formula 1 will become:

$$CM = \frac{C \times D \times 21.6}{2 \times V \times 2}$$
$$= \frac{C \times D \times 21.6}{4\,V}, \qquad \qquad (6)$$

in which C = Sum of current required by all of the lamps on both sides of the neutral conductor;
D = Length of circuit—that is, of any one of the three conductors;
V = Loss allowed in the lamps, i. e., one-half the total loss in the two outside conductors.

In the same manner, all of the other formulæ may be adapted for making calculations for three-wire systems. Of course the calculation of a three-wire system could be made as if it were a two-wire system, by taking one-half the total number of lamps supplied, at one-half the voltage between the outside conductors.

It is understood, of course, that the size of the conductor in Formula 6 is the size of each of the two outside ones; but, inasmuch as the *Rules of the National Electric Code* require that for interior wiring the neutral conductor shall be at least equal in size to the outside conductors, it is not necessary to calculate the size of the neutral conductor. It must be remembered, however, that, in a three-wire system where the neutral conductor is made equal in capacity to the combined size of the two outside conductors, and where the two outside conductors are joined together, we have virtually a two-wire system arranged so that it can be converted into a three-wire system later. In this case the calculation is exactly the same as in the case of the two-wire circuits, except that one of the two conductors is split into two smaller wires of the same capacity. This is frequently done where isolated plants are installed, and where the generators are wound for 125 volts and it may be desired at times to take current from an outside three-wire 125-250-volt system.

METHOD OF PLANNING A WIRING INSTALLATION

The first step in planning a wiring installation, is to gather all the data which will affect either directly or indirectly the system of wiring and the manner in which the conductors are to be installed. These data will include: Kind of building; construction of building; space available for conductors; source and system of electric-current supply; and all details which will determine the method of wiring to be employed. These last items materially affect the cost of the work, and are usually determined by the character of the building and by commercial considerations.

Method of Wiring. In a modern fireproof building, the only system of wiring to be recommended is that in which the conductors are installed in rigid conduits; although, even in such cases, it may be desirable, and economy may be effected thereby, to install the larger feeder and main conductors exposed on insulators using weatherproof slow-burning wire. This latter method should be used, however, only where there is a convenient runway for the conductors, so that they will not be crowded and will not cross pipes, ducts, etc., and also will not have too many bends. Also, the local inspection authorities should be consulted before using this method.

For mills, factories, etc., wires exposed on cleats or insulators are usually to be recommended, although rigid conduit, flexible conduit, or armored cable may be desirable.

In finished buildings, and for extensions of existing outlets, where the wiring could not readily or conveniently be concealed, moulding is generally used, particularly where cleat wiring or other exposed methods of wiring would be objectionable. However, as has already been said, moulding should not be employed where there is any liability to dampness.

In finished buildings, particularly where they are of frame construction, flexible steel conduits or armored cable are to be recommended.

While in new buildings of frame construction, knob and tube wiring are frequently employed, this method should be used only where the question of first cost is of prime importance. While armored cable will cost approximately 50 to 100 per cent more than knob and tube wiring, the former method is so much more permanent and is so much safer that it is strongly recommended.

Systems of Wiring. The system of wiring—that is, whether the two-wire or the three-wire system shall be used—is usually determined by the source of supply. If the source of supply is an isolated plant, with simple two-wire generators, and with little possibility of current being taken from the outside at some future time, the wiring in the building should be laid out on the two-wire system. If, on the other hand, the isolated plant is three-wire (having three-wire generators, or two-wire generators with balancer sets), or if the current is taken from an outside source, the wiring in the building should be laid out on a three-wire system.

It very seldom happens that current supply from a central station is arranged with other than the three-wire system inside of buildings, because, if the outside supply is alternating current, the transformers are usually adapted for a three-wire system. For small buildings, on the other hand, where there are only a few lights and where there would be only one feeder, the two-wire system is used. As a rule, however, when the current is taken from an outside source, it is best to consult the engineer of the central station supplying the current, and to conform with his wishes. As a matter of fact, this should be done in any event, in order to ascertain the proper voltage for the lamps and for the motors, and also to ascertain whether the central station will supply transformers, meters, and lamps—for, if these are not thus supplied, they should be included in the contract for the wiring.

Location of Outlets. It is not within the scope of this treatise to discuss the matter of *illumination*, but it is desirable, at this point, to outline briefly the method of procedure.

A set of plans, including elevation and details, if any, and showing decorative treatment of the various rooms, should be obtained from the Architect. A careful study should then be made by the Architect, the Owner, and the Engineer, or some other person qualified to make recommendations as to illumination. The location of the outlets will depend: *First,* upon the decorative treatment of the room, which determines the æsthetic and architectural effects; *second,* upon the type and general form of fixtures to be used, which should be previously decided on; *third,* upon the tastes of the owners or occupants in regard to illumination in general, as it is found that tastes vary widely in regard to amount and kind of illumination.

The location of the outlets, and the number of lights required at each, having been determined, the outlets should be marked on the plans.

The Architect should then be consulted as to the location of the centers of distribution, the available points for the risers or feeders, and the available space for the branch circuit conductors.

In regard to the *rising points for the feeders and mains*, the following precautions should be used in selecting chases:

1. The space should be amply large to accommodate all the feeders and mains likely to rise at that given point. This seems trite and unnecessary, but it is the most usual trouble with chases for risers. Formerly architects and builders paid little attention to the requirements for chases for electrical work; but in these later days of 2-inch and 2½-inch conduit, they realize that these pipes are not so invisible and mysterious as the force they serve to distribute, particularly when twenty or more such conduits must be stowed away in a building where no special provision has been made for them.

2. If possible, the space should be devoted solely to electric wiring. Steam pipes are objectionable on account of their temperature; and these and all other pipes are objectionable in the same space occupied by the electrical conduits, for if the space proves too small, the electric conduits are the first to be crowded out.

The chase, if possible, should be continuous from the cellar to the roof, or as far as needed. This is necessary in order to avoid unnecessary bends or elbows, which are objectionable for many reasons.

In similar manner, the location of *cut-out cabinets or distributing centers* should fulfil the following requirements:

1. They should be accessible at all times.

2. They should be placed sufficiently close together to prevent the circuits from being too long.

3. Do not place them in too prominent a position, as that is objectionable from the Architect's point of view.

4. They should be placed as near as possible to the rising chases, in order to shorten the feeders and mains supplying them.

Having determined the system and method of wiring, the location of outlets and distributing centers, the next step is to lay out the *branch circuits* supplying the various outlets.

Before starting to lay out the branch circuits, a drawing showing the floor construction, and showing the space between the top of the beams and girders and the flooring, should be obtained from the Architect. In f--proof buildings of iron or steel construction, it is almost the invariable practice, where the work is to be concealed, to run the conduits over the beams, under the rough flooring, carrying them between the sleepers when running parallel to the sleepers, and notching the latter when the conduits run across them (see Fig. 31). In wooden frame buildings, the conduits run parallel to the beams and to the furring (see Fig. 32); they are also sometimes run below the

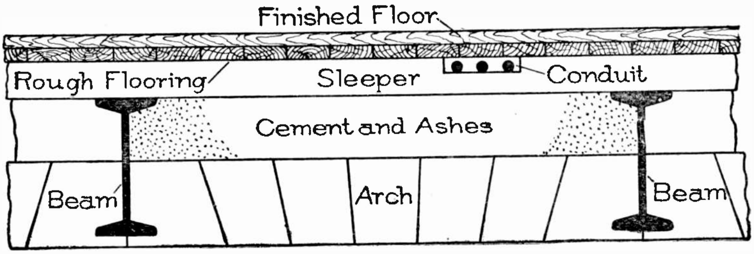


Fig. 31. Running Conductors Concealed under Floor in Fireproof Building.

beams. In the latter case the beams have to be notched, and this is allowable only in certain places, usually near the points where the beams are supported. The Architect's drawing is therefore necessary in order that the location and course of the conduits may be indicated on the plans.

The first consideration in laying out the branch circuit is the *number of outlets* and *number of lights* to be wired on any one branch circuit. The *Rules of the National Electric Code* (Rule 21-D) require that "no set of incandescent lamps requiring more than 660 watts, whether grouped on one fixture or on several fixtures or pendants, will be dependent on one cut-out." While it would be possible to have branch circuits supplying more than 660 watts, by placing various cut-outs at different points along the route of the branch circuit, so as to subdivide it into small sections to comply with the rule, this method is not recommended, except in certain cases, for exposed wiring in factories or mills. As a rule, the proper method is to have the cut-outs located at the center of distribution, and to limit each branch circuit to 660 watts, which corresponds to twelve or thirteen 50-watt lamps, twelve being the usual limit. Attention is called to the fact that the inspectors usually allow 50 watts for each socket connected to a branch circuit; and although 8-candle-power lamps may be placed at some of the outlets, the inspectors hold that the standard lamp is approximately 50 watts, and for that reason there is always the likelihood of a lamp of that capacity being used, and their inspection is based on that assumption. Therefore, to comply with the requirements, an allowance of not more than twelve lamps per branch circuit should be made.

In ordinary practice, however, it is best to reduce this number still further, so as to make allowance for future extensions or to increase the number of lamps that may be placed at any outlet. For this reason, it is wise to keep the number of the outlets on a circuit at the lowest point consistent with economical wiring. It has been proven by actual practice, that the best results are obtained by limiting the number to five or six outlets on a branch circuit. Of course, where all the outlets have a single light each, it is frequently necessary, for reasons of economy, to increase this number to eight, ten, and, in some cases, twelve outlets.

We have already referred to the location of the wires or conduits. This question is generally settled by the peculiarities of the construction of the building. It is necessary to know this, however, before laying out the circuit work, as it frequently determines the course of a circuit.

Now, as to the course of the circuit work, little need be said, as it is largely influenced by the relative position of the outlets, cut-

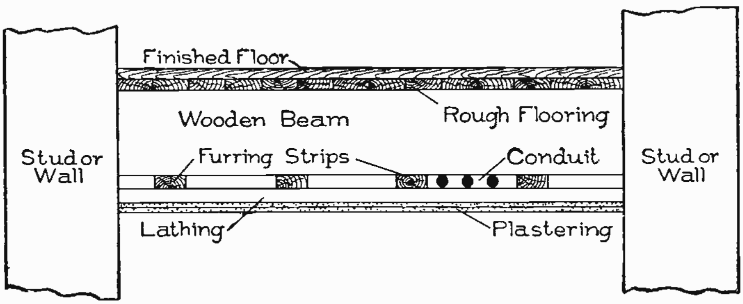


Fig. 32. Running Conductors Concealed under Floor in Wooden Frame Building.

outs, switches, etc. Between the cut-out box and the first outlet, and between the outlets, it will have to be decided, however, whether the circuits shall run at right angles to the walls of the building or room, or whether they shall run direct from one point to another, irrespective of the angle they make to the sleepers or beams. Of course, in the latter case, the advantages are that the cost is somewhat less and the number of elbows and bends is reduced. If the tubes are bent, however, instead of using elbows, the difference in cost is usually very slight, and probably does not compensate for the disadvantages that would result from running the tubes diagonally. As to the number of bends, if branch circuit work is properly laid out and installed, and a proper size of tube used, it rarely happens that there is any difference in "pulling" the branch circuit wires. It may happen, in the event of a very long run or one having a large number of bends, that it might be advisable to adopt a short and most direct route.

Up to this time, the location of the distribution centers has been made solely with reference to architectural considerations; but they must now be considered in conjunction with the branch circuit work.

It frequently happens that, after running the branch circuits on the plans, we find, in certain cases, that the position of centers of distribution may be changed to advantage, or sometimes certain groups may be dispensed with entirely and the circuits run to other points. We now see the wisdom of ascertaining from the Architect where cut-out groups may be located, rather than selecting particular points for their location.

As a rule, wherever possible, it is wise to limit the length of each branch circuit to 100 feet; and the number and location of the distributing centers should be determined accordingly.

It may be found that it is sometimes necessary and even desirable to increase the limit of length. One instance of this may be found in hall or corridor lights in large buildings. It is generally desirable, in such cases, to control the hall lights from one point; and, as the number of lights at each outlet is generally small, it would not be economical to run mains for sub-centers of distribution. Hence, in instances of this character, the length of runs will frequently exceed the limit named. In the great majority of cases, however, the best results are obtained by limiting the runs to 90 or 100 feet.

There are several good reasons for placing such a limit on the length of a branch circuit. To begin with, assuming that we are going to place a limit on the loss in voltage (drop) from the switchboard to the lamp, it may be easily proven that up to a certain reasonable limit it is more economical to have a larger number of distributing centers and shorter branch circuits, than to have fewer centers and longer circuits. It is usual, in the better class of work, to limit the

CONSTRUCTION OF TELEPHONE CONDUIT USING CEMENT PIPE FOR DUCT MATERIAL

loss in voltage in any branch circuit to approximately one volt. Assuming this limit (one volt loss), it can readily be calculated that the number of lights at one outlet which may be connected on a branch circuit 100 feet long (using No. 14 B. & S. wire), is *four*; or in the case of outlets having a single light each, *five* outlets may be connected on the circuit, the first being 60 feet from the cut-out, the others being 10 feet apart.

These examples are selected simply to show that if the branch circuits are much longer than 100 feet, the loss must be increased to more than one volt, or else the number of lights that may be connected to one circuit must be reduced to a very small quantity, provided, of course, the size of the wire remains the same.

Either of these alternatives is objectionable—the first, on the score of regulation; and the second, from an economical standpoint. If, for instance, the loss in a branch circuit with all the lights turned on is four volts (assuming an extreme case), the voltage at which a lamp on that circuit burns will vary from four volts, depending on the number of lights burning at a time. This, of course, will cause the lamp to burn below candle-power when all the lamps are turned on, or else to diminish its life by burning above the proper voltage when it is the only lamp burning on the circuit. Then, too, if the drop in the branch circuits is increased, the sizes of the feeders and the mains must be correspondingly increased (if the total loss remains the same), thereby increasing their cost.

If the number of lights on the circuit is decreased, we do not use to good advantage the available carrying capacity of the wire.

Of course, one solution of the problem would be to increase the size of the wire for the branch circuits, thus reducing the drop. This, however, would not be desirable, except in certain cases where there were a few long circuits, such as for corridor lights or other special control circuits. In such instances as these, it would be better to increase the sizes of the branch circuit to No. 12 or even No. 10 B. & S. Gauge conductors, than to increase the number of centers of distribution for the sake of a few circuits only, in order to reduce the number of lamps (or loss) within the limit.

The method of calculating the loss in conductors has been given elsewhere; but it must be borne in mind, in calculating the loss of a branch circuit supplying more than one outlet, that separate calculations must be made for each portion of the circuit. That is, a calculation must be made for the loss to the first outlet, the length in this case being the distance from the center of distribution to the first outlet, and the load being the total number of lamps supplied by the circuit. The next step would be to obtain the loss between the first and second outlet, the length being the distance between the two outlets, and the load, in this case, being the total number of lamps supplied by the circuit, *minus* the number supplied by the first outlet; and so on. The loss for the total circuit would be the sum of these losses for the various portions of the circuit.

Feeders and Mains. If the building is more than one story, an elevation should be made showing the height and number of stories. On this elevation, the various distributing centers should be shown diagrammatically; and the current in amperes supplied through each center of distribution, should be indicated at each center. The next step is to lay out a tentative system of feeders and mains, and to ascertain the load in amperes supplied by each feeder and main. The estimated length of each feeder and main should then be determined, and calculation made for the loss from the switchboard to each center of distribution. It may be found that in some cases it will be necessary to change the arrangement of feeders or mains, or even the centers of distribution, in order to keep the total loss from the switchboard to the lamps within the limits previously determined. As a matter of fact, in important work, it is always best to lay out the entire work tentatively in a more or less crude fashion, according to the "cut and dried" method, in order to obtain the best results, because the entire layout may be modified after the first preliminary layout has been made. Of course, as one becomes more experienced and skilled in these matters, the final layout is often almost identical with the first preliminary arrangement.

TESTING

Where possible, two tests of the electric wiring equipment should be made, one after the wiring itself is entirely completed, and switches, cut-out panels, etc., are connected; and the second one after the fixtures have all been installed. The reason for this is that if a ground or short circuit is discovered before the fixtures are installed, it is more easily remedied; and secondly, because there is no division of the responsibility, as there might be if the first test were made only after the fixtures were installed. If the test shows no grounds or short circuits before the fixtures are installed, and one does develop after they are installed, the trouble, of course, is that the short circuit or ground is one or more of the fixtures. As a matter of fact, it is a wise plan always to make a separate test of each fixture after it is delivered at the building and before it is installed.

While a *magneto* is largely used for the purpose of testing, it is at best a crude and unreliable method. In the first place, it does not give an indication, even approximately, of the total insulation resistance, but merely indicates whether there is a ground or short circuit, or not. In some instances, moreover, a magneto test has led to serious errors, for reasons that will be explained. If, as is nearly always the case, the magneto is an alternating-current instrument, it may sometimes happen—particularly in long cables, and especially where there is a lead sheathing on the cable—that the magneto will ring, indicating to the uninitiated that there is a ground or short circuit on the cable. This may be, and usually is, far from being the case; and the cause of the ringing of the magneto is not a ground or short circuit, but is due to the capacity of the cable, which acts as a condenser under certain conditions, since the magneto producing an alternating current repeatedly charges and discharges the cable in opposite directions, this changing of the current causing the magneto to ring. Of course, this defect in a magneto could be remedied by using a commutator and changing it to a direct-current machine; but as the method is faulty in itself, it is hardly worth while to do this.

A portable *galvanometer* with a resistance box and Wheatstone bridge, is sometimes employed; but this method is objectionable because it requires a special instrument which cannot be used for many other purposes. Furthermore, it requires more skill and time to use than the *voltmeter* method, which will now be described.

The advantage of the voltmeter method is that it requires merely a direct-current voltmeter, which can be used for many other purposes, and which all engineers or contractors should possess, together with a box of cells having a potential of preferably over 30 volts. The voltmeter should have a scale of not over 150 volts, for the reason that if the scale on which the battery is used covers too wide a range (say 1,000 volts) the readings might be so small as to make the test inaccurate. A good arrangement would be to have a voltmeter having two scales—say, one of 60 and one of 600—which would make the voltmeter available for all practical potentials that are likely to be used inside of a building. If desired, a voltmeter could be obtained with three connections having three scales, the lowest scale of which would be used for testing insulation resistances.

Before starting a test, all of the fuses should be inserted and switches turned on, so that the complete test of the entire installation can be made. When this has been done, the voltmeter and battery should be connected, so as to obtain on the lowest scale of the voltmeter the electromotive force of the entire group of cells. This connection is shown in Fig. 33. Immediately after this has been done, the insulation resistance to be tested is placed in circuit, whether the insulation to be tested is a switchboard, slate panel-board, or the entire wiring installation; and the connections are made as shown in Fig. 34. A reading should then again be taken of the voltmeter; and the leakage is in proportion to the difference between the first and second readings of the voltmeter. The explanation given below will show how this resistance may be calculated: It is evident that the resistance in the first case was merely the resistance of the voltmeter and the internal resistance of the battery. As a rule, the internal resistance of the battery is so small in comparison with the resistance of the voltmeter and the external resistance, that it may be entirely neglected, and this will be done in the following calculation. In the second case, however, the total resistance in circuits is the resistance of the voltmeter and the battery, *plus* the entire insulation resistance on all the wires, etc., connected in circuit.

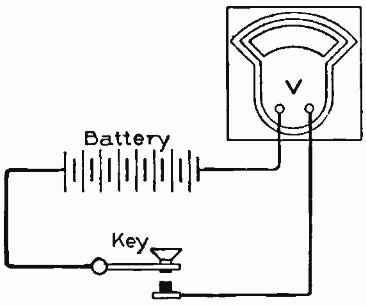


Fig. 33. Connections of Voltmeter and Battery for Testing Insulation Resistance.

To put this in mathematical form, the voltage of the cells may be indicated by the letter E; and the reading of the voltmeter when the insulation resistance is connected by the circuit, by the letter E'. Let R represent the resistance of the voltmeter and R_x represent the insulation resistance of the installation which we wish to measure.

It is a fact which the reader undoubtedly knows, that the E. M. F. as indicated by the voltmeter in Fig. 34 is inversely proportional to the resistance: that is, the greater the resistance, the lower will be the reading on the voltmeter, as this reading indicates the leakage or current passing through the resistance. Putting this in the shape of a formula, we have from the theory of proportion:

$$E : E' :: R + R_x : R;$$

or;

$$E' R + E' R_x = E R.$$

Transposing,

$$E' R_x = E R - E' R = R (E-E'),$$

and

$$R_x = \frac{R (E - E')}{E'}.$$

Or, expressed in words, the insulation resistance is equal to the resistance of the voltmeter *multiplied by* the difference between the first reading (or the voltage in the cells) and the second reading (or the reading of the voltmeter with the insulation resistance in series with the voltmeter), *divided by* this last reading of the voltmeter.

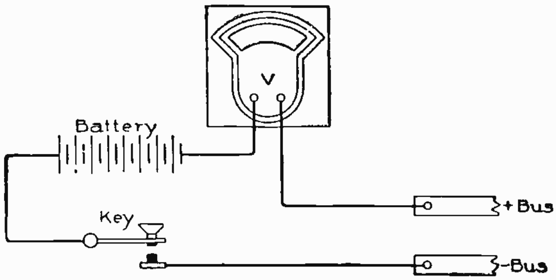


Fig. 34. Insulation Resistance Placed in Circuit, Ready for Testing.

Example. Assume a resistance of a voltmeter (R) of 20,000 ohms, and a voltage of the cells (E) of 30 volts; and suppose that the insulation resistance test of a wiring installation, including switchboard, feeders, branch circuits, panel-boards, etc., is to be made, the insulation resistance being represented by the letter R_x. By substituting in the formula

$$R_x = \frac{R (E - E')}{E'},$$

and assuming that the reading of the voltmeter with the insulation resistance connected is 5, we have:

$$R = \frac{20{,}000 \times (30-5)}{5} = 100{,}000 \text{ ohms.}$$

If the test shows an excessive amount of leakage, or a ground or short circuit, the location of the trouble may be determined by the process of elimination—that is, by cutting out the various feeders until the ground or leakage disappears, and, when the feeder on which the trouble exists has been located, by following the same process with the branch circuits.

Of course, the larger the installation and the longer and more numerous the circuits, the greater the leakage will be; and the lower will be the insulation resistance, as there is a greater surface exposed for leakage. The *Rules of the National Electric Code* give a sliding scale for the requirements as to insulation resistance, depending upon the amount of current carried by the various feeders, branch circuits, etc. The rule of the *National Electric Code* (No. 66) covering this point, is as follows:

"The wiring in any building must test free from grounds; *i. e.*, the complete installation must have an insulation between conductors and between all conductors and the ground (not including attachments, sockets, receptacles, etc.) not less than that given in the following table:

Up to	5 amperes	4,000,000 ohms
"	10 "	2,000,000 "
"	25 "	800,000 "
"	50 "	400,000 "
"	100 "	200,000 "
"	200 "	100,000 "
"	400 "	50,000 "
"	800 "	25,000 "
"	1,600 "	12,500 "

"The test must be made with all cut-outs and safety devices in place. If the lamp sockets, receptacles, electroliers, etc., are also connected, only one-half of the resistances specified in the table will be required."

ALTERNATING-CURRENT CIRCUITS

It is not within the province of this chapter to treat the various alternating-current phenomena, but simply to outline the modifications which should be made in designing and calculating electric light wiring, in order to make proper allowance for these phenomena.

The most marked difference between alternating and direct current, so far as wiring is concerned, is the effect produced by self-induction, which is characteristic of all alternating-current circuits. This self-induction varies greatly with conditions depending upon the arrangement of the circuit, the medium surrounding the circuit, the devices or apparatus supplied by or connected in the circuit, etc.

For example, if a coil having a resistance of 100 ohms is included in the circuit, a current of one ampere can be passed through the coil with an electric pressure of 100 volts, if direct current is used; while it might require a potential of several hundred volts to pass a current of one ampere if alternating-current were used, depending upon the number of turns in the coil, whether it is wound on iron or some other non-magnetic material, etc.

It will be seen from this example, that greater allowance should be made for self-induction in laying out and calculating alternating-current wiring, if the conditions are such that the self-induction will be appreciable.

On account of self-induction, the two wires of an alternating-current circuit must never be installed in separate iron or steel conduits, for the reason that such a circuit would be virtually a *choke coil* consisting of a single turn of wire wound on an iron core, and the self-induction would not only reduce the current passing through the circuit, but also might produce heating of the iron pipe. It is for this reason that the *National Electric Code* requires conductors constituting a given circuit to be placed in the same conduit, if that conduit is iron or steel, whenever the said circuit is intended to carry, or is liable to carry at some future time, an alternating current. This does not mean, in the case of a two-phase circuit, that all four conductors need be placed in the same conduit, but that the two conductors of a given phase must be placed in the same conduit. If, however, the three-wire system be used for a two-phase system, all three conductors should be placed in the same conduit, as should also be the case in a three-wire three-phase system. Of course, in a single-phase two- or three-wire system, the conductors should all be placed in the same conduit.

In calculating circuits carrying alternating current, no allowance usually should be made for self-induction when the conductors of the same circuit are placed close together in an iron conduit. When, however, the conductors are run exposed, or are separated from each other, calculation should be made to determine if the effects of self-induction are great enough to cause an appreciable inductive drop. There are several methods of calculating this drop due to self-induction—one by formula, and one by a mathematical method which will be described.

Skin Effect. Skin effect in alternating-current circuits is caused by an incorrect distribution of the current in the wire, the current tending to flow through the outer portion of the wire, it being a well-known fact that in alternating currents, the current density decreases toward the center of the conductor, and that in large wires, the current density at the center of the conductor is relatively quite small.

The skin effect increases in proportion to the square of the diameter, and also in direct ratio to the frequency of the alternating current.

For conductors of No. 0000 B. & S. Gauge, and smaller, and for frequencies of 60 cycles per second, or less, the skin effect is negligible and is less than one-half of one per cent.

For very large cables and for frequencies above 60 cycles per second, the skin effect may be appreciable; and in certain cases, allowance for it should be made in making the calculation. In ordinary practice, however, it may be neglected. Table IX, taken from *Alternating-Current Wiring and Distribution*, by W. R. Emmet, gives the data necessary for calculating the skin effect. The figures given in the first and third columns are obtained by multiplying the size of the conductor (in circular mils) by the frequency (number of cycles per second); and the figures in the second and fourth columns show the factor to be used in multiplying the ohmic resistance, in order to obtain the combined resistance and skin effect.

TABLE IX

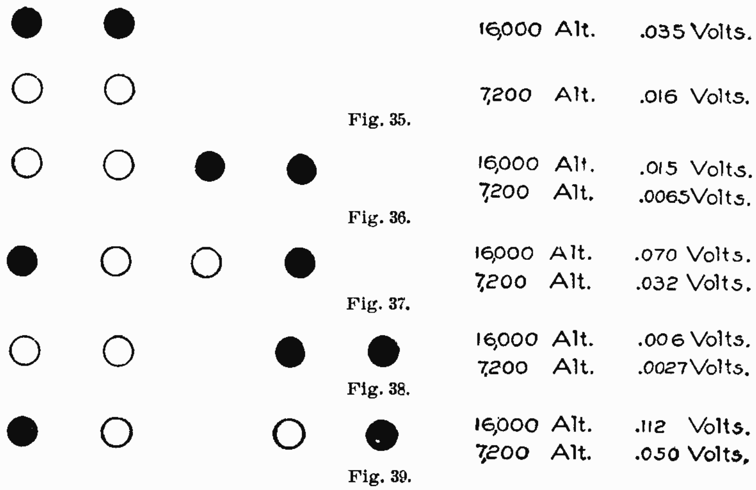
Data for Calculating Skin Effect

Product of Circular Mils × Cycles per Sec.	Factor	Product of Circular Mils × Cycles per Sec.	Factor
10,000,000	1.00	70,000,000	1.13
20,000,000	1.01	80,000,000	1.17
30,000,000	1.03	90,000,000	1.20
40,000,000	1.05	100,000,000	1.25
50,000,000	1.08	125,000,000	1.34
60,000,000	1.10	150,000,000	1.43

The factors given in this table, *multiplied by* the resistance to direct currents, will give the resistance to alternating currents for copper conductors of circular cross-section.

Mutual Induction. When two or more circuits are run in the same vicinity, there is a possibility of one circuit inducing an electromotive force in the conductors of an adjoining circuit. This effect may result in raising or lowering the E. M. F. in the circuit in which a mutual induction takes place. The amount of this induced E. M. F. set up in one circuit by a parallel current, is dependent upon the current, the frequency, the lengths of the circuits running parallel to each other, and the relative positions of the conductors constituting the said circuits.

Under ordinary conditions, and except for long circuits carrying high potentials, the effect of mutual induction is so slight as to be negligible, unless the conductors are improperly arranged. In order to prevent mutual induction, the conductors constituting a given circuit should be grouped together. Figs. 35 to 39, inclusive, show



Various Groupings of Conductors in Two Two-Wire Circuits, Giving Various Effects of Induction.

five arrangements of two two-wire circuits; and show how relatively small the effect of first induction is when the conductors are properly arranged, as in Fig. 38, and how relatively large it may be when improperly arranged, as in Fig. 39. These diagrams are taken from a publication of Mr. Charles F. Scott, entitled *Polyphase Transmission*, issued by the Westinghouse Electric & Manufacturing Company.

Line Capacity. The effect of capacity is usually negligible, except in long transmission lines where high potentials are used; no calculations or allowance need be made for capacity, for ordinary circuits.

Calculation of Alternating-Current Circuits. In the instruction paper on "Power Stations and Transmission," a method is given for calculating alternating-current lines by means of formulæ, and data are given regarding power factor and the calculation of both single-phase and polyphase circuits. For short lines, secondary wiring, etc., however, it is probably more convenient to use the chart method devised by Mr. Ralph D. Mershon, described in the *American Electrician* of June, 1897, and partially reproduced as follows:

DROP IN ALTERNATING-CURRENT LINES

When alternating currents first came into use, when transmission distances were short and the only loads carried were lamps, the question of *drop* or *loss of voltage* in the transmitting line was a simple one, and the same methods as for direct current could without serious error be employed in dealing with it. The conditions existing in alternating practice to-day—longer distances, polyphase circuits, and loads made up partly or wholly of induction motors—render this question less simple; and direct-current methods applied to it do not lead to satisfactory results. Any treatment of this or of any engineering subject, if it is to benefit the majority of engineers, must not involve groping through long equations or complex diagrams in search of practical results. The results, if any, must be in available and convenient form. In what follows, the endeavor has been made to so treat the subject of drop in alternating-current lines that if the reader be grounded in the theory the brief space devoted to it will suffice; but if he do not comprehend or care to follow the simple theory involved, he may nevertheless turn the results to his practical advantage.

Calculation of Drop. Most of the matter heretofore published on the subject of drop treats only of the inter-relation of the E. M. F.'s involved, and, so far as the writer knows, there have not appeared in convenient form the data necessary for accurately calculating this quantity. Table X (page 47) and the chart (page 46) include, in a form suitable for the engineer's pocketbook, everything necessary for calculating the drop of alternating-current lines.

The chart is simply an extension of the vector diagram (Fig. 40), giving the relations of the E. M. F.'s of line, load and generator. In

Fig. 40, E is the generator E. M. F.; e, the E. M. F. impressed upon the load; c, that component of E which overcomes the back E. M. F. due to the impedance of the line. The component c is made up of two components at right angles to each other. One is a, the component overcoming the IR or back E. M. F. due to resistance of the line. The other is b, the component overcoming the reactance E. M. F. or back E. M. F. due to the alternating field set up around the wire by the current in the wire. The drop is the difference between E and e. It is d, the radial distance between two circular arcs, one of which is drawn with a radius e, and the other with a radius E.

The chart is made by striking a succession of circular arcs with O as a center. The radius of the smallest circle corresponds to e, the E. M. F. of the load, which is taken as 100 per cent. The radii of the succeeding circles increase by 1 per cent of that of the smallest circle; and, as the radius of the last or largest circle is 140 per cent of that of the smallest, the chart answers for drops up to 40 per cent of the E. M. F. delivered.

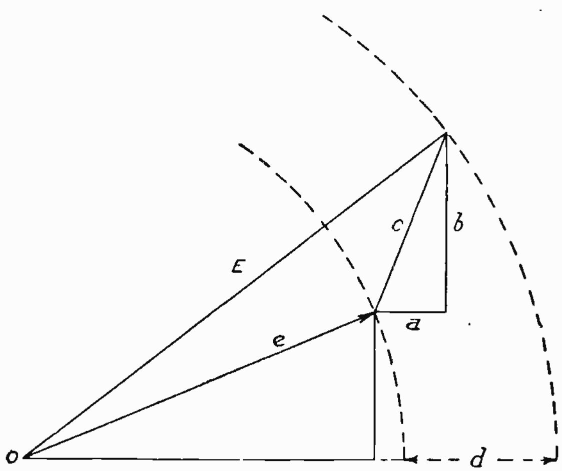


Fig. 40. Vector Diagram.

The terms *resistance volts*, *resistance E. M. F.*, *reactance volts*, and *reactance E. M. F.*, refer, of course, to the voltages for overcoming the back E. M. F.'s due to resistance and reactance respectively. The figures given in the table under the heading "Resistance-Volts for One Ampere, etc." are simply the resistances of 2,000 feet of the various sizes of wire. The values given under the heading "Reactance-Volts, etc.," are, a part of them, calculated from tables published some time ago by Messrs. Houston and Kennelly. The remainder were obtained by using Maxwell's formula.

The explanation given in the table accompanying the chart

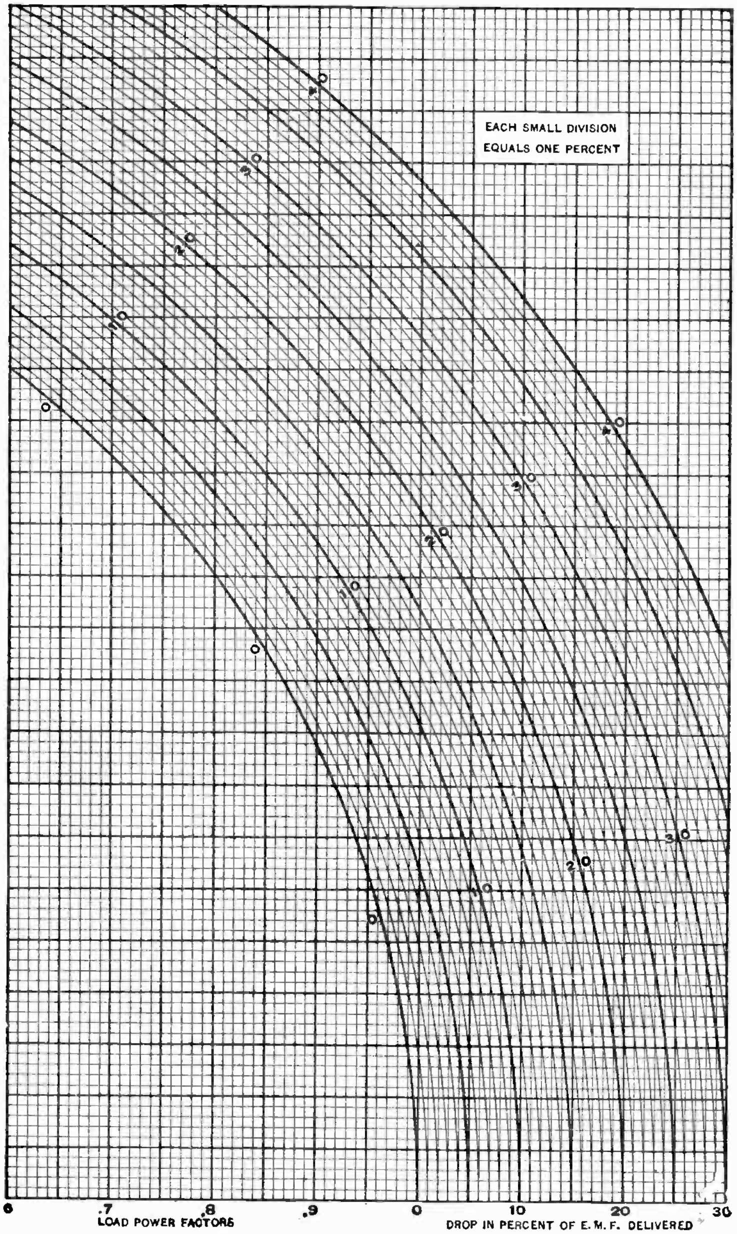


Chart for Calculating Drop in Alternating-Current Lines.

TABLE X

Data for Calculating Drop in Alternating-Current Lines

To be used in conjunction with Chart on opposite page.

By means of the table, calculate the *Resistance-Volts* and the *Reactance-Volts* in the line, and find what per cent each is of the E. M. F. delivered at the end of the line. Starting from the point on the chart where the vertical line corresponding with the power-factor of the load intersects the smallest circle, lay off in per cent the resistance E. M. F. horizontally and to the right; from the point thus obtained, lay off upward in per cent the reactance-E. M. F. The circle on which the last point falls gives the drop, in per cent, of the E. M. F. delivered at the end of the line. Every tenth circle arc is marked with the per cent drop to which it corresponds.

Throughout the table the lower figures in the squares give values for ONE MILE of line, corresponding to those of the upper figures for 1,000 feet of line.

Upper figures are REACTANCE-VOLTS in 1,000 ft. of Line (= 2,000 ft. of Wire) for One Ampere at 7,200 Alternations per Minute (60 Cycles per Second) for the distance given between Centers of Conductors.

Size of wire—B. & S.	Upper figures are Weight in Lbs. per 1,000 ft. Single Wire	Upper figures are RESISTANCE-VOLTS in 1,000 ft. of Line (2,000 ft. of wire) for One Ampere	½"	1"	2"	3"	6"	9"	12"	18"	24"	30"	36"
0000	639 3,376	.098 .518	.046 .243	.079 .417	.111 .586	.130 .687	.161 .850	.180 .951	.193 1.02	.212 1.12	.225 1.19	.235 1.24	.244 1.29
000	507 2,677	.124 .653	.052 .275	.085 .449	.116 .613	.135 .713	.167 .882	.185 .977	.199 1.05	.217 1.15	.230 1.22	.241 1.27	.249 1.32
00	402 2,123	.156 .824	.057 .301	.090 .475	.121 .639	.140 .739	.172 .908	.190 1.00	.204 1.08	.222 1.17	.236 1.25	.246 1.30	.254 1.34
0	319 1,685	.197 1.04	.063 .332	.095 .502	.127 .671	.145 .766	.177 .935	.196 1.04	.209 1.10	.228 1.20	.241 1.27	.251 1.33	.259 1.37
1	253 1,335	.248 1.31	.068 .359	.101 .533	.132 .687	.151 .797	.183 .966	.201 1.06	.214 1.13	.233 1.23	.246 1.30	.256 1.35	.265 1.40
2	201 1,059	.313 1.65	.074 .391	.106 .560	.138 .728	.156 .824	.188 .993	.206 1.09	.220 1.16	.238 1.26	.252 1.33	.262 1.38	.270 1.43
3	159 840	.394 2.08	.079 .417	.112 .591	.143 .755	.162 .856	.193 1.02	.212 1.12	.225 1.19	.244 1.29	.257 1.36	.267 1.41	.275 1.45
4	126 666	.497 2.63	.085 .449	.117 .618	.149 .787	.167 .882	.199 1.05	.217 1.15	.230 1.22	.249 1.32	.262 1.38	.272 1.44	.281 1.48
5	100 528	.627 3.31	.090 .475	.121 .639	.154 .813	.172 .908	.204 1.08	.223 1.18	.236 1.25	.254 1.34	.268 1.42	.278 1.47	.286 1.51
6	79 419	.791 4.18	.095 .502	.127 .671	.158 .834	.178 .940	.209 1.10	.228 1.20	.241 1.27	.260 1.37	.272 1.44	.283 1.49	.291 1.54
7	63 332	.997 5.27	.101 .533	.132 .697	.164 .866	.183 .966	.214 1.13	.233 1.23	.246 1.30	.265 1.40	.278 1.47	.288 1.52	.296 1.56
8	50 263	1.260 6.64	.106 .560	.138 .729	.169 .893	.188 .993	.220 1.16	.238 1.26	.252 1 33	.270 1.43	.284 1.50	.293 1.55	.3 02 1.60

(Table X) is thought to be a sufficient guide to its use, but a few examples may be of value.

Problem. Power to be delivered, 250 K.W.; E. M. F. to be delivered, 2,000 volts; distance of transmission, 10,000 feet; size of wire, No. 0; distance between wires, 18 inches; power factor of load, .8; frequency, 7,200 alternations per minute. Find the line loss and drop.

Remembering that the power factor is that fraction by which the apparent power of volt-amperes must be multiplied to give the true power, the apparent power to be delivered is

$$\frac{250 \text{ K.W.}}{.8} = 312.5 \text{ apparent K.W.}$$

The current, therefore, at 2,000 volts will be

$$\frac{312{,}500}{2{,}000} = 156.25 \text{ amperes.}$$

From the table of reactances under the heading "18 inches," and corresponding to No. 0 wire, is obtained the constant .228. Bearing the instructions of the table in mind, the reactance-volts of this line are, 156.25 (amperes) × 10 (thousands of feet) × .228 = 356.3 volts, which is 17.8 per cent of the 2,000 volts to be delivered.

From the column headed "Resistance-Volts" and corresponding to No. 0 wire, is obtained the constant .197. The resistance-volts of the line are, therefore, 156.25 (amperes) × 10 (thousands of feet) × .197 = 307.8 volts, which is 15.4 per cent of the 2,000 volts to be delivered.

Starting, in accordance with the instructions of the table, from the point where the vertical line (which at the bottom of the chart is marked "Load Power Factor" .8) intersects the inner or smallest circle, lay off horizontally and to the right the resistance-E. M. F. in per cent (15.4); and *from the point thus obtained,* lay off vertically the reactance-E. M. F. in per cent (17.8). The last point falls at about 23 per cent, as given by the circular arcs. This, then, is the drop, in per cent, of *the E. M. F. delivered.* The drop, in per cent, of the *generator* E. M. F. is, of course,

$$\frac{23}{100+23} = 18.7 \text{ per cent.}$$

The percentage *loss of power* in the line has not, as with direct current, the same value as the percentage drop. This is due to the fact that the line has reactance, and also that the apparent power delivered to the load is not identical with the true power—that is, the load power factor is less than unity. The loss must be obtained by calculating $I^2 R$ for the line, or, what amounts to the same thing, by multiplying the resistance-volts by the current.

The resistance-volts in this case are 307.8, and the current 156.25 amperes. The loss is $307.8 \times 156.25 = 48.1$ K. W. The percentage *loss* is

$$\frac{48.1}{250 + 48.1} = 16.1 \text{ per cent.}$$

Therefore, for the problem taken, the *drop* is 18.7 per cent, and the *loss* is 16.1 per cent. If the problem be to find the size wire for a given drop, it must be solved by trial. Assume a size of wire and calculate the drop; the result in connection with the table will show the direction and extent of the change necessary in the size of wire to give the required drop.

The effect of the line reactance in increasing the drop should be noted. If there were no reactance, the drop in the above example would be given by the point obtained in laying off on the chart the resistance-E. M. F. (15.4) only. This point falls at 12.4 per cent, and the drop in terms of the generator E. M. F. would be

$$\frac{12.4}{112.4} = 11 \text{ per cent, instead of } 18.7 \text{ per cent.}$$

Anything therefore which will reduce reactance is desirable.

Reactance can be reduced in two ways. One of these is to diminish the distance between wires. The extent to which this can be carried is limited, in the case of a pole line, to the least distance at which the wires are safe from swinging together in the middle of the span; in inside wiring, by the danger from fire. The other way of reducing reactance is to split the copper up into a greater number of circuits, and arrange these circuits so that there is no inductive interaction. For instance, suppose that in the example worked out above, two No. 3 wires were used instead of one No. 0 wire. The resistance-volts would be practically the same, but the reactance-volts would be less in the ratio $\frac{1}{2} \times \frac{.244}{.228} = .535$, since each circuit would bear half the current the No. 0 circuit does, and the constant for No. 3 wire is .244, instead of .228—that for No. 0. The effect of subdividing the copper is also shown if in the example given it is desired to reduce the drop to, say, one-half. Increasing the copper from No. 0 to No. 0000 will not produce the required result, for, although the resistance-volts will be reduced one-half, the reactance-volts will be reduced only in the ratio $\frac{.212}{.228}$. If, however, *two* inductively independent circuits of No. 0 wire be used, the resistance- and reactance-volts will both be reduced one-half, and the drop will therefore be diminished the required amount.

The component of drop due to reactance is best diminished by subdividing the copper or by bringing the conductors closer together. It is little affected by change in size of conductors.

An idea of the manner in which changes of power factor affect drop is best gotten by an example. Assume distance of transmission, distance between conductors E. M. F., and frequency, the same as in the previous example. Assume the *apparent* power delivered the same as before, and let it be constant, but let the power factor be given several different values; the true power will therefore be a variable depending upon the value of the power factor. Let the size of wire be No. 0000. As the apparent power, and hence the current, is the same as before, and the line resistance is one-half, the resistance-E. M. F. will in this case be

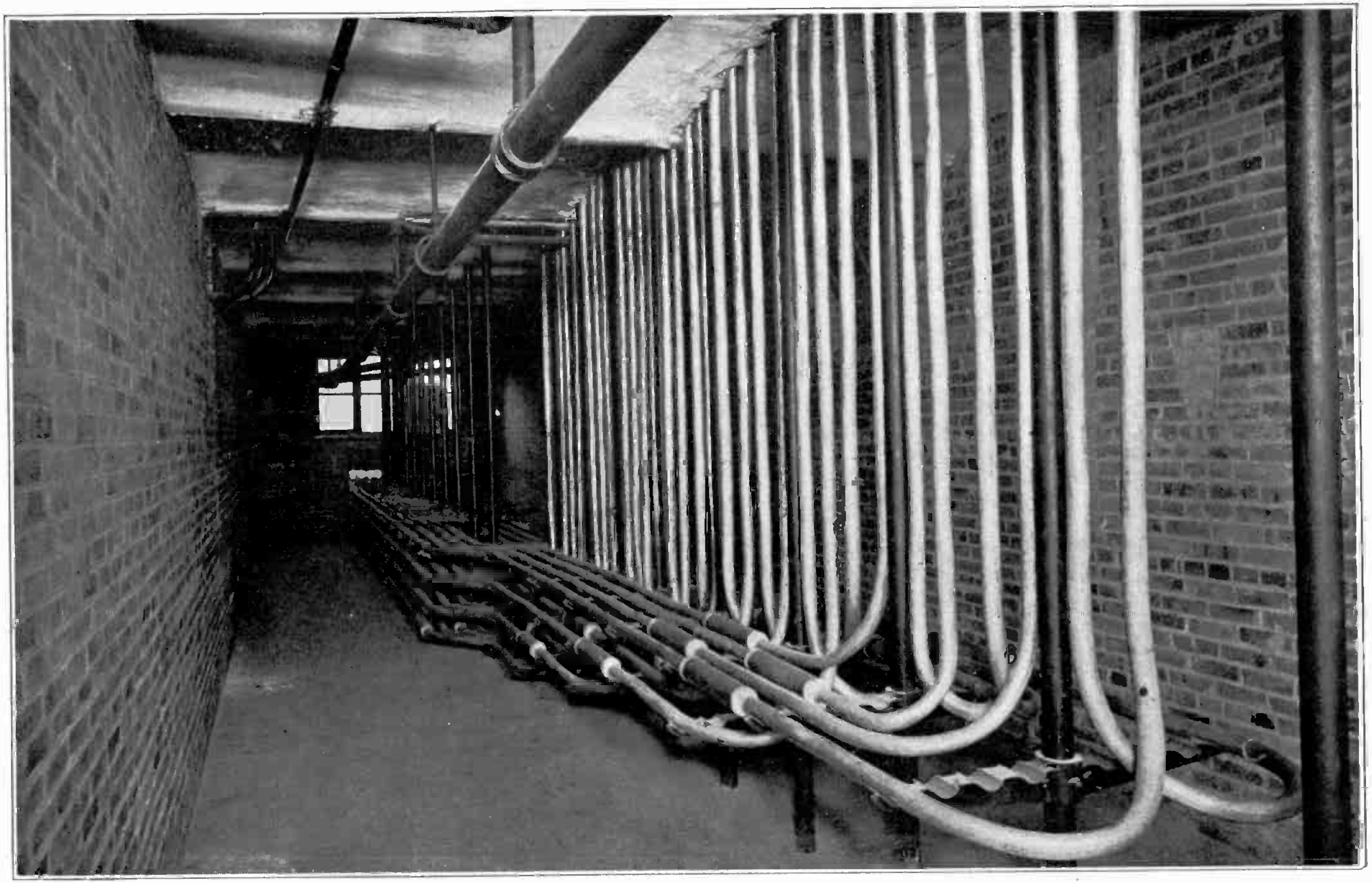
$$\frac{15.4}{2}, \text{ or } 7.7 \text{ per cent of the E. M. F. delivered.}$$

Also, the reactance-E. M. F. will be

$$\frac{.212 \times 17.8}{.228} = 16.5 \text{ per cent.}$$

Combining these on the chart for a power factor of .4, and deducing the drop, in per cent, of the generator E. M. F., the value obtained is 15.3 per cent; with a power factor of .8, the drop is 14 per cent; with a power factor of unity, it is 8 per cent. If in this example the *true* power, instead of the *apparent* power, had been taken as constant, it is evident that the values of drop would have differed more widely, since the current, and hence the resistance- and reactance-volts, would have increased as the power factor diminished. The condition taken more nearly represents that of practice.

If the line had resistance and no reactance, the several values of drop, instead of 15.3, 14, and 8, would be 3.2, 5.7, and 7.2 per cent respectively, showing that for a load of lamps the drop will not



CABLE ENTRANCE TO LARGE TELEPHONE OFFICE BUILDINGS

The Cables Enter the Basement from the Street Ducts and Pass in a Single Row through a Fireproof Floor Directly to the Distributing Frame Above.

be much increased by reactance; but that with a load, such as induction motors, whose power factor is less than unity, care should be taken to keep the reactance as low as practicable. In all cases it is advisable to place conductors as close together as good practice will permit.

When there is a transformer in circuit, and it is desired to obtain the combined drop of transformer and line, it is necessary to know the resistance- and reactance-volts of the transformer. The resistance-volts of the combination of line and transformer are the sum of the resistance-volts of the line and the resistance-volts of the transformer. Similarly, the reactance-volts of the line and transformer are the sum of their respective reactance-volts. The resistance- and reactance-E. M. F.s of transformers may usually be obtained from the makers, and are ordinarily given in per cent.* These percentages express the values of the resistance- and reactance-E. M. F.'s when the transformer delivers its normal *full-load* current; and they express these values in terms of the normal *no-load* E. M. F. of the transformer.

Consider a transformer built for transformation between 1,000 and 100 volts. Suppose the resistance- and reactance-E. M. F.'s given are 2 per cent and 7 per cent respectively. Then the corresponding voltages when the transformer delivers full-load current, are 2 and 7 volts or 20 and 70 volts according as the line whose drop is required is connected to the low-voltage or high-voltage terminals. These values, 2—7 and 20—70, hold, no matter at what voltage the trans-

*When the required values cannot be obtained from the makers, they may be measured. Measure the resistance of both coils. If the line to be calculated is attached to the high-voltage terminals of the transformer, the equivalent resistance is that of the high-voltage coil, *plus* the resistance obtained by *increasing* in the square of the ratio of transformation the measured resistance of the low-voltage coil That is, if the ratio of transformation is 10, the equivalent resistance referred to the high-voltage circuit is the resistance of the high-voltage coil, *plus* 100 times that of the low-voltage coil. This equivalent resistance multiplied by the high-voltage current gives the transformer resistance-volts referred to the high-voltage circuit. Similarly, the equivalent resistance referred to the low-voltage circuit is the resistance of the low-voltage coil, *plus* that of the high-voltage coil *reduced* in the square of the ratio of transformation. It follows, of course, from this, that the values of the resistance-volts referred to the two circuits bear to each other the ratio of transformation. To obtain the reactance-volts, short-circuit one coil of the transformer and measure the voltage necessary to force through the other coil its normal current at normal frequency. The result is, nearly enough, the reactance-volts. It makes no difference which coil is short-circuited, as the results obtained in one case will bear to those in the other the ratio of transformation. If a close value is desired, subtract from the square of the voltage reading the square of the *resistance*-volts, and take the square root of the difference as the reactance-volts.

former is operated, since they depend only upon the strength of current, providing it is of the normal frequency. If any other than the full-load current is drawn from the transformer, the reactance- and resistance-volts will be such a proportion of the values given above as the current flowing is of the full-load current. It may be noted, in passing, that when the resistance- and reactance-volts of a transformer are known, its regulation may be determined by making use of the chart in the same way as for a line having resistance and reactance.

As an illustration of the method of calculating the drop in a line and transformer, and also of the use of table and chart in calculating low-voltage mains, the following example is given:

Problem. A single-phase induction motor is to be supplied with 20 amperes at 200 volts; alternations, 7,200 per minute; power factor, .78. The distance from transformer to motor is 150 feet, and the line is No. 5 wire, 6 inches between centers of conductors. The transformer reduces in the ratio $\frac{2,000}{200}$, has a capacity of 25 amperes at 200 volts, and, when delivering this current and voltage, its resistance-E. M. F. is 2.5 per cent, its reactance-E. M. F. 5 per cent. Find the drop.

The reactance of 1,000 feet of circuit consisting of two No. 5 wires, 6 inches apart, is .204. The reactance-volts therefore are

$$.204 \times \frac{150}{1,000} \times 20 = .61 \text{ volts.}$$

The resistance-volts are

$$.627 \times \frac{150}{1,000} \times 20 = 1.88 \text{ volts.}$$

At 25 amperes, the resistance-volts of the transformer are 2.5 per cent of 200, or 5 volts. At 20 amperes, they are $\frac{20}{25}$ of this, or 4 volts. Similarly, the transformer reactance-volts at 25 amperes are 10, and at 20 amperes are 8 volts. The combined reactance-volts of transformer and line are $8 + .61 = 8.61$, which is 4.3 per cent of the 200 volts to be delivered. The combined resistance-volts are 1.88 +4, or 5.88, which is 2.94 per cent of the E. M. F. to be delivered. Combining these quantities on the chart with a power factor of .78, the drop is 5 per cent of the delivered E. M. F.,

$$\text{or } \frac{5}{105} = 4.8 \text{ per cent}$$

of the impressed E. M. F. The transformer must be supplied with

$$\frac{2{,}000}{.952} = 2{,}100 \text{ volts},$$

in order that 200 volts shall be delivered to the motor.

Table X (page 47) is made out for 7,200 alternations, but will answer for any other number if the values for reactance be changed in direct proportion to the change in alternations. For instance, for 16,000 alternations, multiply the reactances given by $\frac{16{,}000}{7{,}200}$. For other distances between centers of conductors, interpolate the values given in the table. As the reactance values for different sizes of wire change by a constant amount, the table can, if desired, be readily extended for larger or smaller conductors.

The table is based on the assumption of sine currents and E. M. F.'s. The best practice of to-day produces machines which so closely approximate this condition that results obtained by the above methods are well within the limits of practical requirements.

Polyphase Circuits. So far, single-phase circuits only have been dealt with. A simple extension of the methods given above adapts them to the calculation of polyphase circuits. A four-wire *quarter-phase* (two-phase) transmission may, so far as loss and regulation are concerned, be replaced by two single-phase circuits identical (as to size of wire, distance between wires, current, and E. M. F.) with the two circuits of the quarter-phase transmission, provided that in both cases there is no inductive interaction between circuits. Therefore, to calculate a four-wire, quarter-phase transmission, compute the single-phase circuit required to transmit one-half the power at the same voltage. The quarter-phase transmission will require two such circuits.

A three-wire, *three-phase* transmission, of which the conductors are symmetrically related, may, so far as loss and regulation are concerned, be replaced by two single-phase circuits having no inductive interaction, and identical with the three-phase line as to size, wire, and distance between wires. Therefore, to calculate a three-phase transmission, calculate a single-phase circuit to carry one-half the load at the same voltage. The three-phase transmission will require three wires of the size and distance between centers as obtained for the single-phase.

A three-wire, two-phase transmission may be calculated *exactly* as regards loss, and *approximately* as regards drop, in the same way as for three-phase. It is possible to exactly calculate the drop, but this involves a more complicated method than the approximate one. The error by this approximate method is generally small. It is possible, also, to get a somewhat less drop and loss with the same copper by proportioning the cross-section of the middle and outside wires of a three-wire, quarter-phase circuit to the currents they carry, instead of using three wires of the same size. The advantage, of course, is not great, and it will not be considered here.

WIRING AN OFFICE BUILDING

The building selected as a typical sample of a wiring installation is that of an office building located in Washington, D. C. The figures shown are reproductions of the plans actually used in installing the work.

The building consists of a basement and ten stories. It is of fireproof construction, having steel beams with terra-cotta flat arches. The main walls are of brick and the partition walls of terra-cotta blocks, finished with plaster. There is a space of approximately five inches between the top of the iron beams and the top of the finished floor, of which space about three inches was available for running the electric conduits. The flooring is of wood in the offices, but of concrete, mosaic, or tile in the basement, halls, toilet-rooms, etc.

The electric current supply is derived from the mains of the local illuminating company, the mains being brought into the front of the building and extending to a switchboard located near the center of the basement.

As the building is a very substantial fireproof structure, the only method of wiring considered was that in which the circuits would be installed in iron conduits.

Electric Current Supply. The electric current supply is direct current, two-wire for power, and three-wire for lighting, having a potential of 236 volts between the outside conductors, and 118 volts between the neutral and either outside conductor.

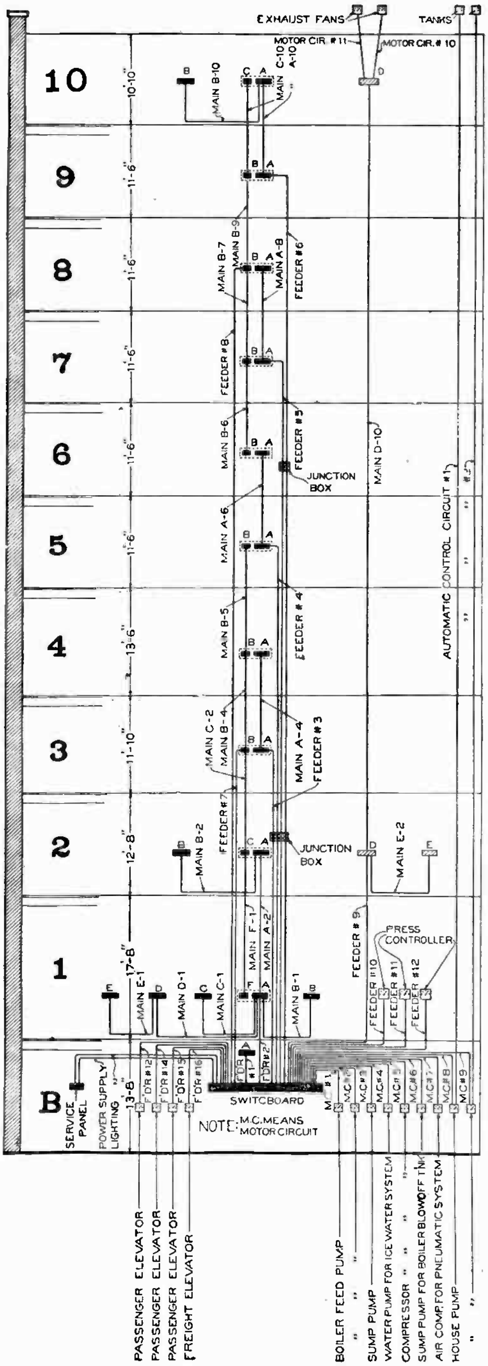
Switchboard. On the switchboard in the basement are mounted wattmeters, provided by the local electric company, and the various switches required for the control and operation of the lighting and power feeders. There are a total of ten triple-pole switches for lighting, and eighteen for power. An indicating voltmeter and ampere meter are also placed in the switchboard. A voltmeter is provided with a double-throw switch, and so arranged as to measure the potential across the two outside conductors, or between the neutral conductor and either of the outside conductors. The ampere meter is arranged with two shunts, one being placed in each outside leg; the shunts are connected with a double-pole, double-throw switch, so that the ampere meter can be connected to either shunt and thus measure the current supplied on each side of the system.

Character of Load. The building is occupied partly as a newspaper office, and there are several large presses in addition to the usual linotype machines, trimmers, shavers, cutters, saws, etc. There are also electrically-driven exhaust fans, house pumps, air-compressors, etc. The upper portion of the building is almost entirely devoted to offices rented to outside parties. The total number of motors supplied was 55; and the total number of outlets, 1,100, supplying 2,400 incandescent lamps and 4 arc lamps.

Feeders and Mains. The arrangement of the various feeders and mains, the cut-out centers, mains, etc., which they supply, are shown diagrammatically in Fig. 41, which also gives in schedule the sizes of feeders, mains, and motor circuits, and the data relating to the cut-out panels.

Although the current supply was to be taken from an outside source, yet, inasmuch as there was a probability of a plant being installed in the building itself at some future time, the three-wire system of feeders and mains was designed, with a neutral conductor equal to the combined capacity of the two outside conductors, so that 120-volt two-wire generators could be utilized without any change in the feeders.

Basement. The plan of the basement, Fig. 42, shows the branch circuit wiring for the outlets in the basement, and the location of the main switchboard. It also shows the trunk cables for the interconnection system serving to provide the necessary wires for telephones,



FEEDERS

NO.	END AT FLOOR	END AT CUT-OUT	BRANCH CIR.	LIGHTS	LENGHT-FT (ONE WAY)	LOSS IN VOLTS	SIZE OF WIRE: NO. MIDDLE COND'R	SIZE OF WIRE: NO. OUTSIDE COND'R	INSIDE DIA. OF CONDUIT ALLOWED *
1	BASMT	A	18	115	48	0.84	2	4	1.25"
2	1 ST	"	83	533	88	1.18	400000	4-0	2.5"
3	3 RD	"	43	288	119	1.68	4-0	0	2"
4	5 TH	"	44	296	147	1.78	250000	2-0	2.5"
5	7 TH	"	"	292	173	1.72	300000	3-0	"
6	9 TH	"	124	365	200	1.61	450000	250000	3"
7	3 RD	B	26	131	119	1.5	0	3	1.5"
8	8 TH	"	27	128	185	1.8	2-0	2	2"
L.S.	SW.B	"		2165	138	1.5	4000000	2000000	***
9	2 ND	D			148		400000		3"
10	PRESS				83		700000		**
11	"				118		"		"
12	"				"		"		"
13	PASS.ELV.				58		4-0		2"
14	"				"		"		"
15	"				"		"		"
16	FRGT.ELV.				148		"		"
P.S.	SW B				138		2000000		****

* ALL CONDUCTORS IN ONE CONDUIT.
** SEPARATE CONDUIT FOR EACH CONDUCTOR
*** THIS FEEDER IS TO BE DIVIDED INTO FOUR (4)
" CONDUCTORS OF #2000000 C.M. EACH.
" EACH CONDUCTOR IS TO BE INSTALLED IN A SEP-
" ARATE 3" (INSIDE DIAM.) CONDUIT
L.S.=LIGHTING SUPPLY
P.S.=POWER "
**** SEPARATE 3" (INSIDE DIAM.) CONDUIT FOR EACH
" CONDUCTOR

MAINS

MAINS	SUPPLIED BY FEEDER #	SUPPLIED BY CUT OUT	SUPPLIED BY FLOOR	LIGHTS	LENGTH-FT (ONE WAY)	LOSS IN VOLTS	SIZE OF WIRE: NO. MIDDLE COND'R	SIZE OF WIRE: NO. OUTSIDE COND'R	INSIDE DIA. OF CONDUIT ALLOWED *
A-2	2	A	1 ST	284	63	0.72	250000	2-0	2.5"
A-4	3	"	3 RD	147	18	0.41	2	4	1.25"
A-6	4	"	5 TH	146	"	0.4	"	"	"
A-8	5	"	7 TH	"	"	"	"	"	"
A-10	6	"	9 TH	171	"	0.29	0	3	1.5"
B-1	2	"	1 ST	76	70	0.51	"	"	"
B-2	"	"	"	206	58	0.58	4-0	0	2"
B-10	6	"	10 TH	87	44	0.37	0	3	1.5"
D-1	2	"	1 ST	120	12	0.22	2	4	1.25"
C-1	"	"	"	70	44	0.30	0	3	1.5"
F-1	7	C	2 ND	22	61	0.41	8	10	1"
C-2	"	B	3 RD	47	18	0.52	"	"	"
B-4	"	"	"	56	"	0.60	"	"	"
B-5	"	"	4 TH	28	"	0.31	"	"	"
B-6	8	"	7 TH	32	"	0.35	"	"	"
B-7	"	"	8 TH	56	"	0.60	"	"	"
B-9	"	"	"	44	"	0.48	"	"	"
C-10	"	"	9 TH	16	"	0.28	10	12	"
E-1	2	A	1 ST	61	92	0.86	2	4	1.25"
E-2	9	D	2 ND		84		0	0	1.5"
D-10	"	"	"		108		2	2	1.25"

* ALL CONDUCTORS IN ONE CONDUIT

MOTOR CIRCUITS

NO.	SUPPLIED BY FEEDER	SUPPLIED BY CUTOUT	SUPPLIED BY FLOOR	H.P. SUPPLIED	CURRENT IN AMP.	LENGTH IN FEET (ONE WAY)	SIZE OF WIRE	INSIDE DIAM. OF CONDUIT ALLOWED *
1			BSMT	15	60	74	2	1.25"
2			"	"	"	"	"	"
3			"	5	20	50	8	1"
4			"	"	"	40	"	"
5			"	15	60	"	2	1.25"
6			"	3	12	48	10	0.75"
7			"		20	"	8	1"
8			"	15	60	80	2	1.25"
9	MAIN		"	"	"	"	"	"
10	D-10	D	10 TH	7.5	30	134	6	1"
11	"	"	"	"	"	28	"	"

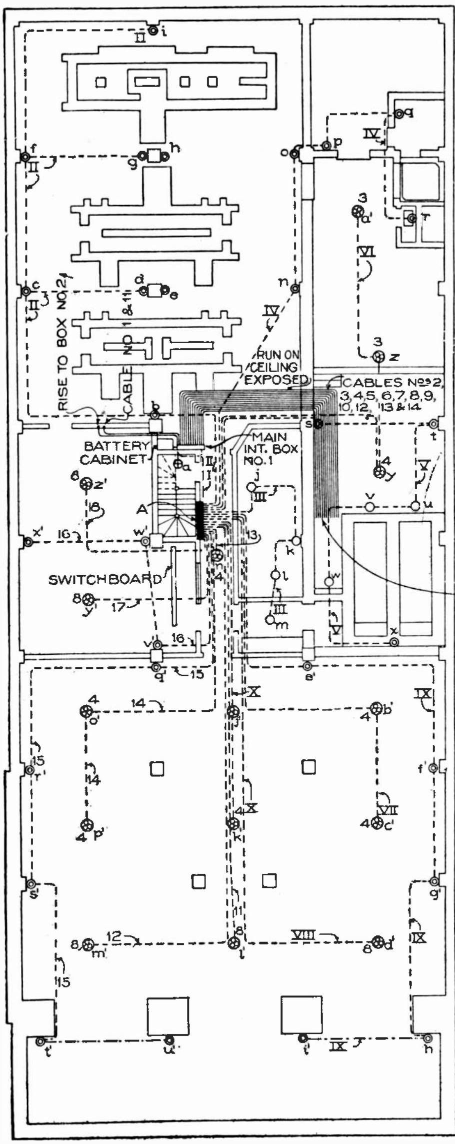
* BOTH CONDUCTORS IN ONE CONDUIT

CUT-OUTS

NAME	FLOOR	MAINS	BRANCH CIRCUITS	P.B. SWITCHES	METERS	T.P.S.T. 25 AMP.	T.P.S.T. 50 "	T.P.S.T. 100 "	T.P.S.T. 150 "	T.P.S.T. 200 "	D.P.S.T. 25 "	D.P.S.T. 50 "	D.P.S.T. 100 "	D.P.S.T. 125 "	D.P.S.T. 150 "
A	BSMT		20	10											
"	1 ST	4					2	1		1					
B	"		10	10											
C	"		"	"											
D	"	1	12	8			2								
E	"		"	4											
F	"		8	6											
A	2 ND	1	16	1			1*		1						
B	"		32	3											
C	"	1	4	4		2									
D	"	1									24		1	1	
E	"										4	6			
A	3 RD	1	22	1				2							
B	"	2	4	4		3									
A	4 TH		24	1											
B	"	1	4	4		2									
A	5 TH	1	24	1				2							
B	"		4	4											
A	6 TH		28	1											
B	"		4	4											
A	7 TH	1	24	1				2							
B	"	1	4	4		2									
A	8 TH		24	1											
B	"	2	4	4		3									
A	9 TH	1	24	1				1*	1						
B	"	1	4	4		2									
A	10 TH	1	24	1			1*	1							
B	"		16	1											
C	"		4	4											
D	"										4	2			

* MAIN SWITCH

Fig. 41. Wiring of an Office Building. Diagram Showing Arrangement of Feeders and Mains, Cut-Out Centers, etc.



SCHEDULE OF CIRCUITS

NO.	SUPPLIED by CUTOUT	SUPPLIED by MAIN	No. of BRANCHES	OUTLETS SUPPLIED	TOTAL OUTLETS	TOTAL LIGHTS	AT WHAT POINT CONTROLLED
I	A	F'D'R NO. 1	1	a	1	1	
II	"	"	3	bcdefghi	8	8	
III	"	"	1	jklm	4	4	
IV	"	"	1	nopqr	5	5	
V	"	"	1	stuvwx	6	6	
VI	"	"	1	yza'	3	10	S at A
VII	"	"	1	b'c'	2	8	" " "
VIII	"	"	1	d'	1	8	" " "
IX	"	"	1	e'f'g'h'i'	5	5	
X	"	"	1	j'k'	2	8	S at A
11	"	"	1	l'	1	8	" " "
12	"	"	1	m'	1	8	" " "
13	"	"	1	n'	1	4	" " "
14	"	"	1	o'p'	2	8	" " "
15	"	"	1	q'r's't'u'	5	5	
16	"	"	1	v'w'x	3	3	
17	"	"	1	y'	1	8	S at A
18	"	"	1	z'	1	8	" " "
					52	115	

CABLE NO. 2 RISES TO 2nd FLOOR
" " 3 " " 3rd "
" " 4 " " 4th "
" " 5 " " 5th "
" " 6 " " 6th "
" " 7 " " 7th "
" " 8 " " 8th "
" " 9 " " 9th "
" " 10 " " 10th "
" " 12 " " 2nd "
" " 13 " " 5th "
" " 14 " " 8th "

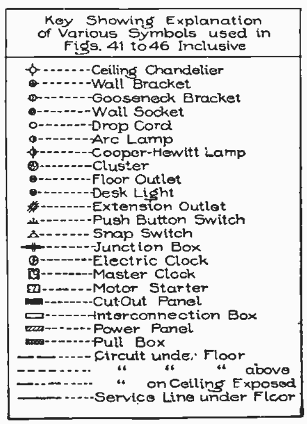


Fig. 42. Wiring an Office Building. Basement Plan Showing Branch Circuit Wiring for Outlets in Basement, Location of Main Switchboard, and Trunk Cables of the Interconnection System Providing Wires for Telephone, Ticker, and Messenger Call Service, etc,

tickers, messenger calls, etc., in all the rooms throughout the building, as will be described later.

To avoid confusion, the feeders were not shown on the basement plan, but were described in detail in the specification, and installed in accordance with directions issued at the time of installation. The electric current supply enters the building at the front, and a service switch and cut-out are placed on the front wall. From this point, a two-wire feeder for power and a three-wire feeder for lighting, are run to the main switchboard located near the center of the basement. Owing to the size of the conduits required for these supply feeders, as well as the main feeders extending to the upper floors of the building, the said conduits are run exposed on substantial hangers suspended from the basement ceiling.

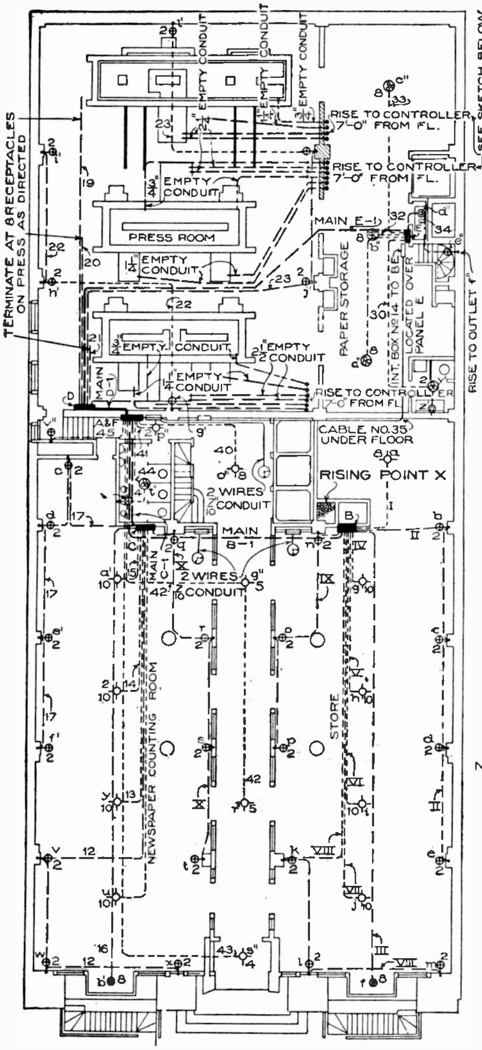
First Floor. The rear portion of the building from the basement through the first floor, Fig. 43, and including the mezzanine floor, between the first and second floors, at the rear portion of the building only, is utilized as a press room for several large and heavy, modern newspaper presses. The motors and controllers for these presses are located on the first floor. A separate feeder for each of these press motors is run directly from the main switchboard to the motor controller in each case. Empty conduits were provided, extending from the controllers to the motor in each case, intended for the various control wires installed by the contractor for the press equipments.

One-half of the front portion of the first floor is utilized as a newspaper office; the remaining half, as a bank.

Second Floor. The rear portion of the second floor, Fig. 44, is occupied as a composing and linotype room, and is illuminated chiefly by means of drop-cords from outlets located over the linotype machines and over the compositors' cases. Separate $\frac{1}{8}$-horse-power motors are provided for each linotype machine, the circuits for the same being run underneath the floor.

Upper Floors. A typical plan (Fig. 45) is shown of the upper floors, as they are similar in all respects with the exception of certain changes in partitions, which are not material for the purpose of illustration or for practical example. The circuit work is sufficiently intelligible from the plan to require no further explanation.

Interconnection System. Fig. 46 is a diagram of the interconnection system, showing the main interconnection box located in the



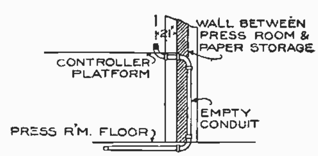
NOTE: ALL CONDUITS FOR THE PRESSES MUST COME THROUGH THE CONTROLLER PLATFORM 21" FROM THE WALL.

ALL CONDUITS ARE TO TERMINATE IN PRESS AS DIRECTED.

SCHEDULE OF CIRCUITS

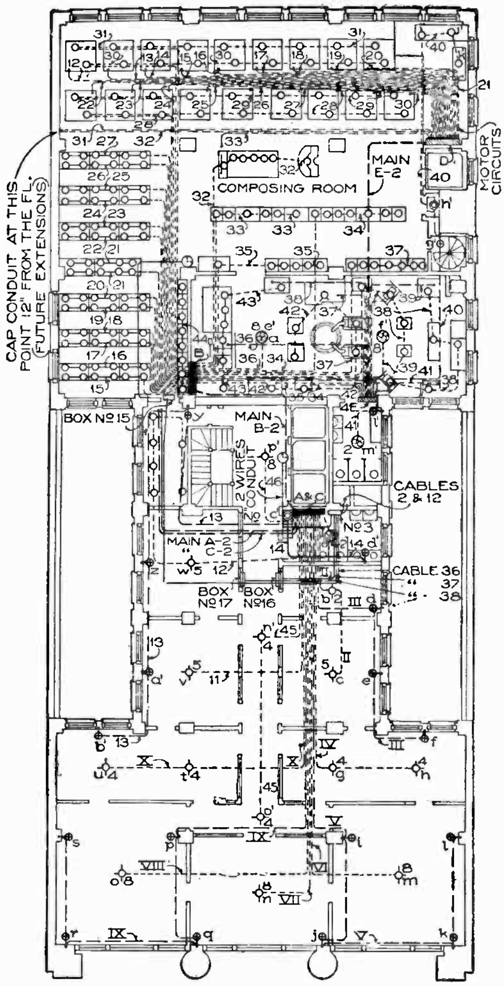
NO.	SUPPLIED by CUTOUT	SUPPLIED by MAIN	No. of BRANCHES	OUTLETS SUPPLIED	TOTAL OUTLETS	TOTAL LIGHTS	AT WHAT POINT CONTROLLED
I	B	F'DR NO. 2	1	a	1	8	S at B
II	"	"	1	bcde	4	8	" " "
III	"	"	1	f	1	8	" " "
IV	"	"	1	g	1	10	" " "
V	"	"	1	h	1	10	" " "
VI	"	"	1	i	1	10	" " "
VII	"	"	1	j	1	10	" " "
VIII	"	"	1	klm	3	6	" " "
IX	"	"	1	nop	3	6	" " "
			1		16	76	
X	C	C-1	1	qrst	4	8	S at C
11	"	"	1	u	1	10	" " "
12	"	"	1	vwx	3	6	" " "
13	"	"	1	y	1	10	" " "
14	"	"	1	z	1	10	" " "
15	"	"	1	a'	1	10	" " "
16	"	"	1	b'	1	8	" " "
17	"	"	1	c'd'e'f'	4	8	" " "
					16	70	
19	D	D-1	1	8 Receptacles	8	8	
20	"	"	1		8	8	
21	"	"	1		8	8	
22	"	"	1	g'h'i'	3	6	S at D
23	"	"	1	j'k'l'	3	6	" " "
24							
25							
26	SEE MEZZ. PLAN						
27							
28							
29							
30	E	E-1	1	y'z"	2	3	S at E
31	"	"	1	a"	1	8	" " "
32	"	"	1	b"	1	8	" " "
33	"	"	1	c"	1	8	" " "
34	"	"	1	d"e"f", g"	4	4	" " "
35							
36							
37	SEE MEZZ. PLAN						
38							
39							
40	F		1	o"	1	8	S at F
41	"	"	1	p"	1	2	" " "
42	"	"	1	q"r"	2	10	" " "
43	"	"	1	s"	1	4	" " "
44	"	"	1	t"u"	2	6	" " "
45	"	"	1	v"	1	1	" " "
					8	31	" " "

NOTE: THE CLOCKS IN STORE AND COUNTING ROOM ARE TO BE LOCATED AS DIRECTED BY ARCHITECT.



SKETCH SHOWING ROUTE OF EMPTY CONDUITS RISING TO CONTROLLER PLATFORM IN PRESS ROOM.

Fig. 43. Wiring of an Office Building.
First-Floor Plan, Showing Press Room in Rear, Containing Motors and Controllers for Newspaper Presses, Fed Directly from Main Switchboard in Basement; also, in front, Newspaper Counting Room and Bank Offices.



SCHEDULE OF CIRCUITS

NO.	SUPPLIED by CUTOUT	SUPPLIED by MAIN	No. of BRANCHES	OUTLETS SUPPLIED	TOTAL OUTLETS	TOTAL LIGHTS	AT WHAT POINT CONTROLLED
I	A	A-2	1	a	1	2	S at A
II	"	"	1	b c	2	7	
III	"	"	1	d e f	3	3	
IV	"	"	1	g h	2	8	
V	"	"	1	i j k l	4	4	
VI	"	"	1	m	1	8	
VII	"	"	1	n	"	"	
VIII	"	"	1	o	"	"	
IX	"	"	1	p q r s	4	4	
X	"	"	1	t u	2	8	
11	"	"	1	v	1	5	
12	"	"	1	w & 6 Drop Cds	7	11	
13	"	"	1	y z a' b'	4	4	
14	"	"	1	c' d'	2	2	
					30	78	
15	B	B-2	1	Drop Cords	6	6	
16	"	"	1	" "	"	"	
17	"	"	1	" "	"	"	
18	"	"	1	" "	"	"	
19	"	"	1	" "	"	"	
20	"	"	1	" "	"	"	
21	"	"	1	" "	10	10	
22	"	"	1	" "	6	6	
23	"	"	1	" "	"	"	
24	"	"	1	" "	"	"	
25	"	"	1	" "	"	"	
26	"	"	1	" "	"	"	
27	"	"	1	" "	"	"	
28	"	"	1	" "	9	9	
29	"	"	1	" "	"	"	
30	"	"	1	" "	"	"	
31	"	"	1	" "	"	"	
32	"	"	1	" "	7	7	
33	"	"	1	" "	6	6	
34	"	"	1	" "	7	7	
35	"	"	1	" "	6	6	
36	"	"	1	e'	1	8	S at B
37	"	"	1	Drop Cords	7	7	
38	"	"	1	" "	9	9	
39	"	"	1	f'	1	8	S at B
40	"	"	1	g' h' i' j' k'	5	5	
41	"	"	1	l' m'	2	3	S at B
42	"	"	1	Drop Cords	7	7	
43	"	"	1	" "	7	7	
44	"	"	1	" "	8	8	
45	C	C-2	1	n' o'	2	8	S at C
46	"	"	1	p'	1	8	" " "

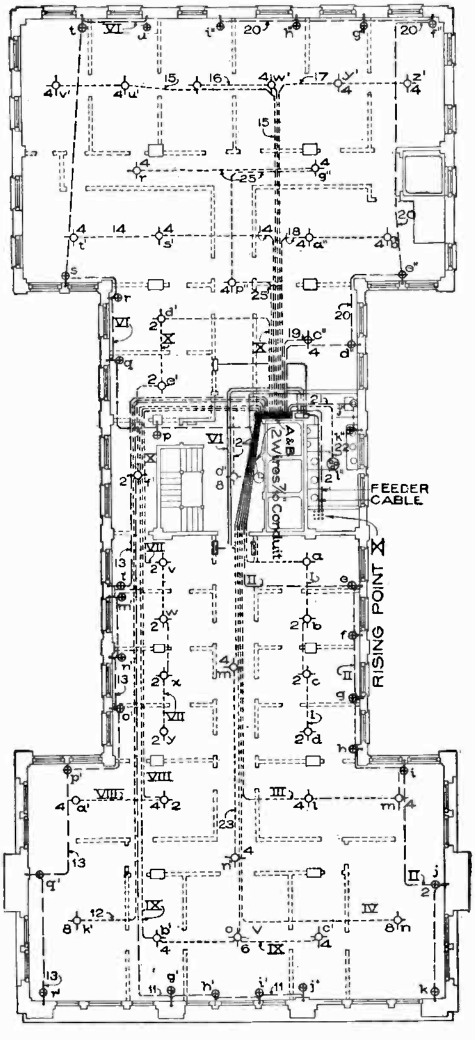
TERMINATE ALL MOTOR CIRCUITS AT MOTOR CONTROLLER AS DIRECTED

MOTOR CIRCUITS

NO.	SUPPLIED BY FEEDER NO.	SUPPLIED BY CUT-OUT	SUPPLIED BY FLOOR	H.P. SUPPLIED	CURRENT IN AMPERES	LENGTH IN FT. (ONE WAY)	SIZE OF WIRE	INSIDE DIA. OF CONDUIT ALLOWED *
12	9	D	2ND	* *		98	10	7/16"
13	"	"	"	"		90	"	"
14	"	"	"	"		82	"	"
15	"	"	"	"		76	"	"
16	"	"	"	"		68	"	"
17	"	"	"	"		60	"	"
18	"	"	"	"		52	"	"
19	"	"	"	"		46	"	"
20	"	"	"	"		38	"	"
21	"	"	"	"		28	"	"
22	"	"	"	"		94	"	"
23	"	"	"	"		86	"	"
24	"	"	"	"		78	"	"
25	"	"	"	"		70	"	"
26	"	"	"	"		62	"	"
27	"	"	"	"		54	"	"
28	"	"	"	"		46	"	"
29	"	"	"	"		38	"	"
30	"	"	"	"		30	"	"
31	"	"	"	"		90	"	"
32	"	"	"	"		"	"	"
33	"	"	"	$\frac{1}{2}$		82	"	"
34	"	E	"	3		28	"	"
35	"	"	"	"		32	"	"
36	"	"	"	"		52	"	"
37	"	"	"	"		34	"	"
38	"	"	"	1		48	12	"
39	"	"	"	2		46	10	"
40	"	"	"	3		30	"	"
41	"	"	"	2		28	"	"
42	"	"	"	3		18	"	"

* BOTH CONDUCTORS IN ONE CONDUIT
* * $\frac{1}{2}$ H.P. REDUCED TO $\frac{1}{4}$ H.P.

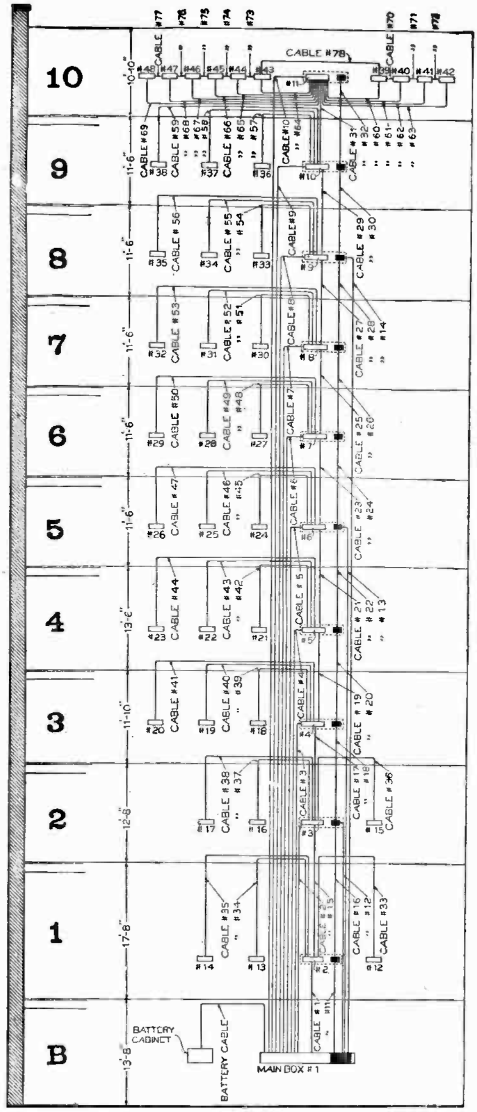
Fig. 44. Wiring of an Office Building. Plan of Second Floor. Rear Portion Occupied as a Composing and Linotype Room.



SCHEDULE OF CIRCUITS

NO.	SUPPLIED by CUTOUT	SUPPLIED by MAIN	No. of BRANCHES	OUTLETS SUPPLIED	TOTAL OUTLETS	TOTAL LIGHTS	AT WHAT POINT CONTROLLED
I	A		1	abcd	4	8	
II	"	"	1	efghijk	7	7	
III	"	"	1	lm	2	8	
IV	"	"	1	n	1	8	
V	"	"	1	o	1	6	
VI	"	"	1	pqrstu	6	6	
VII	"	"	1	vwxy	4	8	
VIII	"	"	1	z a'	2	8	
IX	"	"	1	b'c'	2	8	
X	"	"	1	d'e'f'	3	6	
11	"	"	1	g'h'i'j'	4	4	
12	"	"	1	k'	1	8	
13	"	"	1	l'm'n'o'p'q'r'	7	7	
14	"	"	1	s't'	2	8	
15	"	"	1	u'v'	2	8	
16	"	"	1	w'x'	2	8	
17	"	"	1	y'z'	2	8	
18	"	"	1	a"b"	2	8	
19	"	"	1	c"	1	4	
20	"	"	1	d"e"f"g"h"i"	6	6	
21	"	"	1	j"k"	2	2	
22	"	"	1	l"	1	2	S at A
					64	146	
23	B		1	m"n"	2	8	S at B
24	"	"	1	o"	1	8	S " "
25	"	"	1	p"q"r"	3	12	S " "
					6	28	

Fig. 45. Wiring of an Office Building.
Typical Plan of Upper Floors, Showing Circuit Work, Schedule, etc. All the Floors above the Second are Similar to One Another in Plan, Differing Only in Comparatively Unimportant Details of Partitions.



— CABLES. —

NO.	START AT BOX NO.	START AT FLOOR	END AT BOX NO.	END AT FLOOR	NO. OF WIRES	LENGTH IN FEET	INSIDE DIA. OF CONDUIT ALLOWED
1	1	BAS'MT	2	1 ST	50	122	1½"
2	"	"	3	2 ND	"	116	"
3	"	"	4	3 RD	"	128	"
4	"	"	5	4 TH	"	139	"
5	"	"	6	5 TH	"	154	"
6	"	"	7	6 TH	"	165	"
7	"	"	8	7 TH	"	176	"
8	"	"	9	8 TH	"	187	"
9	"	"	10	9 TH	"	208	"
10	"	"	11	10 TH	"	219	"
11	"	"	2	1 ST	10	122	[illegible]
12	"	"	3	2 ND	"	116	"
13	"	"	6	5 TH	"	154	"
14	"	"	9	8 TH	"	187	"
15	2	1 ST	3	2 ND	"	22	1"
16	"	"	"	"	"	"	1½"
17	3	2 ND	4	3 RD	"	16	1"
18	"	"	"	"	"	"	1½"
19	4	3 RD	5	4 TH	"	15	1"
20	"	"	"	"	"	"	1½"
21	5	4 TH	6	5 TH	"	"	1"
22	"	"	"	"	"	"	1½"
23	6	5 TH	7	6 TH	"	"	1"
24	"	"	"	"	"	"	1½"
25	7	6 TH	8	7 TH	"	"	1"
26	"	"	"	"	"	"	1½"
27	8	7 TH	9	8 TH	"	"	1"
28	"	"	"	"	"	"	1½"
29	9	8 TH	10	9 TH	"	"	1"
30	"	"	"	"	"	"	1½"
31	10	9 TH	11	10 TH	"	"	1"
32	"	"	"	"	"	"	1½"
33	2	1 ST	12	1 ST	"	61	1"
34	"	"	13	"	"	22	"
35	"	"	14	"	"	84	"
36	3	2 ND	15	2 ND	"	55	"
37	"	"	16	"	"	28	"
38	"	"	17	"	"	22	"
39	4	3 RD	18	3 RD	"	25	"
40	"	"	19	"	"	53	"
41	"	"	20	"	"	51	"
42	5	4 TH	21	4 TH	"	25	"
43	"	"	22	"	"	53	"
44	"	"	23	"	"	51	"
45	6	5 TH	24	5 TH	"	25	"
46	"	"	25	"	25	53	1½"
47	"	"	26	"	10	51	1"
48	7	6 TH	27	6 TH	"	25	"
49	"	"	28	"	"	53	"
50	"	"	29	"	"	51	"
51	8	7 TH	30	7 TH	"	25	"
52	"	"	31	"	"	53	"
53	"	"	32	"	"	51	"
54	9	8 TH	33	8 TH	"	25	"
55	"	"	34	"	"	53	"
56	"	"	35	"	"	51	"
57	10	9 TH	36	9 TH	"	25	"
58	"	"	37	"	"	53	"
59	"	"	38	"	"	51	"
60	11	10 TH	39	10 TH	"	29	"
61	"	"	49	"	"	36	"
62	"	"	41	"	"	31	"
63	"	"	42	"	"	39	"
64	"	"	43	"	"	40	"
65	"	"	44	"	"	58	"
66	"	"	45	"	"	79	"
67	"	"	46	"	"	93	"
68	"	"	47	"	"	75	"
69	"	"	48	"	"	56	"
70	39	"	49	"	*	11	"
71	49	"	41	"	"	18	"
72	41	"	42	"	"	13	"
73	43	"	44	"	"	33	"
74	44	"	45	"	"	22	"
75	45	"	46	"	"	"	"
76	46	"	47	"	"	"	"
77	47	"	48	"	"	"	"
78	39	"	43	"	"	"	"

* EMPTY CONDUIT ONLY

— BOXES. —

NO.	FLOOR	NO. REQUIRED OF VARIOUS SIZES: 60 F	1-A	14-B	16-B	20-B	2-B	3-A
1	BAS'M'T	1						
2	1 ST			1				
3	2 ND				1			
4	3 RD			1				
5	4 TH			1				
6	5 TH				1			
7	6 TH			1				
8	7 TH			1				
9	8 TH				1			
10	9 TH			1				
11	10 TH					1		
12	1 ST						1	
13	"						1	
14	"						1	
15	2 ND						1	
16	"						1	
17	"						1	
18	3 RD						1	
19	"						1	
20	"						1	
21	4 TH						1	
22	"						1	
23	"						1	
24	5 TH						1	
25	"						1	
26	"						1	
27	6 TH						1	
28	"						1	
29	"						1	
30	7 TH						1	
31	"						1	
32	"						1	
33	8 TH						1	
34	"						1	
35	"						1	
36	9 TH						1	
37	"						1	
38	"						1	
39	10 TH		1					
40	"		1					
41	"		1					
42	"		1					
43	"		1					
44	"		1					
45	"		1					
46	"							1
47	"		1					
48	"		1					
TOTALS		1	9	6	3	1	27	1

— FIXTURES. —

LOCATION	BATTERIES	BATTERY CABINET	CLOCKS	MASTER CLOCK
BASEMENT	28	1		
1 ST FL.			4	
2 ND "			2	
3 RD "			1	
4 TH "			1	
5 TH "			1	
6 TH "			1	
7 TH "			1	
8 TH "			1	
9 TH "			1	
10 TH "			3	1
				1
TOTALS	28	1	16	1

Fig. 46. Wiring of an Office Building. Diagram of the Interconnection System.

basement; adjoining this main box is located the terminal box of the local telephone company. A separate system of feeders is provided for the ticker system, as these conductors require somewhat heavier insulation, and it was thought inadvisable to place them in the same conduits with the telephone wires, owing to the higher potential of ticker circuits. A separate interconnection cable runs to each floor, for telephone and messenger call purposes; and a central box is placed near the rising point at each floor, from which run subsidiary cables to several points symmetrically located on the various floors. From these subsidiary boxes, wires can be run to the various offices requiring telephone or other service. Small pipes are provided to serve as raceways from office to office, so as to avoid cutting partitions. In this way, wires can be quickly provided for any office in the building without damaging the building in any way whatever; and, as provision is made for a special wooden moulding near the ceiling to accommodate these wires, they can be run around the room without disfiguring the walls. All the main cables and subsidiary wires are connected with special interconnection blocks numbered serially; and a schedule is provided in the main interconnection box in the basement, which enables any wire originating thereat, to be readily and conveniently traced throughout the building. All the main cables and subsidiary cables are run in iron conduits.

OUTLET-BOXES, CUT-OUT PANELS, AND OTHER ACCESSORIES

Outlet-Boxes. Before the introduction of iron conduits, outlet-boxes were considered unnecessary, and with a few exceptions were not used, the conduits being brought to the outlet and cut off after the walls and ceilings were plastered. With the introduction of iron conduits, however, the necessity for outlet-boxes was realized; and the *Rules* of the Fire Underwriters were modified so as to require their use. The *Rules of the National Electric Code* now require outlet-boxes to be used with rigid iron and flexible steel conduits, and with armored cables. A portion of the rule requiring their use is as follows:

All interior conduits and armored cables "must be equipped at every outlet with an approved outlet-box or plate.

"Outlet-plates must not be used where it is practicable to install outlet-boxes.

"In buildings already constructed, where the conditions are such that neither outlet-box nor plate can be installed, these appliances may be omitted by special permission of the inspection department having jurisdiction, providing the conduit ends are bushed and secured."

Fig. 47 shows a typical form of outlet-box for bracket or ceiling outlets of the *universal type.* When it is desired to make an opening for the conduits, a blow from a hammer will remove any of the weakened portion of the wall of the outlet-box, as may be required. This form of outlet-box is frequently referred to as the *knock-out type.* Other forms of outlet-boxes are made with the openings cast in the box at the required points, this class being usually stronger and better made than the universal type. The advantages of the universal type of outlet-box are that one form of box will serve for any ordinary conditions, the openings being made according to the number of conduits and the directions in which they enter the box.

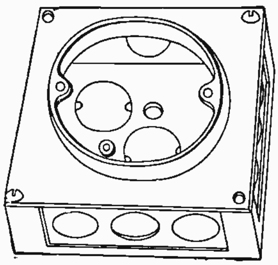


Fig. 47. Universal and Knock-Out Type of Outlet Box.

Fig. 48 shows a waterproof form of outlet-box used out of doors, or in other places where the conditions require the use of a water-tight and waterproof outlet-box.

It will be seen in this case, that the box is threaded for the conduits, and that the cover is screwed on tightly and a flange provided for a rubber gasket.

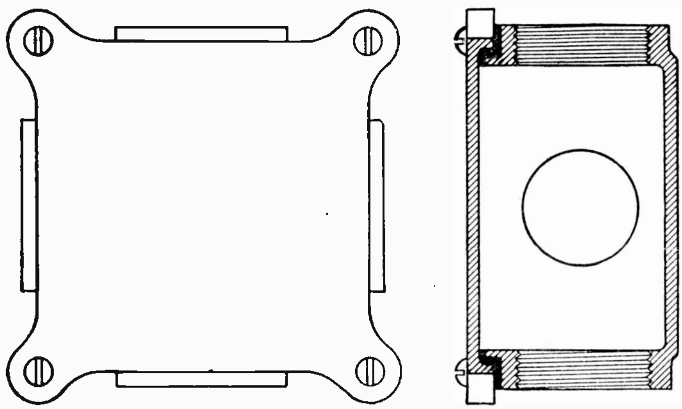


Fig. 48. Water-Tight Outlet Box.
Courtesy of H. Krantz Manufacturing Co., Brooklyn, N. Y.

Figs. 49 and 50 show water-tight floor boxes which are for outlets located in the flocr. While the rules do not require that the floor outlet-box shall be water-tight, it is strongly recommended that a water-tight outlet be used in all cases for floor connections. In this case also, the conduit opening is threaded, as well as the stem cover through which the extension is made in the conduit to the desk or table. When the floor outlet connection is not required, the stem cover may be removed and a flat, blank cover be used to replace the same.

A form of outlet-box used for flexible steel cables and steel armored cable, has already been shown (see Fig. 5).

There is hardly any limit to the number and variety of makes of outlet-boxes on the market, adapted for ordinary and for special con-

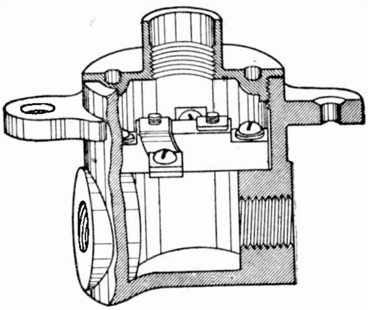


Fig. 49.

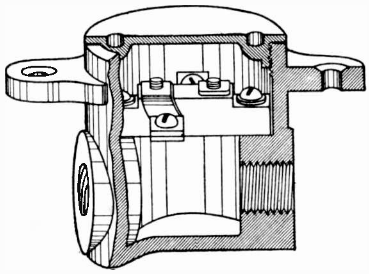


Fig. 50.

Types of Floor Outlet-Boxes.

ditions; but the types illustrated in these pages are characteristic and typical forms.

Bushings. The *Rules of the National Electric Code* require that conduits entering junction-boxes, outlet-boxes, or cut-out cabinets shall be provided with approved *bushings,* fitted to protect the wire from abrasion.

Fig. 51 shows a typical form of conduit bushing. This bushing is screwed on the end of the conduit after the latter has been introduced into the outlet-box, cut-out cabinet, etc., thereby forming an insulated orifice to protect the wire at the point where it leaves the conduits, and to prevent abrasion, grounds, short circuits, etc. A lock-nut (Fig. 52) is screwed on the threaded end of the conduit before the conduit is placed in the outlet-box or cut-out cabinet, and this lock-nut and bushing clamp the conduit securely in position. Fig.

53 shows a terminal bushing for panel-boxes used for flexible steel conduit or armored cable.

The *Rules of the National Electric Code* require that the metal of conduits shall be permanently and effectually grounded, so as to insure a positive connection for grounds or leaking currents, and in order to provide a path of least resistance to prevent the current from finding a path through any source which might cause a fire. At outlet-boxes, the conduits and gaspipes must be fastened in such a manner as to insure good electrical connection; and at centers of distribution, the conduits should be joined by suitable bond wires, preferably of copper, the said bond wires being connected to the metal structure of the building, or, in case of a building not having an iron or steel structure, being grounded in a permanent manner to water or gas piping.

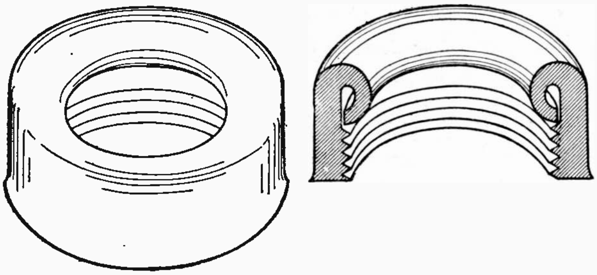


Fig. 51. Conduit Bushing.

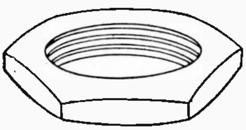


Fig. 52. Lock-Nut.

Fuse-Boxes, Cut-Out Panels, etc. From the very outset, the necessity was apparent of having a protective device in circuit with the conductor to protect it from overload, short circuits, etc. For this purpose, a fusible metal having a low melting point was employed. The form of this fuse has varied greatly. Fig. 54 shows a characteristic form of what is known as the *link fuse* with copper terminals, on which are stamped the capacity of the fuse.

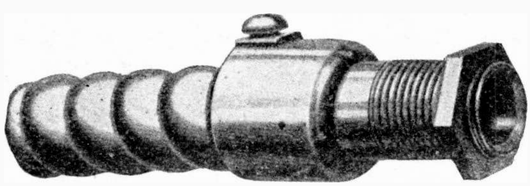
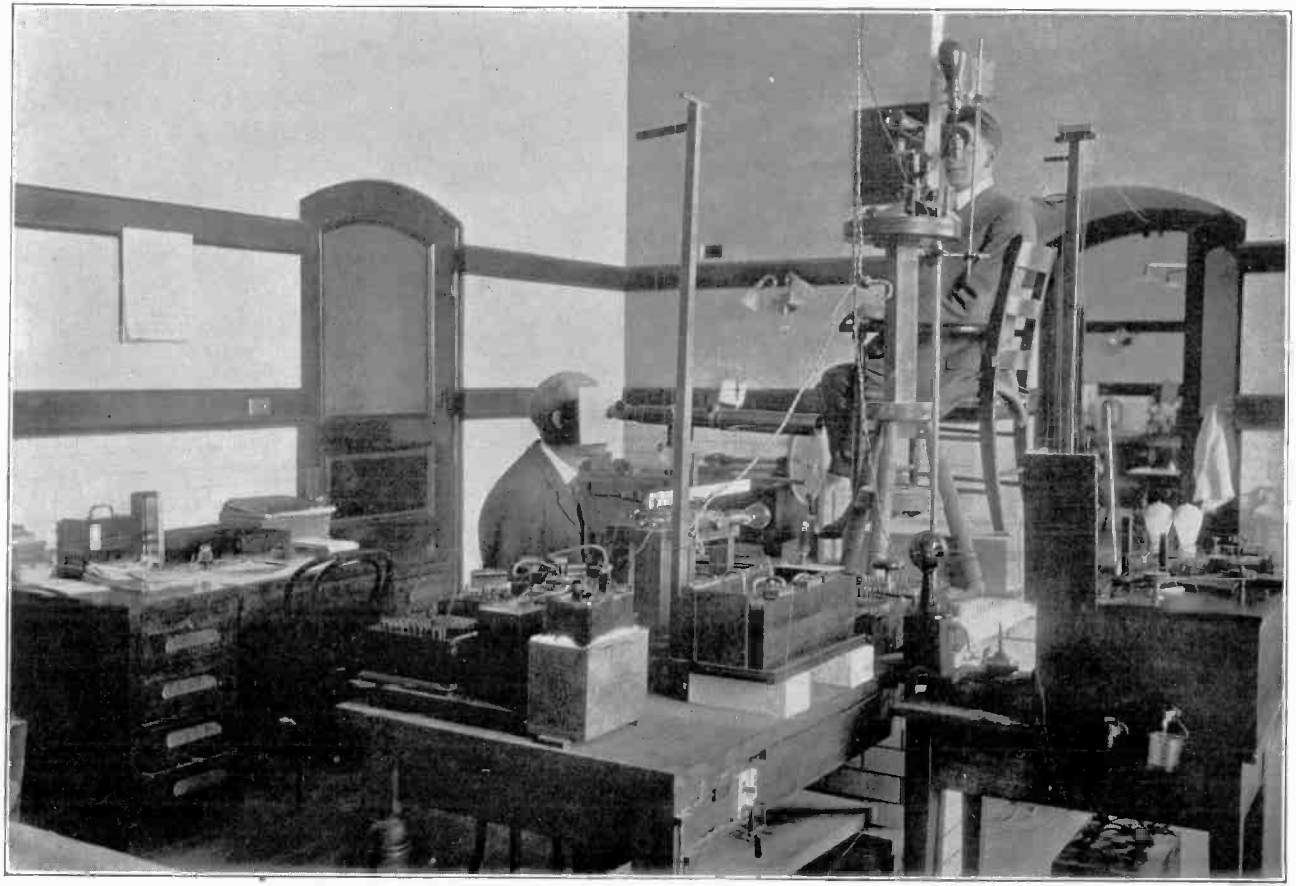


Fig. 53. Panel-Box Terminal Bushing.
Courtesy of Sprague Electric Co., New York, N. Y.

The form of fuse used probably to a greater extent than any other, although it is now being superseded by other more modern forms,



AN ELECTRIC LABORATORY AT THE U. S. GOVERNMENT BUREAU OF STANDARDS

Showing Potentiometer and Regulating Resistances. The Observer is Reading the Deflection of a Balance by Means of Which the Exact Value of the Current is Determined

is that known as the *Edison fuse-plug*, shown in Fig. 55. A porcelain *cut-out block* used with the Edison fuse is shown in Fig. 56.

Within the last four or five years, a new form of fuse, known as the *enclosed fuse*, has been introduced and used to a considerable

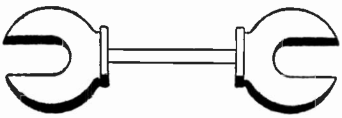


Fig. 54. Copper-Tipped Fuse Link.

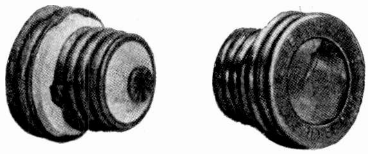


Fig. 55. Edison Fuse-Plug,
Courtesy of General Electric Co., Schenectady. N. Y.

extent. A fuse of this type is shown in Fig. 57. Fig. 58 gives a sectional view of this fuse, showing the porous filling surrounding the fuse-strips, and also the device for indicating when the fuse has blown. This form of fuse is made with various kinds of terminals; it can be used with spring clips in small sizes, and with a post screw contact in larger sizes. For ordinary low potentials this fuse is desirable for currents up to 25 amperes; but it is a debatable question whether it is desirable to use an enclosed fuse for heavier currents. Fig. 59 shows a *cut-out box* with Edison plug fuse-blocks used with knob and tube wiring. It will be seen that there is no connection compartment in this fuse-box, as the circuits enter directly opposite the terminals with which they connect.

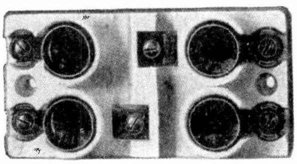


Fig. 56. Porcelain Cut-Out Block.
Courtesy of General Electric Co., Schenectady, N. Y.

Fig. 60 shows a *cut-out panel* adapted for enclosed fuses, and installed in a cabinet having a connection compartment. As will be seen from the cut, the tablet itself is surrounded on the four sides by slate, which is secured in the corners by angle-irons. The outer box may be of wood lined with sheet iron, or it may be of iron. Fig. 61 shows a door and trim for a cabinet of this type. It will be seen that

Fig. 57. Enclosed or "Cartridge" Fuse.

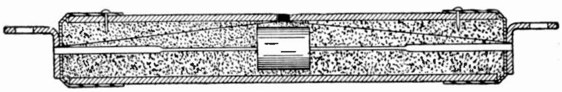


Fig. 58. Section of Enclosed Fuse.

the door opens only on the center panel, and that the trim covers and conceals the connection compartment. The inner side of the door should be lined with slate, and the inner side of the trim should be lined with sheet iron. Fig. 62 shows a sectional view of the cabinet and panel. In this type of cabinet, the conduits may enter at any point, the wires being run to the proper connectors in the connection compartment.

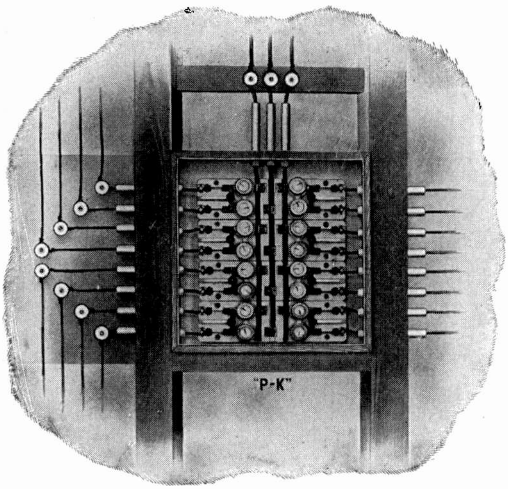


Fig. 59. Porcelain Cut-Outs in Wooden Box.
Courtesy of H. T. Paiste Co., Philadelphia, Pa.

Figs. 63 and 64 illustrate a type of panel-board and cabinet having a push-button switch connected with each branch circuit and so arranged that the cut-out panel itself may be enclosed by locked doors, and access to the switches may be obtained through two separate doors provided with latches only. This type of panel was arranged and designed by the author of this instruction paper.

OVERHEAD LINEWORK

The advantages of overhead linework as compared with underground linework are that it is much less expensive; it is more readily and more quickly installed; and it can be more readily inspected and repaired.

Its principal disadvantages are that it is not so permanent as underground linework; it is more easily deranged; and it is more unsightly.

For large cities, and in congested districts, overhead linework should not be used. However, the question of first cost, the question of permanence, and the municipal regulations, are usually the factors which determine whether overhead or underground linework shall be used.

The principal factors to be considered in overhead linework will be briefly outlined.

Placing of Poles. As a general rule, the poles should be set from 100 to 125 feet apart, which is equivalent to 53 to 42 poles per mile. Under certain conditions, these spacings given will have to be modified; but if the poles are spaced too far apart, there is danger of too great a strain on the poles themselves, and on the cross-arms, pins, and conductors. If, on the other hand, they are placed too close together, the cost is unnecessarily increased. The size and number of conductors, and the potential of the linework, determine to a great extent the distance between the poles; the smaller the size, the less the number of conductors; and the lower the potential, the greater the distance between the poles may be made. Of course, the exact location of the poles is subject to variation because of trees, buildings, or other obstructions. The usual method employed in locating poles, is first to make a map on a fairly large scale, showing the course of the linework, and then to locate the poles on the ground according to the actual conditions.

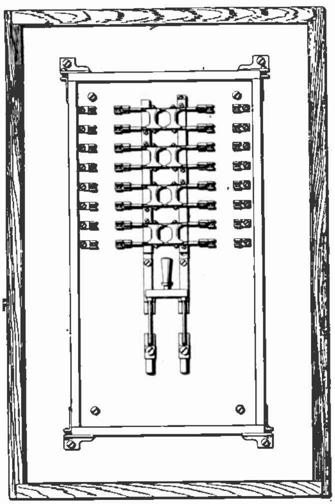


Fig. 60. Plan View, Cover, and Section of Double Cut-Out Box.

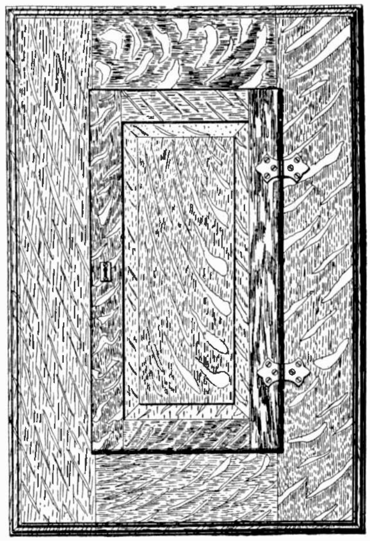


Fig. 61.

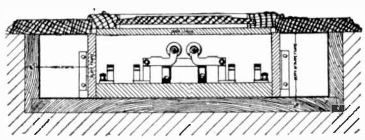


Fig. 62.

Poles. Poles should be of selected quality of chestnut or cedar, and should be sound and free from cracks, knots, or other flaws. Experience has proven that chestnut and cedar poles are the most durable and best fitted for linework. If neither chestnut nor cedar poles can be obtained, northern pine may be used, and even other timber in localities where these poles cannot be obtained; but it is found that the other woods do not last so long as those mentioned,

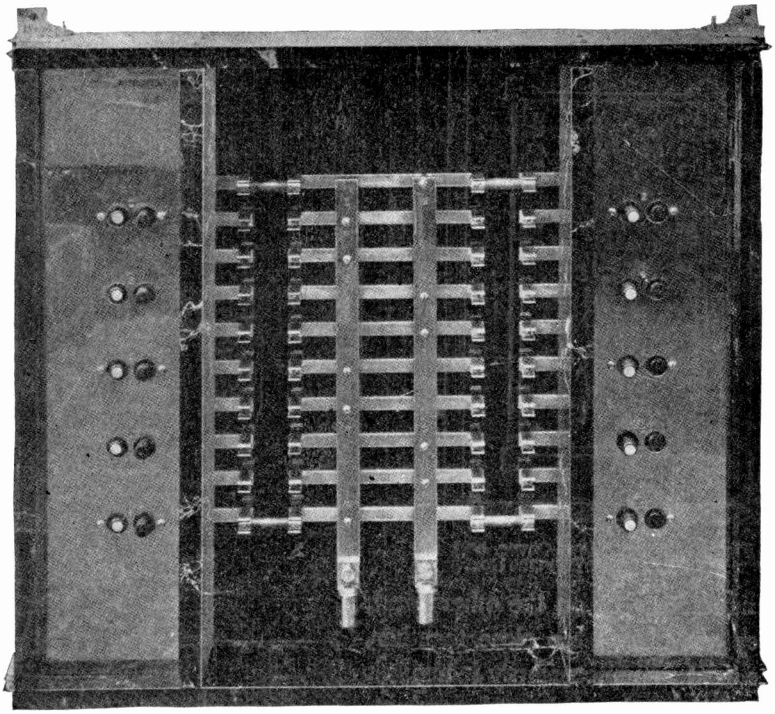


Fig. 63. Cut-Out Panel with Push-Button Switches. Cover Removed.

and some of the other woods are not only less strong initially, but are apt to rot much quicker at the "wind and water line"—that is, just above and below the surface of the ground.

The proper height of pole to be used depends upon conditions. In country and suburban districts, a pole of 25 to 30 feet is usually of sufficient height, unless there are more than two or three cross-arms required. In more densely populated districts and in cities where a great number of cross-arms are required, the poles may have to be

40 to 60 feet, or even longer. Of course, the longer the pole, the greater the possibility of its breaking or bending; and as the length increases, the diameter of the butt end of pole should also increase. Table XI gives the average diameters required for various heights of poles, and the depth the poles should be placed in the ground. These data have been compiled from a number of standard specifications.

TABLE XI

Pole Data

Length of Pole	Diameter 6 In. from Butt	Diameter at Top	Depth Pole should be Placed in Ground
25 feet	9 to 10 in.	6 to 8 in.	5 feet
30 "	11 "	"	5½ "
35 "	12 "	"	5½ "
40 "	13 "	"	6 "
45 "	14 "	"	6½ "
50 "	15 "	"	7 "
55 "	16 to 17 "	"	7½ "
60 "	18 "	"	7½ "
65 "	19 "	"	8 "
70 "	20 "	"	8 "
75 "	21 "	"	8½ "
80 "	22 "	"	9 "

As it is somewhat difficult, because of irregularities in size, to measure the diameter of some poles, the circumference may be measured instead: then, by multiplying the diameters given in the above table, by 3,1416, the measurements may be reduced to the circumference in inches.

The minimum diameters of the pole at the top, which should be allowed, will depend largely on the size of the conductors used, and on the potential carried by the circuits; the larger the conductors and the higher the potentials, the greater should be the diameter at the top of the pole.

Poles should be shaved, housed, and gained, also cleaned and ready for painting, before erection.

Poles should usually be painted, not only for the sake of appearance, but also in order to preserve them from the weather. It is particularly important that they should be protected at their butt end, not only where they are surrounded by the ground, but for a foot or two above the ground, as it is at this point that poles usually deteriorate most rapidly. Painting is not so satisfactory at this point as the use of tar, pitch, or creosote. The life of the pole can be increased considerably by treating it with one or another of these preservatives.

Before any poles are erected, they should be closely inspected for flaws and for crookedness or too great departure from a straight line.

Where appearance is of considerable importance, octagonal poles may be used, although these cost considerably more than round poles. *Gains* or notches for the cross-arms should be cut in the poles before they are erected, and should be cut square with the axis of the pole, and so that the cross-arms will fit snugly and tightly within the space thus provided. These gains should be not less than 4½ inches wide,

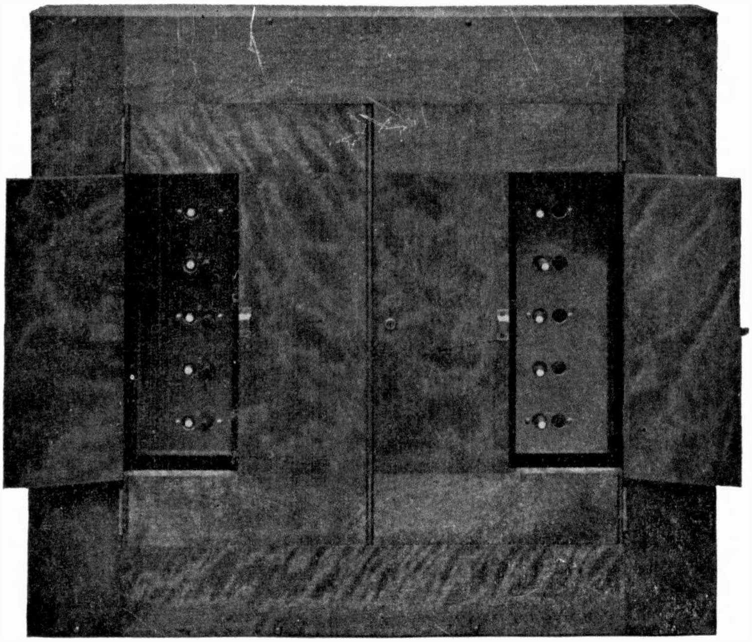


Fig. 64. Cut-Out Panel with Push-Button Switches. With Cover.

nor less than ½ inch deep. Gains should not be placed closer than 24 inches between centers, and the top gains should be at least 9 inches from the apex of the pole.

Pole Guying. Where poles are subject to peculiar strains due to unusual stress of the wires, such as at corners, etc., *guys* should be employed to counteract the strain and to prevent the pole from being bent and finally broken, or from being pulled from its proper position.

Where there are a considerable number of wires on the poles, or in case of unusually long poles, or where the linework is subject to severe storms, it is frequently necessary to guy the poles even on straight linework. In such cases, the guys should extend from a point near the top of the pole to a point near the butt of the adjacent pole. Straight guying should also be employed at the terminal pole, the guy extending to a stub beyond the last pole, to counteract the strain of the wires pulling in the opposite direction. On particularly heavy lines, it is sometimes necessary to use straight guys for the second and even the third pole from the terminal pole, to prevent undue strain on the terminal pole itself, as shown in Fig. 65.

Where there are three or more cross-arms, either two sets of guys should be employed, or else a "Y" form of guy should be used. If a single guy is used on a long pole or on a pole carrying a number of cross-arms, or on which there is unusual strain, the pole is apt to break where the guy is attached. Figs. 66 and 67 show respectively a proper and an improper method of guying, and their effect.

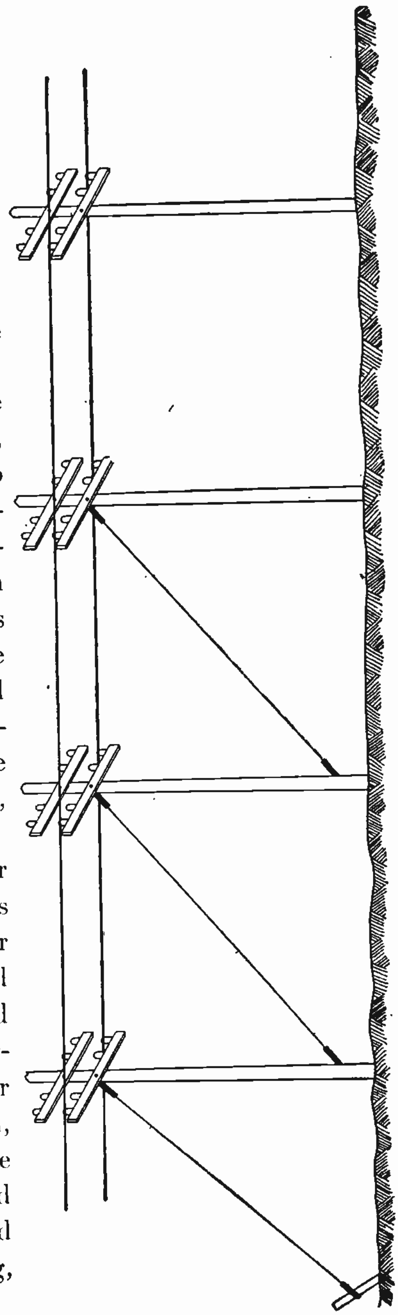


Fig. 65. Use of Straight Guys on Poles at Terminus of Heavy Line.

At corners, or wherever the direction of the linework changes, guys should be provided to counteract the strain due to the change in direction. Guys are also necessary at points where poles are set in other than a vertical position.

Where the soil is not firm or solid, or where poles are subject to unusual stress, it is sometimes necessary to obtain additional stiffness by what is known as *crib-bracing*, as may be seen from Fig. 68. This consists of placing two short logs at the butt of the pole. These logs need not be more than 4 to 5 feet long, or more than 8 to 9 inches

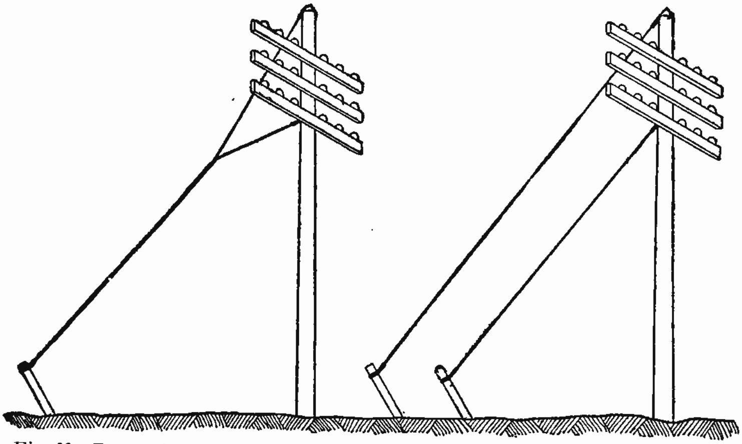


Fig. 66. Proper Method of Guying where there are Three or More Cross-Arms. A Y-form of Guy is Used at Left; Double Guy at Right.

in diameter. This crib-bracing is sometimes also necessary to give greater stability to stubs or short poles to which guys are fastened.

While, as a rule, it is not advisable to use trees for guy supports, it is sometimes necessary to do this, but the trees should be sound and should be protected in a proper manner from injury. On private property, permission should first be obtained from the owner to use the tree for such purpose.

The guy itself should be of standard cable, consisting of 7 strands of No. 12 B. & S. Gauge iron or steel wire. This is the standard *guy cable*, and should be used in all cases, except for very light poles and light linework, where a smaller cable having a minimum diameter of $\frac{1}{4}$ inch may be used. The guy wires should be fastened at the ends by means of suitable clamps. All guy cables and clamps should be heavily galvanized, to prevent rusting.

Corners. In cases of heavy linework where there are a considerable number of wires and cross-arms, the turns should be made,

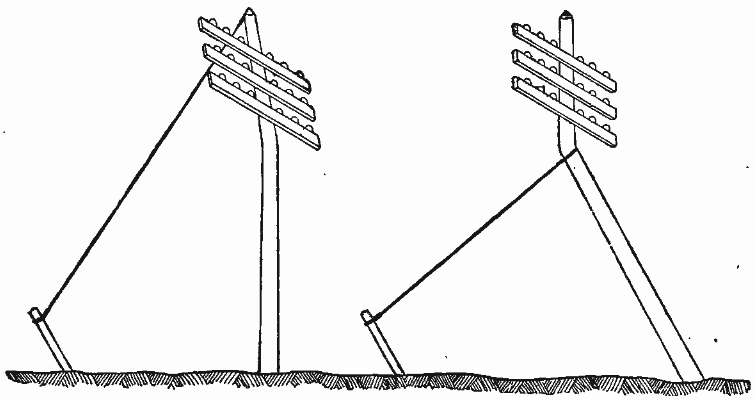


Fig. 67. Improper Method of Guying where there are Three or More Cross-Arms. Strain is Concentrated at one Point, Causing Rupture of Pole.

if possible, by the use of two poles. In cases where there are only a few wires, a double cross-arm may be employed, using a single pole. The two methods are illustrated in Figs. 69 and 70.

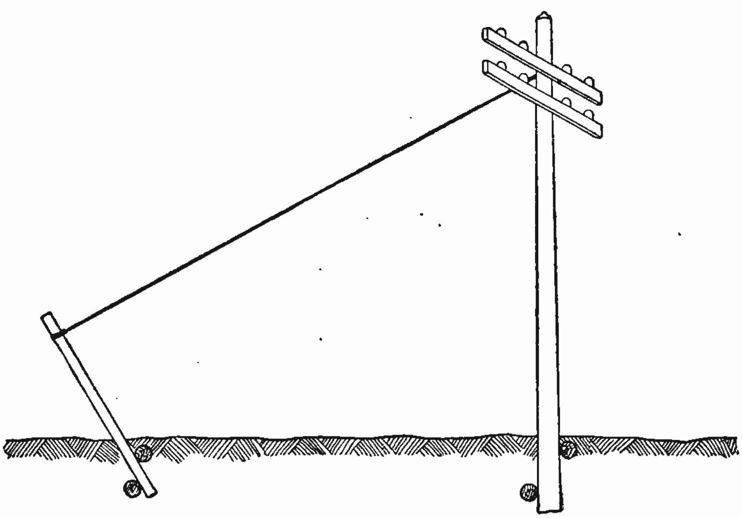


Fig. 68. Additional Stiffness Secured by Use of Crib-Bracing.

Cross-Arms. Cross-arms, where possible, should be of long leaf yellow pine, or of Oregon or Washington fir, of sound wood, thoroughly seasoned and free from sap, cracks, or large knots. They should be not less than $3\frac{1}{4}$ inches thick by $4\frac{1}{4}$ inches deep, the length depending upon the number of pins required.

Cross-arms, after being properly seasoned, should be painted with two coats of lead paint before erection. They should then be snugly fitted into the gain of the pole, and securely fastened with a bolt not less than $\frac{5}{8}$ inch in diameter driven through a hole of slightly less diameter previously bored in the pole. A galvanized-iron washer not less than 2 inches in diameter should be placed under the head and nut of each bolt. The cross-arms should be at right angles to the pole, and should be parallel to one another where two or more arms are used on the same pole.

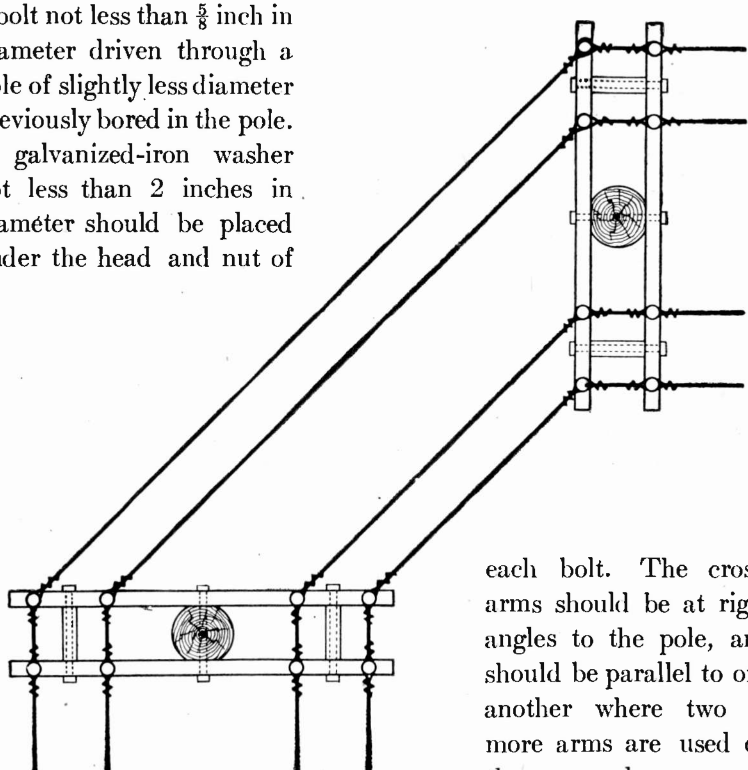


Fig. 69. Two-Poles Used in Making Turn on Heavy Line.

The cross-arms should be braced with galvanized-iron *braces* approximately $1\frac{1}{4}$ inches wide, $\frac{1}{4}$ inch thick, and from 18 to 30 inches in length. The braces should be fastened to the cross-arm by means of $\frac{3}{8}$-inch galvanized-iron bolts passing through the brace and the cross-arm, washers being used under the nut and head of each bolt. Guys should be provided for the cross-arms in case of unusual strain. The dimensions of cross-arms required for various numbers of pins, are given very completely in a paper read by Mr. Paul Spencer before the Atlantic City Convention of the National Electric Light Association in 1906, and reprinted in a number of the technical journals.

Wherever practicable, cross-arms should be placed on the poles before the poles are erected, as not only can they be more securely fastened when the poles are on the ground, but the cost of erection is thereby considerably reduced.

Pins. Pins should be of selected locust, not less than $\frac{3}{4}$ inch diameter at the shank portion, and not less than $1\frac{1}{2}$ inches in diameter at the point where they rest upon the cross-arm. For potentials of 20,000 volts or over, the pins should be of metal, to avoid carbonization of the wood due to static leakage. The top portion of the pin (if of wood) should be not less than one inch in diameter. The length of both the shank and the upper portion should be each approximately $4\frac{1}{2}$ inches, making the total length approximately 9 inches. The pin should be threaded and tapered, and accurately cut. The pin should fit the hole in the cross-arm snugly, and should be nailed to the cross-arm with a sixpenny galvanized-iron wire nail driven **straight** through the center of the shank of the pin.

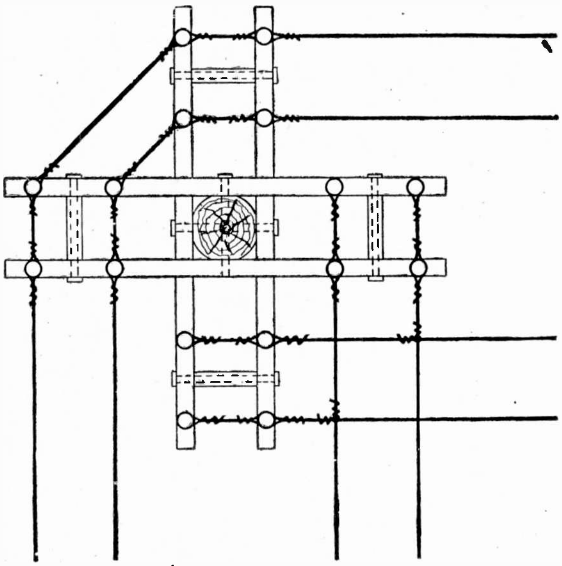


Fig. 70. Double Cross-Arm Used on Single Pole to Make Turn in Heavy Line Carrying Only a Few Wires.

Insulators. For potentials of 3,000 volts or less, insulators should be of flint glass, of double-petticoat, deep-grooved type. For potentials of over 3,000 volts, they should be of the triple-petticoat type, and preferably of porcelain, and should be of special pattern adapted for the potential.

Service Mains, Pole Wiring, etc. For service connections—

that is, for the mains run to service switches in consumers' residences or other buildings, conductors of not less than No. 8 B. & S. Gauge should be used in order to obtain the necessary tensile strength. Where possible, the circuits should be arranged in such a manner as to have the service main connect with the line on the lowest cross-arm, in order to prevent crossing of wires. The transformers should be installed either on poles or in vaults outside of the building, or, where this is impracticable, in a fireproof vault or other enclosed space inside of the building itself. Small transformers may be fastened to a pair of cross-arms secured to the pole itself. For transformers of 25 K.W. and over, it is usually best to provide special poles. It is inadvisable to place transformers on building walls.

Where appearance is of importance, when the transformer is placed underground, or when the wires enter the lower portion of a building, the conductors must be run underground. In such cases, a splice should be made between the weatherproof conductors and rubber-insulated lead-sheathed conductors, at a height of about 15 to 20 feet above the ground, and the mains run in iron pipe down the pole to a point underground, where they may be continued either in iron pipe or in vitrified or fiber conduits underground to the point of entrance.

All circuit wiring on poles should be so arranged as to leave one side free for the linemen to climb the poles without injuring the conductors. As a rule, all poles on which transformers, lightning arresters, or fuse-boxes are located, should be provided with steps.

In order to limit the area of disturbance of a short circuit or overload, fuses should be inserted in each leg of a primary circuit in making connections to transformers, or where tap or branch connections are made. The fuses should have a capacity of approximately 50 per cent greater than the transformer or conductor which they protect. Of course, it would be undesirable to have an excessive number of fuses, and for short branch lines they might frequently be undesirable; but for important branch lines, they should be employed in order to prevent the fuse on the main feeder from being *blown* in case of disturbance on the branch line.

Lightning arresters should be placed on the linework in places particularly exposed to lightning discharges, and at all points where connections are made to enter a building. The location and number of lightning arresters will depend upon local conditions, the likelihood and frequency of thunderstorms, etc. Where lightning arresters are provided, it is essential that a good ground connection be obtained. The ground connection should be made by a fairly good-sized insulated rubber conductor, not less than No. 6 B. & S. Gauge, connecting either with a water pipe to which it should be clamped, or fastened in such a manner as to obtain a good electric contact, or else to a ground-plate of copper embedded in crushed charcoal or coke.

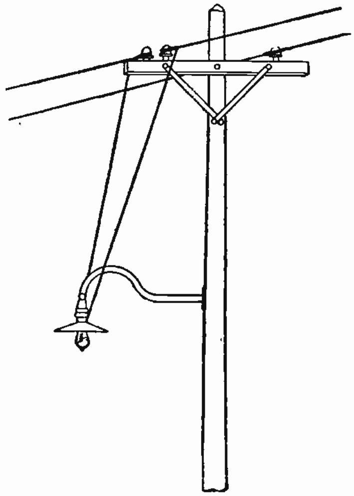


Fig. 71. Method of Wiring to and Supporting Lamp on Pole.

The neutral wire of a three-wire of both secondary alternating-current systems and direct-current systems, should be properly grounded as required by the *National Electric Code* (see Rules 12, 13, and 13-A).

Lamps on Poles. Fig. 71 shows the method of wiring to and supporting a lamp located on a pole.

UNDERGROUND LINEWORK

In large cities, or in congested districts, or where the appearance of overhead linework is objectionable, it is generally necessary to place the conductors underground instead of overhead.

The advantages of underground linework are—*first*, that of appearance; *second*, it is more permanent and less liable to interruption than overhead work.

The principal disadvantage of underground work is the greater first cost. In overhead linework, conductors having weatherproof insulators consisting of cotton dipped in a special compound similar to pitch, are used, the cost of which is relatively small. For underground linework, however, the conductors must not only have rubber insulation, but also a lead sheathing for mechanical protection.

Furthermore, the cost of the ducts, trenching, concrete work, laying the ducts, etc., is much greater than the cost of poles, cross-arms, etc.

As in the case of inside wiring, underground linework should be so arranged that the conductors may be readily removed and replaced without disturbing the underground conduits or ducts. The system should be arranged with *manholes*, and in such a manner that changes or additions or branches may be readily and conveniently made. In order to provide for the removal and replacing of conductors, and also for growth in the system, the method formerly in vogue, of embedding the conductors in wooden boxes, or in trenches underground, has been abandoned; and the conductors are now placed in *conduits* or *ducts*. A number of different forms of ducts and conduits have been introduced, some of which have been dropped as cheaper and better forms have been introduced. The forms of conduits or ducts now most generally employed include *iron pipe, vitrified conduits,* and *fibre conduit.* As all three of these forms of conduit are very generally employed, they will now be described, as well as the method of installing them.

Iron Pipe. Three-inch iron conduit is frequently used for underground linework, particularly for short runs or where there are not more than two or three ducts required, or where the soil is bad and where the longer lengths and more stable joints of the iron conduit would make it more desirable than vitrified duct or fibre conduit. This conduit, however, is generally undesirable on account of its greater first cost, and also on account of its liability to deterioration from rust or corrosion. Where iron conduit is used, and where it is subject to corrosion, it should be coated with asphaltum or other similar protective composition. While it is not necessary to have a concrete bed under iron pipe, it is better to provide such a bed, especially where the soil is shifting or not solid.

Vitrified Tile Conduit. This type of conduit in both the single- and multiple-duct form, is used more extensively than any other form of conduit for underground work. It is made in lengths of 18 inches for the single-duct form, and in considerably greater lengths in the multiple-duct form. Fig. 72 shows the single-duct conduit, and Fig. 73 shows a multiple-duct form of conduit.

Vitrified conduit requires less space for the same number of ducts than any other form. and is particularly desirable where a great number of ducts are required in a small space. The advantages of this form of conduit are that it is cheap in first cost; after being laid, it is practically indestructible; it is not subject to corrosion or

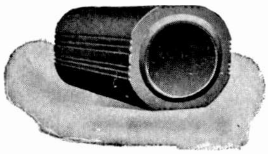


Fig. 72. Self-Centering Duct, Vitrified Conduit.
Courtesy of Standard Vitrified Conduit Co., New York, N. Y.

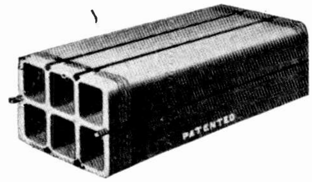


Fig. 73. Multiple Duct, Vitrified Conduit.
Courtesy of Standard Vitrified Conduit Co., New York, N. Y.

deterioration; it is not combustible; it is fairly strong mechanically; and it does not require skilled labor to install.

Table XII gives the principal data of one of the well-known makes of vitrified conduit.

TABLE XII

Standard Vitrified Conduit

Style of Conduit	Dimension of Square Duct (Inches)	Dimension of Round Duct (Inches)	Outside Dimensions of End Section (In.)	Reg. Stock Lengths (Inches)	Short Lengths (Inches)	Approx. Weight per Duct (Foot)
2-duct multiple...	$3\frac{3}{8}$ sq.	$3\frac{1}{4}$	5 x 9	24	6, 9, 12	8 lbs.
3-duct multiple...	$3\frac{3}{8}$ sq.	$3\frac{1}{4}$	5 x 13	24	6, 9, 12	8 "
4-duct multiple...	$3\frac{3}{8}$ sq.	$3\frac{1}{4}$	9 x 9	36	6, 9, 12	8 "
6-duct multiple...	$3\frac{3}{8}$ sq.	$3\frac{1}{4}$	9 x 13	36	6, 9, 12	8 "
9-duct multiple...	$3\frac{3}{8}$ sq.	$3\frac{1}{4}$	13 x 13	36	6, 9, 12	8 "
Common single duct		$3\frac{3}{8}$	5 x 5	18	6, 9, 12	8 "
Single duct, self-centering......		$3\frac{3}{8}$	5 x 5	18	6, 9, 12	10 "
Round single duct, self-centering...		$3\frac{1}{4}$	5 in. round	18	6, 9, 12	10 "

In installing vitrified conduit, a trench following as straight lines as possible should be dug to such a depth that there will be a space of at least 18 inches from the top layer of the duct to the street surface. The bottom of the trench should be level; and a bed of good cement concrete not less than 3 inches thick should be laid. The following instructions* for installing vitrified conduit may be considered as typical of the best up-to-date practice:

*From the Catalogue of the Standard Underground Conduit Company.

Laying of Conduit. When the trench has been properly prepared and the concrete foundation set, the laying of conduit should be begun. The ends of the conduit should be butted against the shoulder of the conduit terminal brick; short length should be used for the breaking of joints.

Care should be taken, when each length of conduit is laid, that the duct hole is perfectly clear and the conduit level. The work may then proceed; and if the following instructions are carried out, no difficulty will be encountered after the duct are laid.

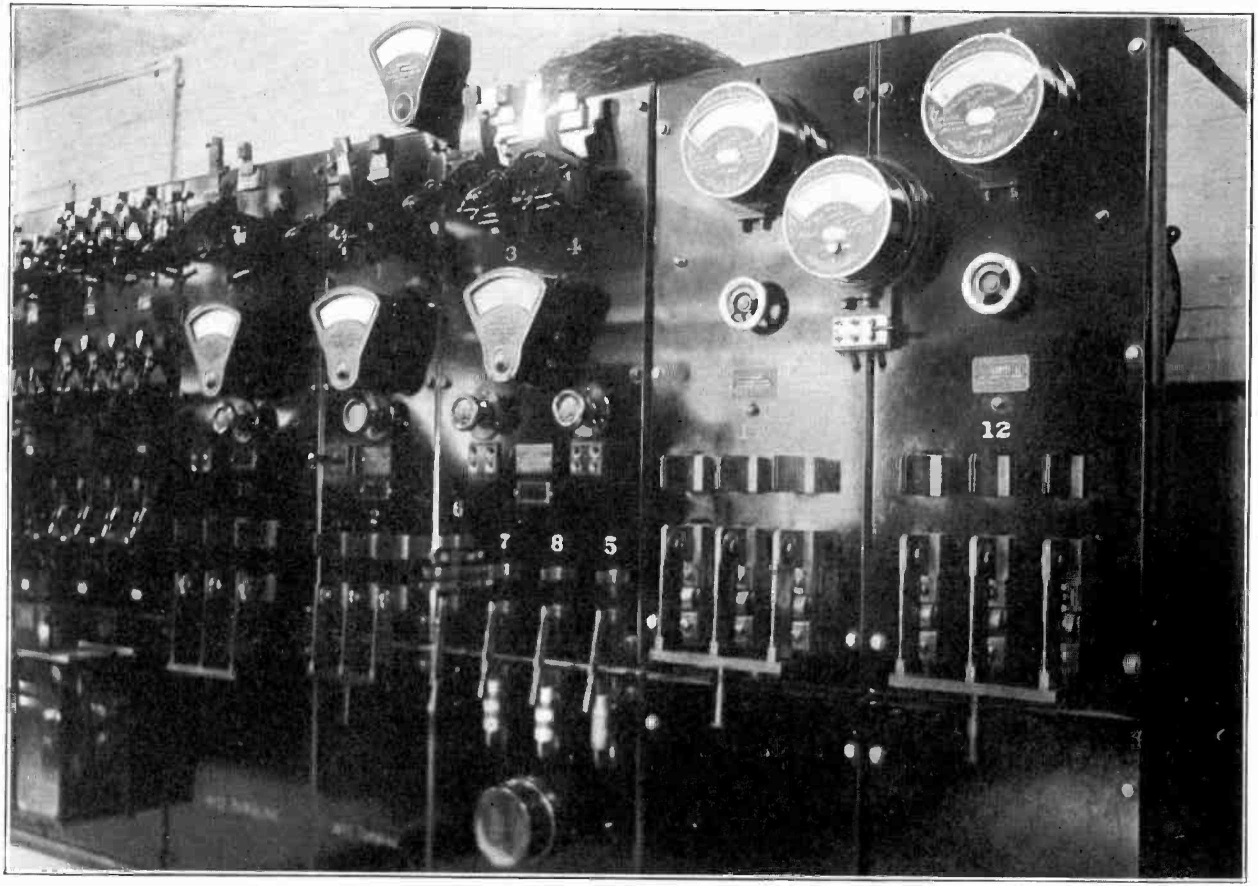
When the first piece of conduit is laid and the keys inserted, one on the top and one on the side of the duct, the burlap for joints should be slipped partly under the conduit, and the next piece brought up and connected. The burlap is then brought up and wrapped around the conduit. After this operation is completed, a thin layer of cement mortar is plastered around the burlap, extending over the edges, so as to cover the scarified portion of the conduit so that it may adhere to it, thus making the joint practically water-tight.

The burlap should be first prepared in strips of not less than 6 inches in width, and of suitable length to wrap around the conduit, overlapping about 6 inches. If possible, the burlap should be saturated in asphaltum or pitch; but if this is not convenient, it may be dipped in water so as to stick to the conduit until the joint has been cemented. The engineer or foreman in charge should personally oversee the making of the joint, and especially see that the keys are inserted, as in many instances they are left out by the workmen, causing considerable trouble and expense. Sufficient time should be allowed for the joints to harden.

After the duct are laid, the sides are filled in with either concrete or dirt, as specified, care being taken that the conduit are not forced out of alignment by the careless filling-in of the sides. The top layer of concrete may then be laid and leveled.

After this the trench is ready for filling in.

In the laying of our self-centering single-duct conduit, no dowel-pins are used, the ducts being self-centering—one piece of conduit socketing into the other. Burlaping and cementing of joint is not necessary. Otherwise the instructions for the laying of multiple-duct should be followed. The use of a mandrel in laying self-centering conduit is superfluous.



THE SWITCHBOARD THAT CONTROLS ALL THE ELECTRIC CIRCUITS IN THE WHITE HOUSE AT WASHINGTON, D. C.

As each section of the system—that is, from manhole to manhole—is completed, it should be rodded to insure the duct being clear. For this purpose wooden rods are employed, the rods being from 3 to 4 feet long by one inch in diameter and provided with brass couplings on the ends. The first rod is pushed into the duct chamber, the second one is then attached, and then the third and so on, until the first rod appears in the manhole at the opposite end.

A wooden mandrel about 10 inches long, made to conform to the shape of the duct, but about ¼ inch smaller in diameter, is attached to the last rod, and a galvanized-iron wire is then attached to the other end of the mandrel. The rods are drawn through the duct and uncoupled, until the mandrel has passed through the ducts. The wire is left remaining in the chamber, and secured in the manhole to prevent its being pulled out. The same operation is repeated until all the ducts are tested and wired. Should obstructions be met with and the mandrel bind, the location of the obstructions can readily be ascertained from the length of rod yet remaining in the duct, and can easily be removed. This method is far better than pulling the mandrel through as the ducts are laid, as in many cases the duct is obstructed or thrown out of alignment by the filling-in of the concrete or trench, and this would not be noticed until an attempt was made to draw the cable. The wire left in the duct is used in drawing the cables.

Fibre Conduit. This type of conduit consists of wood fibre formed into a tube over a mandrel under pressure. After the tube

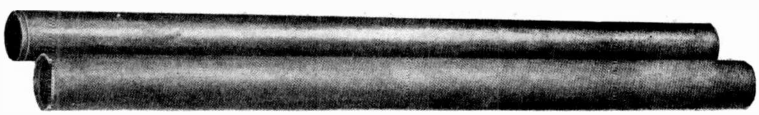


Fig. 74. Socket-Joint Fibre Conduit.

is formed on the mandrel, it is removed, and, after being dried in air, is placed in a tank of preservative and insulating compound.

Fibre conduits are made in three different styles—namely, the *socket-joint*, *sleeve-joint*, and *screw-joint* types, shown respectively in Figs. 74, 75, and 76. The forms of conduit here shown are made by the Fibre Conduit Company, of Orangeburg, New York.

In the socket-joint type, the connections between the lengths of conduit are made by means of male and female joints turned on the ends of the conduit so that it is necessary only to push one length within the other to secure alignment without the use of a sleeve-coupling or other device. While this is the cheapest and simplest

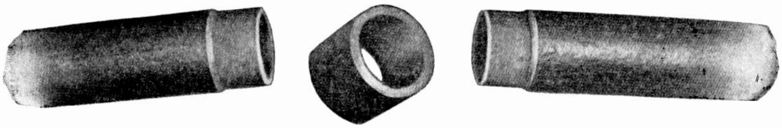


Fig. 75. Sleeve-Joint Fibre Conduit.

form of fibre conduit, the joint is not so secure as in either of the other two types.

The sleeve-joint fibre conduit has the ends of each joint turned so that a sleeve may be slipped over the turned portion and butted up against the shoulder on the tubes. These sleeves are about 4 inches long and $\frac{3}{8}$ inch thick. While this form of joint is more secure than the socket type, it is not so secure as the screw-joint type.

The screw-joint type of fibre conduit is manufactured with a slightly thicker wall than the socket-joint type, in order to obtain the necessary thickness for getting the thread on the end of the pipe. The sleeve in this case is threaded; and, instead of being slipped on the conduit, as in the case of the sleeve-joint type, it is screwed on, and the thread may be filled with compound and a water-tight joint thereby obtained. Various special forms of elbows, bends, junction-boxes, tees, etc., are provided for this conduit, for special connections. Couplings are also made so that joints can be made between fibre conduit and iron pipe, where it is desirable to make such a connection.

The advantages of fibre conduit are—*first*, that it is lighter than any of the other forms of conduit, which reduces the cost of trans-

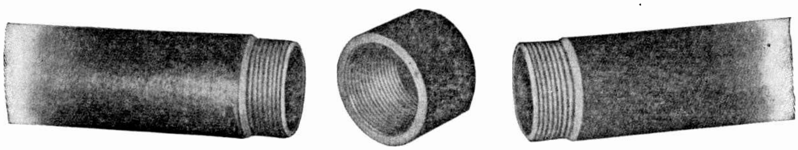


Fig. 76. Screw-Joint Fibre Conduit.

portation, carting, and handling; and *second*, that the cost of labor for installing it is less than in the case of iron pipe, and less than that of the single-duct tile pipe. Table XIII gives the principal data relating to fibre conduit.

TABLE XIII
Fibre Conduit

Inside Diameter (Inches)	Type of Conduit	Length (Feet)	Thickness of Wall (Inches)	Approx. Weight per Foot (lbs.)
1	Socket-joint	2-½	¼	0.50
1½	" "	5	¼	0.70
2	" "	5	¼	0.85
2½	" "	5	¼	1.02
3	" "	5	¼	1.20
3½	" "	5	¼	1.40
4	" "	5	¼	1.60
1½	Sleeve-joint	5	¼	0.80
2	" "	5	¼	0.95
2½	" "	5	¼	1.15
3	" "	5	7/16	2.40
3½	" "	5	7/16	2.90
4	" "	5	½	3.33
1½	Screw-joint	5	5/16	1.00
2	" "	5	⅜	1.45
2½	" "	5	⅜	1.75
3	" "	5	7/16	2.40
3½	" "	5	7/16	2.90
4	" "	5	½	3.33

Fig. 77 shows the method of laying fibre conduit in a trench.

A concrete bed should be provided for all three types of fibre conduit. Where the ground is moist or where there is likelihood of water getting in the joints, it is advisable to make a complete envelope around the conduit.

The joints should be carefully dipped in or coated with a special liquid compound provided for this purpose, so as to insure water-tightness. The cables should be spaced about 1½ inches apart, by means of wooden separators; and the spaces between the ducts, and between the walls of the trench and the outer ducts, should be filled with a thin grouting of cement and sand. If more than one horizontal row of ducts are installed, the grouting of each row should be smoothed over so as to prepare a base for the next row of ducts.

To fish the conductors in fibre conduit, it is not necessary to follow the method of rodding usually required with vitrified conduits; but it is found that by utilizing a solid No. 6 iron wire, and fishing from one manhole to the next, the mandrels and brush can be attached to the end of the wire and pulled through the conduits, thus insuring that the joints are smooth and that there are no obstructions in the conduit. To prevent accidental clogging of the ends of the conduit, wooden plugs should be installed in the openings of all unfinished conduit work, or in all unoccupied cable ducts at manholes.

Drawing In the Cables. After the conduits have been tested by means of the mandrel to ascertain that they are continuous and that the joints are smooth, the work of installing the cables may be started. Special precaution should be taken to prevent sharp bending of the cables, and thus to prevent injury to the lead sheathing of the rubber insulation. If the cable is light and of small diameter, the distance not over 300 feet, and the run fairly straight, the cable can usually be pulled in by hand; but often other means must be provided so as to secure sufficient power. Precautions should be taken, however, to avoid placing too great a strain on the cables, as it is liable to injure them, and the injuries may not show up immediately, but may cause trouble later. The remedy is to avoid placing the manholes too far apart, and to have the runs as straight as possible; also to properly test the conduits for continuity and smoothness before starting to install the cables. Enough slack should be left in each manhole to allow the cables to pass close to the side walls of the manhole, and to have the centers free and accessible for a man to enter the manhole. Where there are a great number of cables in a manhole, shelves or other supports should be

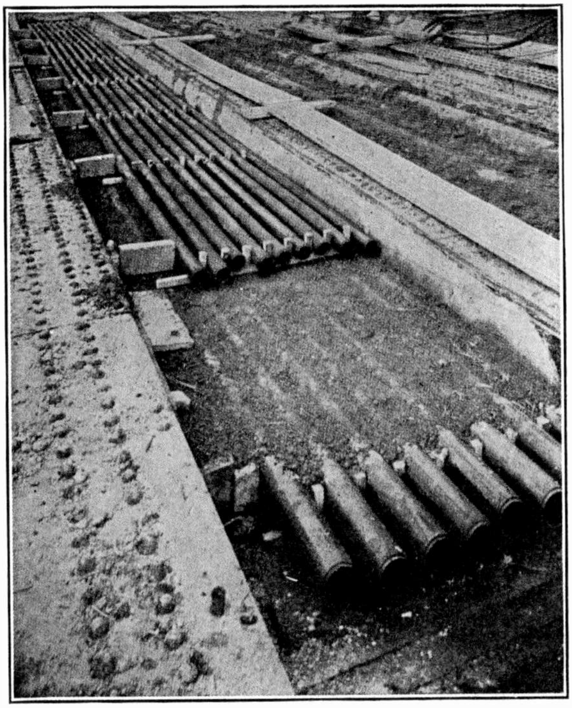


Fig. 77. Method of Laying Fibre Conduit in Trench.

provided for holding the cables apart and in position. Where two or more conductors are placed in the same duct, they should always be pulled in at the same time, for otherwise the cables last pulled in are apt to injure those already installed.

Manholes. Manholes should be provided about every 300 feet, in order to facilitate the installation of the conductors in the duct. The exact distance between manholes should be determined by conditions; in some cases they should be placed even closer together than the figure given, while in other cases their distance apart might be slightly greater.

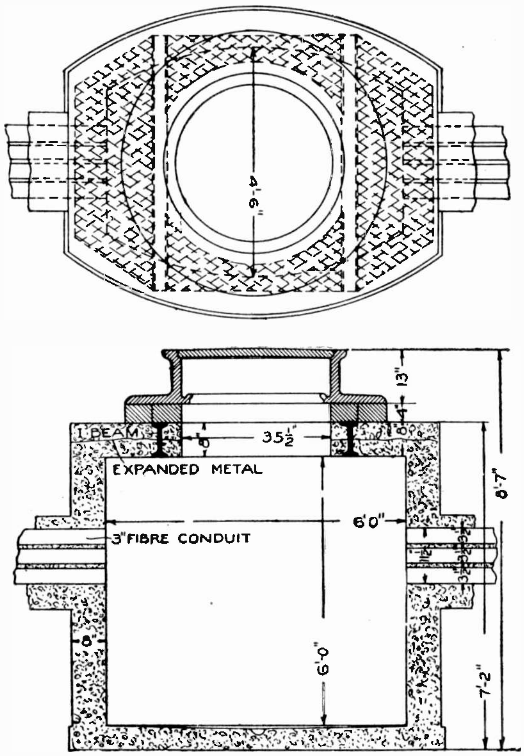
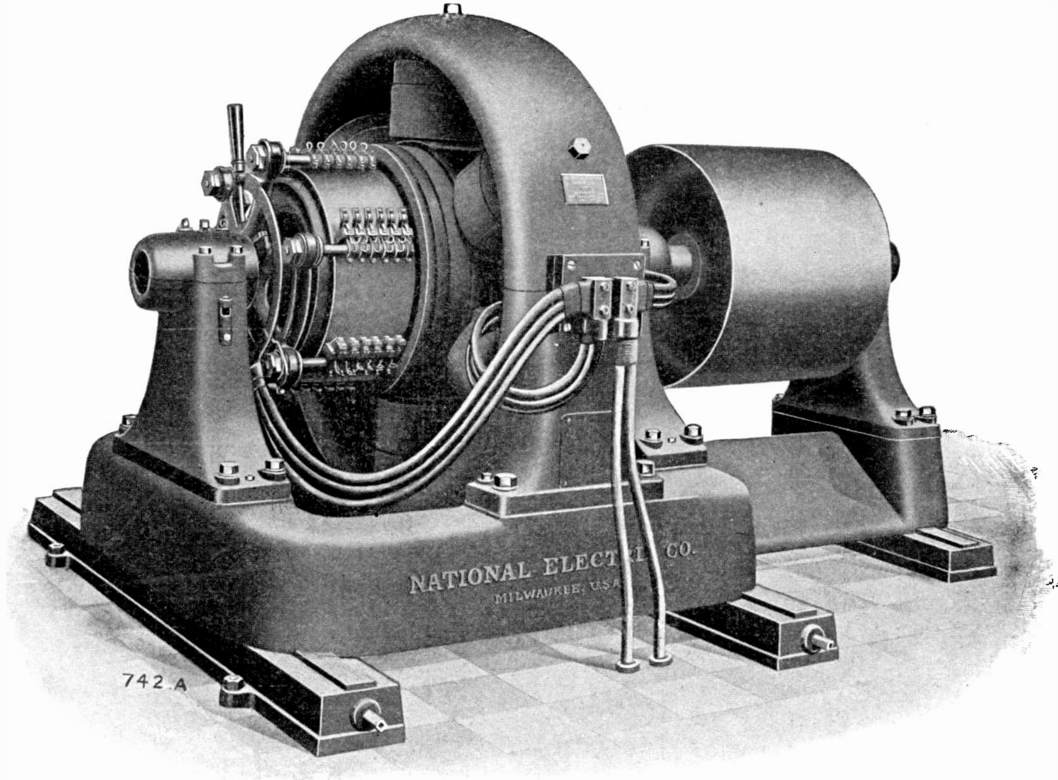


Fig. 78. Plan and Sectional Elevation of Standard Form of Manhole Used in New York City.

Manholes are built of concrete or brick, and provided with a cast-iron frame or cover. The manholes may be of square, round, rectangular, or oval section, the last-mentioned form of manhole being probably the best, as it avoids the liability to sharp bends or kinks being made in the cable. The manhole cover may be of the same form as the manhole itself, or it may be of different form; but round or square covers are usually used. Fig. 78 shows a standard form of manhole used in New York City. This manhole is substantially built, and adapted for heavy traffic passing over the cover. For suburban or country work, manholes may be made of lighter construction.



"NATIONAL" THREE-BEARING BELTED GENERATOR.

150 K.W., 250 Volt, 500 R.P.M.

ELECTRIC BELL WIRING.

In wiring for electric bells to be operated by batteries, the danger of causing fires from short circuits or poor contacts does not exist as in the case of wiring for light and power, because the current strength is so small. Neither is the bell-fitter responsible to city inspectors or fire underwriters. On this account, bell fitting is too often done in a careless and slovenly manner, causing the apparatus to give unsatisfactory results and to require frequent repairs, so that the expense and inconvenience in the end far more than offset any time saved by doing an inferior grade of work. Hence, at the outset it is well to state that as much care should be taken in the matter of joints and insulation of bell wiring as in wiring for light or power.

If properly installed, the electric bell forms a reliable and yet inexpensive means of signaling, and is far superior to any other. On this account practically every new building is fitted throughout with electric bells.

In addition to the necessity of thoroughness already mentioned, care should be taken to use only reliable apparatus which must be installed in accordance with the fundamental principles on which its satisfactory operation depends.

WIRE.

The common sizes of wire in use for bell work are Nos. 18, 20, and 22. In general, however, No. 20 will be found satisfactory as it is usually sufficiently large, while in many cases No. 22 is not strong enough from a mechanical standpoint.

It is important that the wires should be well insulated to pre-

Fig. 1.

vent accidental contacts with the staples or other wires. First of all the wire should be tinned, as this prevents the copper from being acted upon by the sulphur in the insulation. It also facilitates soldering. The inner coating of insulation should be of india rubber, surrounded by several longitudinal strands of cotton, outside of which are wound several strands of colored cotton laid on spirally. This is next immersed in melted paraffin wax and polished by friction. A short length of approved electric bell wire is shown in Fig. 1.

When ordering wire, it is well to have it furnished in several different colors as this greatly facilitates both the original installation and later repairs, because in this way one line may be distinguished from another, taps from main lines, etc. Moreover, a faulty wire having been found, it is possible to identify it at any desired section of its length.

METHODS OF WIRING.

In running wires, the shortest and most direct route should, of course, be taken between the battery, bells, and bell pushes. There are two cases to be considered. The better method is that in which the wires are run before the building is completed, and the wiring should be done as soon as the roof is on and the walls are up. In this case the wires are usually run in zinc tubes secured to the walls with nails. The tubes should be from $\frac{3}{8}$ inch to $\frac{1}{2}$ inch in diameter, preferably the latter. It is better to place the wires and tubes simultaneously, but the tubes may be put in place first and the wires drawn in afterward, although this latter plan has the objection that the insulation is liable to become abraded when the wires are drawn in. In joining up two lengths of tube, the end of one piece should be opened up with the pliers so that it may receive the end of the other tube, which should also be opened up, but to a less extent, to prevent wear upon the insulation. Specially prepared paper tubes are sometimes substituted for the zinc.

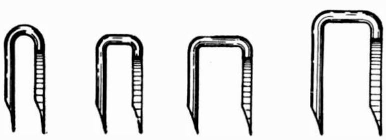


Fig. 2.

If the building is completed before the wiring is done, the concealed method described above cannot be used, and it is necessary to run the wires along the walls supported by staples, where they will be least conspicuous. Fig. 2 shows ordinary double-pointed tacks, Fig. 3 shows an insulating saddle staple which is to be recommended. Two wires should never be secured under the same staple if it can possibly be avoided, owing to the danger of short circuits. With a little care it is usually possible to conceal the wiring behind the picture moulding, along the skirting-board, and beside the door posts, but where it is impossible to conceal it, a light ornamental casing to match the finish of the room, may be used. It is sometimes advisable to use twin wires or two insulated wires run in the same outer covering.

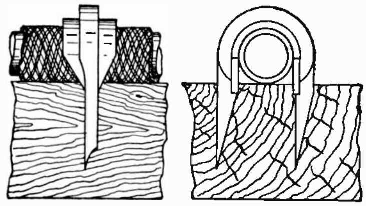


Fig. 3.

In some cases it is well to run the wires under the floors, laying them in notches in the tops of the joists or in holes bored about two inches below the tops of the joists.

JOINTS.

When making a joint, care should be taken to have a firm, clean connection, both mechanically and electrically, and this must always be soldered to prevent corrosion. The insulation should be stripped off the ends of the wires to be joined, for a distance of about 2 inches, and the wires made bright by scraping or sandpapering. They should then be twisted tightly and evenly together as shown in Fig. 4.

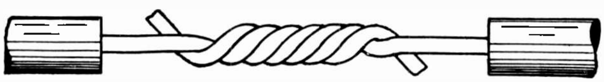


Fig. 4.

Next comes the operation of **soldering**, which is absolutely necessary if a permanent joint from an electrical standpoint is to be obtained. A joint made without solder may be electrically sound at first, but its resistance rapidly increases, due to deterioration of the joint. As has already been stated, the wires should be made bright and clean before they are twisted together. Soldering fluids should never be used, because they cause corrosion of the wire. The best flux to use is resin or composite candle. The soldering should always be done with a copper bit rather than with a blowpipe or wireman's torch.

A convenient form of soldering tool consists of a small copper bit having a semicircular notch near the end. This bit should, of course, be well tinned. It is then heated over a spirit lamp, or wireman's torch, and the notch filled with soft solder. Lay the joint, which has previously been treated with the flux, in this notch and turn it so that the solder runs completely around among the spirals of the joint. The loose solder should be shaken off or removed with a bit of rag. When the joint is set, it should be insulated with rubber tape, so that it will be protected as perfectly as the other portions.

It is often possible to save a considerable length of wire and amount of labor by using a ground return, which, if properly arranged, will give very satisfactory results, although a complete metallic circuit is always to be preferred. Where water or gas mains are available, a good ground may be obtained by connecting to them, being sure to have a good connection. This may be secured by scraping a portion of the pipe perfectly bright and clean and then winding this with bare wire; the whole is then well soldered. An end should be left to which the wire from the bell circuit is twisted and soldered. If such mains are not available, a good ground can be obtained by connecting the wire from the bell circuit, as described above, to a pump pipe. In the absence of water and gas mains, and of a pump pipe, a ground may be obtained by burying beneath permanent moisture level a sheet of copper or lead, having at least five square feet of surface, to which the return wire is connected. The ground plate should be covered with coke nearly to the surface; the hole should then be filled in with ordinary soil well rammed.

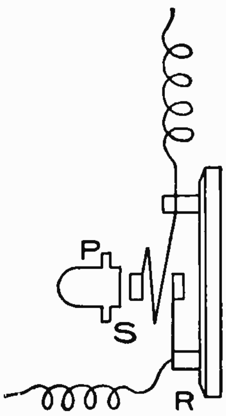


Fig. 5.

OUTFIT.

The three essential parts of the electric bell outfit are the bell push, which furnishes a means of opening and closing the circuit at will, the battery, which furnishes the current for operating the bell, and the bell itself. Before discussing the combination of these pieces of apparatus in the complete circuit, let us take up the individual parts in order.

A bell push is shown diagrammatically in Fig. 5. In this illustration P is the push button; when this is pressed upon it brings the point of the spring S in contact with the metal strip R, thus closing the circuit with which it is connected in series. Normally the springs are separated as shown, and the circuit is accordingly open.

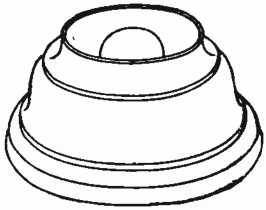


Fig. 6.

Bell pushes are made in various designs and styles, from the simple wooden push shown in Fig. 6 to very elaborate and expensive articles. Fig. 7 shows four cast bronze pushes of neat appearance and moderate price.

Batteries. Electric bells are nearly always operated on the open circuit plan, and hence the battery used is generally of the

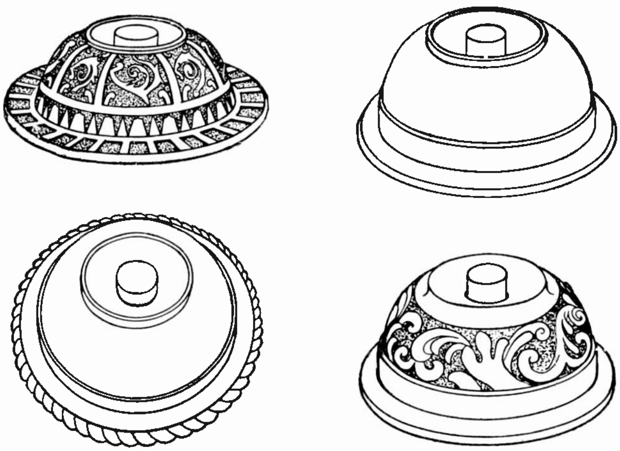


Fig. 7.

open circuit type, such as the Leclanche cell, which is used very largely except for heavy work. This is a zinc-carbon cell in which the excitant is sal-ammoniac dissolved in water. Polarization is prevented by peroxide of manganese, which gives up part of its oxygen, combining with the hydrogen set free and forming water.

Dry Batteries are also frequently used for bell work, their principal advantage being cleanliness, as they cannot spill. Dry cells are really a modification of the Leclanche type, as they use zinc and carbon plates and sal-ammoniac as the exciting agent. The Burnley cell, which is one of the principal types of dry cell, has an electrolyte composed of sal-ammoniac, chloride of zinc, plaster, flour, and water. This compound when mixed is a semi-liquid mass which quickly stiffens after being poured into the cup. The depolarizing agent is peroxide of manganese, the same as is used in the Leclanche cell, this being packed around the carbon cylinder. The top of the cell is sealed with bitumen or some similar substance.

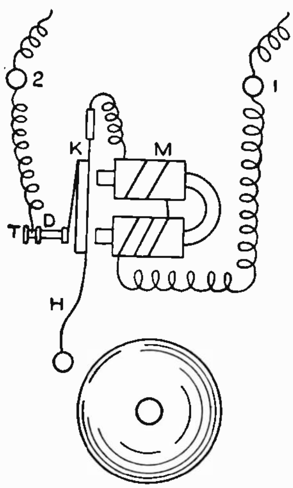


Fig. 8.

For very heavy work the Edison-Lalande and the Fuller types of cell are best suited, while for closed circuit work the gravity cell is most satisfactory.

Bell. It is a well-known fact that if a current of electricity flows through a coil of wire wound on an iron core, the core becomes magnetized and is capable of attracting any magnetic substances to itself. The operation of the electric bell, like that of so many other pieces of electrical apparatus, depends upon this fact. A diagrammatic representation of an electric bell is shown in Fig. 8, in which M is an electromagnet composed of soft-iron cores on which are wound coils of insulated wire. The armature is mounted upon a spring K, and carries a hammer H at its end for striking the gong. On the back of the armature is a spring which makes contact at D with the back stop T. The action of the bell is as follows: When the circuit is closed through the bell a current flows from terminal 1, around the coils of the magnet, through the spring K and contact point D, through the back stop T, to terminal 2. In flowing around the electromagnet the current magnetizes its core, which consequently attracts the armature. This causes the hammer H to strike the gong. While in this position the contact at D is broken, the current ceases to flow around the electromagnet and the cores consequently lose their attractive force. The armature is then carried back to its original position by the spring K, making contact at D, and the process is repeated. The hammer will thus vibrate and the bell continue to ring as long as the circuit is closed.

The type of bell described above is the one most commonly used. Such bells are made in a great variety of shapes and styles, the prices varying accordingly. It is important that platinum tips be furnished at the contact point D, Fig. 8, to prevent cor-

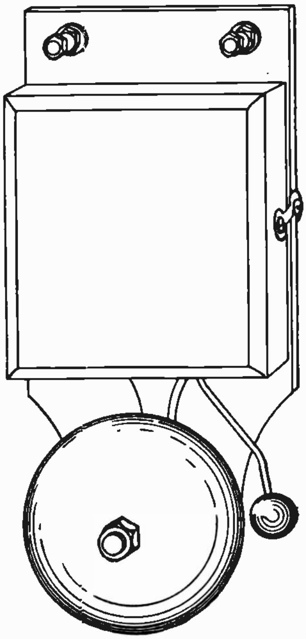


Fig. 9.

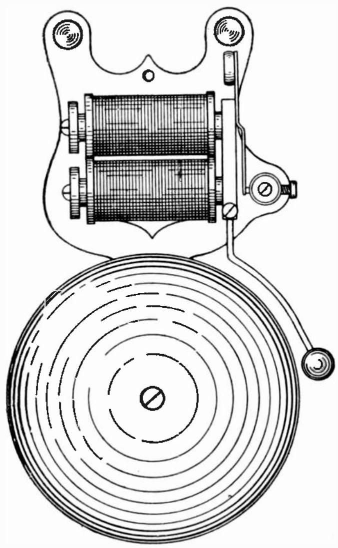


Fig. 10.

rosion. The bells on the market today are of two classes, the iron box bell and the wooden box bell. A bell of the wooden box type is shown in Fig. 9, and a higher grade bell of the iron frame skeleton type is shown in Fig. 10. Bells without covers should never be used, as dust will settle on the contacts and interfere with their action.

CIRCUITS.

The possible combinations of the various parts into complete circuits are so varied that it would be impossible to describe them all; in fact, almost every one is to a certain extent a special problem. It is, however, possible to give typical circuits the underlying principles of which can be applied successfully to any particular case.

Fig. 11 shows a bell circuit in its simplest form, in which P represents the push, B the bell, and C the battery; all connected in series. The circuit is normally open at P, and hence no current flows to exhaust the batteries. When P is pressed, the circuit, otherwise complete, is closed and current passes through the bell causing it to ring, as already explained. For instance, the push might be located beside the front door, the bell in the kitchen and the battery in the cellar; the location depending on the results desired and conditions to be met. The wire between P and C may, if necessary, be dispensed with and connection made to ground at G and G, as shown by the dotted lines.

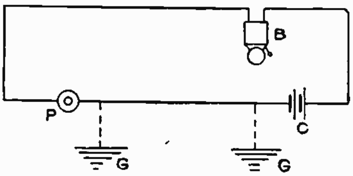


Fig. 11.

Fig. 12 shows an arrangement by means of which one bell B may be controlled by either of the pushes P or P′. This system may be extended to any number of pushes similarly connected.

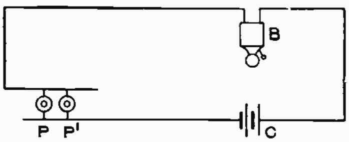


Fig. 12.

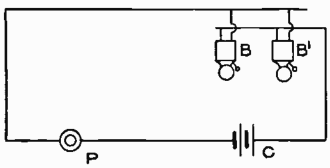


Fig. 13.

A method for ringing two bells simultaneously from one push is shown in Fig. 13, where both bells B and B′ will ring from push P. Bells, if connected in this manner, should have as nearly as possible the same resistance, otherwise the bell of lower resistance will take so much current that there will not be a sufficient amount left for the other. Also, the batteries must be of greater current capacity as the amount of current taken is, of course, doubled. This system can be extended to any number of bells connected in this way, up to the limit of capacity of the battery to ring them. Figs.

12 and 13 may be combined so that two or more bells may be rung from any one of two or more pushes.

In Fig. 14 is shown a scheme for ringing either bell, B or B′, from one push and one battery by means of the two-point switch

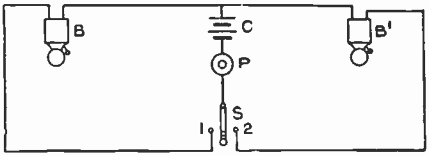


Fig. 14.

S. When the arm of the switch is on contact 1, the push will ring bell B, and when on contact 2 it will ring bell B′.

In Fig. 15 is shown a method of connecting bells in series so that B and B′ may be rung from P. If all the bells so connected were of the vibrating type, they would not work satisfactorily, as it would be impossible to time them so that the vibrations would keep step, hence only one bell should be of the vibrating type, and the others should have the circuit breakers short-circuited, the vibrating bell serving as interrupter for the whole series. Obviously this system requires a higher volt-

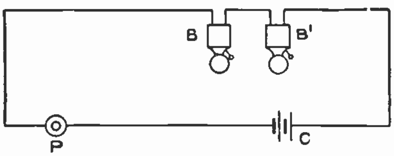


Fig. 15.

age than parallel connection, and the cells must be of sufficient E.M.F. to ring the bells satisfactorily. Several bells may be connected in this way, if desired, up to the limit of voltage of the battery.

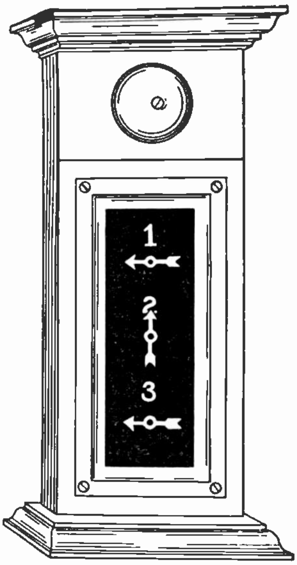


Fig. 16.

Oftentimes a bell is to be rung from several different places. For instance, the bell in an elevator may be rung from any one of several floors, or the bell in the office of a hotel may be rung from any one of several different rooms. In this case it is necessary to have some device to indicate from which push the bell was rung. The annunciator furnishes this information very well. A three-station annunciator is shown in Fig. 16. The connections for an annunciator are shown in Fig. 17 where A represents the annunciator, B the bell, C the battery, and P^1, P^2, and P^3 the pushes. For instance, when P^1 is pressed, the current passes through the electromagnet controlling point 1 on the annunciator which causes

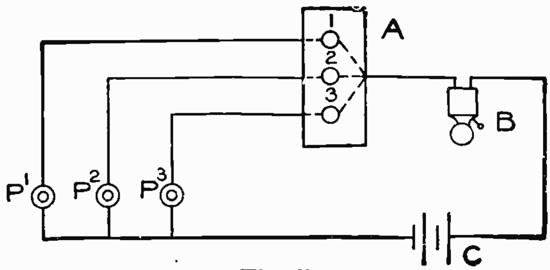


Fig. 17.

the arrow to be turned and at the same time the bell rings. After the attendant has noted the signal, the arrow is restored to its normal position by pressing a lever on the bottom of the annunciator box.

The electric burglar alarm furnishes a very efficient protection and is an application of the principles already described. The circuit, instead of being completed by a push, is completed by contacts placed on the doors or windows so that the opening of either will cause the bell to ring. The same device may be used on money-drawers, safes, etc.

In the case of the electric fire alarm, the signal may be given either automatically when the temperature reaches a certain degree, or pushes may be placed in convenient locations to be operated manually. The pushes should be protected by glass so that they will not be tampered with, it being necessary to break the glass to give the alarm.

ELECTRICALLY WELDED STREET-CAR TRACK
Light Patches on Rail in Foreground Indicate Where Sand Blast was Used. Rail is Ready to Weld. Rail in Background has Been Welded.

ELECTRIC WELDING

METHODS OF WELDING

Ordinary Welding. Welding done by the ordinary method is one of the very skilful processes in the mechanic arts. It is generally performed by heating the pieces to be welded to a temperature at which they are in a more or less plastic condition, and then forcing them together either by direct pressure or by means of blows.

When the pieces are placed together, the temperature must be high enough to melt the scale, or oxide, with which nearly all heated metal is covered. This is necessary in order that the scale may be forced from between the welding surfaces, and a clean joint left. As a general rule, the pieces to be joined are heated in an open fire; and as there is always more or less air present, the oxygen in the air attacks the metal, forming an oxide on the heated surfaces. In order to make a perfect weld, there must be no foreign matter present between the surfaces to be joined, and the oxide formed in the fire must be gotten rid of in some way. With some metals—for example, tool steel—the welding temperature is below the melting temperature of the oxide; and in order to make a sound weld, it is necessary to add *flux* during the heating, to melt this oxide. This flux also aids in the welding by forming a protecting covering over the heating surfaces, shutting out the air, and to some extent reducing the oxidation.

Any metal which passes slowly from the solid to the molten state while being heated, welds easily. In other words, any metal which has a comparatively large range of temperature through which it remains in a semi-pasty condition is easily weldable, as this range of temperature allows an appreciable amount of time for the necessary hammering of the joint together, before the metal becomes too cold to stick properly. On the other hand, any metal which has a comparatively small range of temperature between the solid and molten states is difficult to weld, as the metal cannot be properly worked in the limited time allowed by the cooling. Brass is a metal of the latter sort, while wrought iron is perhaps the best example of the easily weldable metals.

Another difficulty experienced in ordinary welding is that the heat is applied directly only to the outside of the piece, and all which reaches the center must first penetrate the outer metal. This often results, where the heating has been too rapid, in the burning of the outside metal before the center is hot enough to weld.

One great drawback to ordinary welding is that the welding temperature is held by the pieces such a short time that the placing of the pieces together and other manipulating has to be done almost instantly.

All of the above difficulties are very much lessened, if not entirely done away with, in the electric process of welding. In the most common electrical method, the pieces may be placed in exactly the right position, and as much time taken as necessary. Then, when everything is adjusted, and the work clamped firmly in place, the heating and welding are done, the pieces being securely held in place during the entire process.

Electric Welding. All methods of electric welding or heating are based upon one elementary fact—that all substances offer resistance to the passage of an electrical current, and that when a current of electricity is passed through any material, this resistance causes the temperature to rise. The larger the amount of current flowing, the faster the rise in temperature. Consequently it is only necessary to pass a sufficiently large amount of current through a body of metal to heat it to almost any degree in a very short time.

Probably the most common illustration of this principle is found in the ordinary incandescent lamp, where the resistance of the carbon filament causes it to become almost white-hot when the current is passed through it.

If two pieces of metal forming the terminals of an electric current be brought in contact, the point of contact will naturally be the point of greatest resistance. If a current be passed through the pieces, the heating effect will be greatest at the joint; and as the temperature rises, the metal will offer still greater resistance to the current, causing a high local heat at the junction of the two pieces. This point is well shown in the arc lamp, where the resistance of the short air-gap causes an intensely high local heat.

METHODS OF ELECTRIC WELDING

There are three general methods of electric welding in use, briefly described as follows:

1. ARC METHOD. In what is known as the *arc method* of electric welding, the pieces to be welded form together one terminal, and a carbon point or pencil forms the other; or each piece may form a terminal, much after the manner of the arc lamp.

2. SUBMERSION METHOD. In the so-called *submersion method*, the work is heated by *submerging* in a heated bath, or in some moderately conducting liquid contained in a metal-lined tank.

The above two methods are what might be termed *high-voltage methods*, as distinguished from the following process, which is a *low-voltage* method.

3. THOMSON PROCESS. In the *Thomson* process, the heating is done by passing a current of very low voltage through the work while the pieces are in contact.

The first two methods are not so commonly used as the Thomson process, but have certain characteristics which peculiarly fit them for certain purposes.

ARC METHOD

In this process of welding, the pieces to be joined are placed together, and contact made with the positive pole of a continuous current, the negative being a carbon point held in suitable grip.

The carbon is brought in contact with the work, and an arc is drawn, the heat from which raises the joint to a welding or melting temperature. Sometimes plates are welded in this way, being first lightly riveted together to hold them in place.

This method is said to give excellent results for *local* heating, where a spot only is to be heated. Another application of the same principle is the filling of blow-holes in defective castings. A direct current is used, and the holes are filled by melting in metal with the heat of an arc drawn from the negative carbon to the casting, which is connected to the positive side of the circuit.

Sometimes, in place of using a carbon point for a negative electrode, a small bar of the metal which it is desired to melt into the hole is used. When the electrode is made of the metal itself, Houston and Kennelly give the following figures for the size of bar and current required: "The diameter of electrode is usually from 6 to 10 mm., and the current density about 8 amperes per square millimeter of active surface of the metal electrode." Reduced to English measurements, this makes the metal electrode about $\frac{1}{4}$ inch or $\frac{3}{8}$ inch in diameter, and the current required about 5,160 amperes per square inch, or from about 225 to 600 amperes for the sizes of electrodes given.

It should be noted that in this method a comparatively high voltage is used (about 50 volts, or higher); and this to a large extent distinguishes this process from the Thomson method, which is a low-voltage operation.

One precaution must be taken in work of this character, and that is first to heat the casting to be operated on, to as near a red heat as possible, at least all around the part to be treated. This preliminary heating may be done in an ordinary forge fire, the electrical current being used only for melting in the filling. If this preliminary heating is neglected, the unequal contraction in cooling is very liable to cause the filling to loosen from the hole.

In using the arc it is of course necessary to have some variable resistance in the circuit to control the amount of current flowing. It should also be remembered that the positive terminal is always the hottest part of the arc, and for this reason the work itself should always be connected to this side of the circuit.

The arc principle is sometimes used for fusing wires together, where no very great strength is required but favorable conditions for electrical conduction are sought. The wires to be joined are made the terminals, and are brought together until an arc is formed. The current is maintained until the ends are heated to the welding or melting point, when it is shut off, and the ends of the wires pushed together. A direct current at about 50 volts may be used. On the end of the positive wire, a small ball of molten metal will form, and the end of the other wire may be pushed into this to make the joint.

Arc Method of Cutting Steel Beams and Piling. Perhaps the most valuable application of the arc method is its use in cutting—or rather, *melting in two*—of steel beams or other metal parts in wrecking a building, or in cutting holes in parts difficult of access.

The operation is much the same as that followed in filling blow-holes in castings; but in this case the heating is continued until the metal melts and runs, leaving a hole in the work. In this way holes have been cut, or burned, in steel vaults; and it is not at all uncommon to cut out parts of floor-beams in buildings, for stairways, etc., by the same method.

This makes a cheap as well as an effective method of doing the work, as the power used need not be over 25 or 30 horsepower. When central station power is available, it should be used; but when it is not convenient to obtain power from such a source, a self-contained generating set consisting of a gasoline engine and dynamo may be employed to advantage.

Work of this kind has been done in office buildings during the night, utilizing the power which during the daytime is used for running elevators, etc.

Either direct or alternating current may be used.

Messrs. Houston and Kennelly give the following data based on observations in connection with several pieces of actual work:

On some work done in San Francisco, a 25-kilowatt continuous-current generator, direct-connected to a single-cylinder gasoline engine, was used. A 15-inch I-beam was cut in two in about 20 minutes. The current was about 250 amperes at from 90 to 100 volts.

In New York City some work was done with central station alternating current. Four 20-kilowatt single-phase transformers connected in multiple were used with a secondary E. M. F. of 50 volts. In this case some steel piling was cut off, the depth of cut varying from ½ inch at the middle to 3½ inches at the ends. This piling was cut at the rate of about 10 feet per day of 8 hours, using about 256 kilowatt-hours, requiring about 650 amperes at 50 volts.

Calculating current as selling at 10 cents per kilowatt-hour, the above method of cutting piling was found to save over $10.00 per day, in addition to the time gained.

The carbon electrode was 1¼ inches in diameter, and was clamped between copper plates each 5 inches square and ½ inch thick, to which one of the wires was fastened. The other wire was bolted to the piling. It was found necessary to replace the copper plates every 15 hours, as the intense heat would buckle the plates in that time.

When doing this sort of work, it is absolutely necessary that the operator be thoroughly protected with asbestos mask and gloves, and thick black glass goggles. Under no circumstances should the naked eye be exposed to the glare of the bare arc, for, while the effect may not be felt immediately, serious results are almost sure to follow even a comparatively short exposure.

Electric Crucible and Furnace. The electric crucible is one of the applications of the arc principle described above. A graphite or other crucible made of a heat-resisting material which is a good conductor of electricity is used as the positive pole, the negative being a stick of carbon. The arc is formed by turning on the current and placing the carbon in contact with the crucible, and then separating them far enough to draw an arc. The substance to be fused is placed in the crucible, and melted by the heat of the arc. The temperature of the arc is about 3,400° C.

A sketch of a simple arrangement of such a crucible is shown in Fig. 1. This principle is used to some extent in metallurgical work, where an extremely high heat is required; but it has not come into commercial use to any great extent, although there are several large furnaces made on much the same plan.

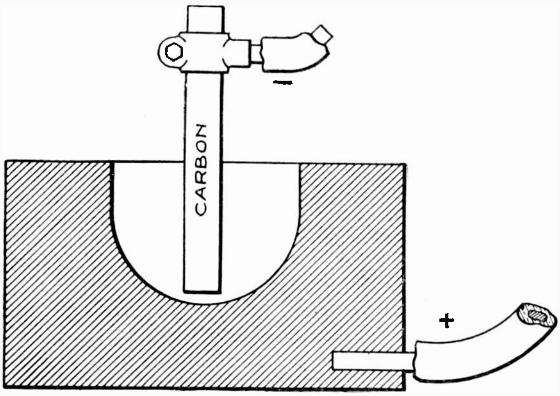


Fig. 1. Electric Crucible.

The same principle, with slight modifications, is used in one form of the electric furnace. In this furnace, two carbons are used, being placed horizontally over a shallow crucible in such a way as to form an arc between the two pieces. The heat is still further confined by means of a cover consisting of the same material as that of which the crucible is made, and having a slight hollow over the arc. The crucible and cover are generally made of lime. A sketch of such a furnace is shown in Fig. 2.

SUBMERSION METHOD

This method, like the arc method above described, is a high-voltage method; but the manner in which the work is handled is very different in the two methods. The submersion process is very limited in use, but spectacular in operation, and for this reason is sometimes used to draw crowds at exhibitions.

A metal-lined tank is used, which is filled with some liquid like brine, acidulated water, or other conducting fluid of similar character.

The lining of the tank is connected to the positive wire, the negative wire being connected to the metal to be heated. This may be done by having the negative wire soldered to a pair of tongs used to hold the work; or the work may be rested against a bar placed across, but insulated from, the tank, this bar being connected to the negative wire.

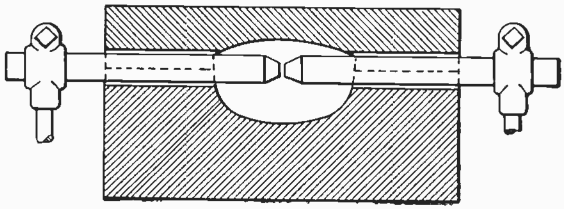


Fig. 2. Electric Furnace.

On arrangement for thi ssort of work is shown in Fig. 3. The heating is regulated by the amount of bar submerged in the liquid, the part below the surface being the part heated. The bar of metal to be heated is grasped in the tongs or rested on the "live" bar, and plunged into the solution in the tank. It begins to glow almost immediately, and soon becomes welding hot. The effect is very startling, particularly as the heated bar may at once be taken in another pair of tongs, and cooled in the same solution it was heated in. Or a switch may be arranged to cut off the current, the piece still held in the same tongs used for heating, plunged back into the bath, and immediately cooled.

By heating under water in this way, oxidation is prevented; but the heat is not very easily controlled. Consequently there is the same danger of overheating, and the same inadaptability to range of temperature, that there is in welding by the ordinary method. When welding is to be done by this method, the pieces must be scarfed in the usual way, heated separately, placed together after heating, and the weld completed by hammering together in the regular way. In fact, the only difference between this method of welding and the ordinary forge method lies in the fact that the heating

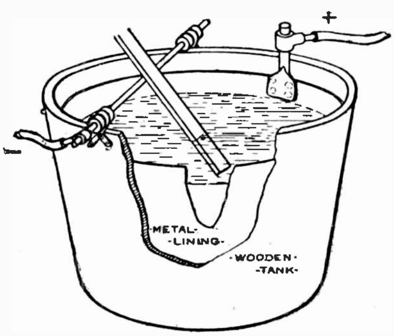


Fig. 3. Submersion Method of Welding.

in one case is done electrically, and in the other in the forge. Only such metals as can be welded at the forge can be handled by this process; and it would hardly be practicable to attempt to work with such materials as copper or tool steel.

Metals may be—and sometimes are—heated in this manner for drop forging, as it gives a very clean heat free from scale.

ELECTRIC BLOWPIPE

Another process used for electric heating or welding is that which employs what is known as the *Werderman electric blowpipe.* In this process an electric arc is drawn between two carbon pencils, and the flame of the arc is blown against the work to be heated, in much the same manner as an ordinary blowpipe flame is used. The arc flame is blown, or deflected, by a small steel or electromagnet which repels the flame against the work. A blast of air may be used in place of a magnet, as it also will blow the flame to one side.

THOMSON PROCESS

By far the most common commercial process of electric welding is what is known as the *Thomson process*—so named after its inventor, Elihu Thomson. This method is about covered by patents. It is perhaps best described in the words of the literature issued by the Thomson Electric Welding Company:

"The principle involved in the art of Electric Welding as invented by Elihu Thomson, is that of causing currents of electricity to pass through abutting ends of the pieces of metal which are to be welded, thereby generating heat at the point of contact, which also becomes the point of greatest resistance, while at the same time mechanical pressure is applied to force the parts together."

This method has one great advantage over other methods of heating for welding, and that is that the metal is heated from the inside and not from the outside.

When the pieces are brought together, the parts of the surfaces which touch are, of course, heated first; and as the heat increases, these parts become soft and flatten down, bringing other parts in contact. A curious fact in connection with this is that the welding temperature is regulated almost automatically. The surfaces which first come in contact serve as conductors of the current; and as the current passes through them, they become heated and gradually soften. As the temperature increases, the resistance increases, and these softened surfaces are gradually flattened out, allowing the cooler surfaces to come together. As the cooler points touch, being of a lower temperature, they offer less resistance to the passage of the current, which is thus automatically switched from the parts that have reached a "soft" heat to those that have not yet reached the welding temperature. This causes the joint to be brought to a uniform temperature throughout.

The heating is thus controlled by the softness of the metal as it flattens together under pressure; and when the union is completed, the soft metal begins to form a sort of burr around the joint, indicating that the weld is completed. The current is now turned off, for, if the heating were continued, the metal would be completely melted and the weld destroyed.

Probably the greatest proportion of defective welds, when welds are made in the forge fire, arises from the presence of some foreign substance between the surfaces. This may be due to oxidation of the metal itself, formation of slag from the flux, sulphur in the coal combining with the iron, or absolute dirt.

All of these factors tending to cause defects in welds are absent in the Thomson process. Since the metal is forced together as fast as it is heated, the heating being done first at the center, and extending outward, there is very little chance for oxide to form between the surfaces; and if any oxidation does take place, the oxidized metal is generally forced completely out of the weld when the pieces are forced together. The waste metal can be easily removed by trimming or grinding off the burr after the weld is completed.

Welds made in this way may be taken immediately from the machine, and hammered or worked in the usual way, to smooth up the joint. On small work, it is generally more practicable to smooth off the burr on an emery wheel.

The time required to make a weld by this process is very short, only a few seconds being required to join pieces as large as a half-inch or so in diameter.

Welds made by this method are considerably stronger than those made in the usual way. The strength of a good weld made by heating in a forge is about 75 to 80 per cent of that of the original bar, whereas, by the electric process, it is possible to make welds as strong as the bar

TABLE I

Metals, Alloys, and Combinations of Different Metals Welded by Thomson Process

METALS

Wrought Iron	Wrought Copper	Tin	Cobalt	Aluminum	Gold (Pure)
Cast Iron	Cast Copper	Zinc	Nickel	Silver	Manganese
Malleable Iron	Lead	Antimony	Bismuth	Platinum	Magnesium

ALLOYS

Various Grades of Tool Steel	Musshet Steel	Wrought Brass	Fuse Metal	Aluminum Alloyed with Iron	Silicon Bronze
Various Grades of Mild Steel	Stubs Steel	Cast Brass	Type Metal	Aluminum Brass	Coin Silver
Steel Castings	Crescent Steel	Gun Metal	Solder Metal	Aluminum Bronze	Various Grades Gold
Chrome Steel	Bessemer Steel	Brass Composition	German Silver	Phos. Bronze	

COMBINATIONS OF METALS

Copper to Brass	Brass to Wrought Iron	Brass to Tin	Wrought Iron to Tool Steel	Wrought Iron to Musshet Steel	Wrought Iron to Nickel
Copper to Wrought Iron	Brass to Cast Iron	Brass to Mild Steel	Gold to German Silver	Wrought Iron to Stub Steel	Tin to Lead
Copper to German Silver	Tin to Zinc	Wrought Iron to Cast Iron	Gold to Silver	Wrought Iron to Crescent Steel	
Copper to Gold	Tin to Brass	Wrought Iron to Cast Steel	Gold to Platinum	Wrought Iron to Cast Brass	
Copper to Silver	Brass to German Silver	Wrought Iron to Mild Steel	Silver to Platinum	Wrought Iron to German Silver	

itself, while a good average would probably be about 85 to 90 per cent of the full strength of the section.

Almost any metal or combination of metals can be welded by the Thomson process, as the range of temperature through which the metal is soft enough to weld has little effect on the welding. As the pieces are forced together instantly as soon as soft, a metal which melts with almost no preliminary softening can be successfully handled. Results obtained in actual practice by the use of the Thomson process in the welding of metals and alloys, are shown in

Table I, compiled by Mr. Hermann Lemp and recently published in *Engineering Magazine.*

Direct Method. On experimental work, when the process was first used, what is known as the *direct method* was employed. The apparatus used consisted of a generator, with clamps to hold the pieces to be welded fastened directly to the generator frame. The machines used were low-voltage dynamos much the same as are now used for plating work. While such a machine may be fairly satisfactory for experimental work in the laboratory or for very light work in a clean shop, it has many unsatisfactory features when used for large work on a commercial scale. It is, of course, hardly practicable to carry a heavy current of low E. M. F. (generally less than 5 volts) for any distance, as the loss in power through resistance would be enormous, and the cost of the heavy copper conductors would make the process too expensive in installation.

The above difficulties have developed what is known as the *indirect process.*

Indirect Method. In this method the power is taken either from the distributing circuit of a central station, or from a central generator in the shop. The current is carried to the point where the welding is to be done, at a comparatively high-voltage, and a transformer is then used to step-down to the required E. M. F. This transformer, as it has no moving parts, is generally carried in the base of the welding machine, with the welding grips, as close to the secondary coil of the transformer as possible.

The apparatus commonly used consists of the following:

An alternating-current generator, or some source of central power.
Some regulating apparatus to control flow of current.
A static transformer to reduce the voltage.
Suitable mechanical arrangement to clamp and force the pieces to be welded together.

A typical plant is outlined in Fig. 4, consisting of generator, regulator for current control, switch for turning the current on and off, transformer for increasing the amperes and lowering the voltage, and clamps for holding the pieces to be welded.

In welding of this character, it is the number of amperes (or current strength) which is the important factor; and only a sufficient voltage (or pressure) is maintained to force the current through the work. The object of the low voltage is, of course, to cut down the amount of power required. This may be easily seen from the following: Suppose that a certain weld requires a current strength of 10,000 amperes, and assume that the generator delivers current at a voltage of 100. Now, if a transformer be used to reduce the

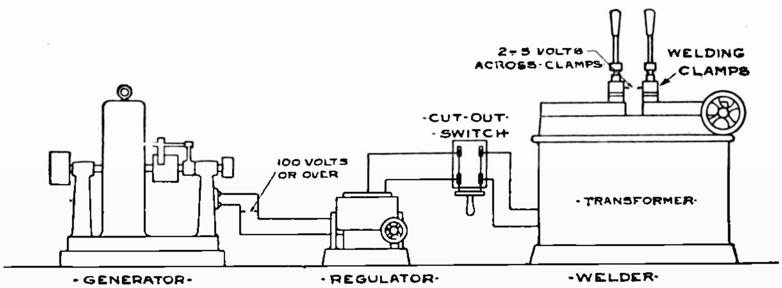


Fig. 4. Electric Welding Plant, Indirect Method.

voltage to 10 volts, and assuming no loss in any of the apparatus, the power used will be:

$$10{,}000 \times 10 = 100{,}000 \text{ watts;}$$

and the power delivered by the dynamo being the same, the *amperes* delivered by the dynamo will be:

$$100{,}000 \div 100 = 1{,}000 \text{ amperes.}$$

Now, if a transformer be used which reduces the voltage from 100 to 5, instead of from 100 to 10, the power used would be:

$$10{,}000 \times 5 = 50{,}000 \text{ watts;}$$

and the amperes delivered by the dynamo will be:

$$50{,}000 \div 100 = 500 \text{ amperes,}$$

this being just half of what it was in the first case. It will be seen from this, that for economical operation the voltage should be reduced as far as possible. It should be remembered that when working with *alternating* current, the power used cannot be taken as the direct product of the volts and amperes, a more complicated calculation being necesary; but the principle illustrated above still holds good.

A diagram of a very simple type of transformer is shown in Fig. 5. The primary or high-voltage coil is that on the outside, and is wound of fine wire; while the secondary or low-voltage coil consists in this case of one single, straight conductor with the terminal connections fastened to the ends. As mentioned before these terminal connections to the welding clamps should be as short as possible, on account of the low voltage.

The current is controlled by a cut-out switch and resistance placed close to the transformer on the primary circuit. In some of the later machines, the cut-out switch, as well as the mechanical means used to force the pieces together, is controlled automatically.

The transformers are substantial in construction; and as there are no moving parts, there is little chance of anything getting out of order. The pieces to be welded are held in suitable clamps which form the terminals of the secondary coils. These clamps are mounted on a slide which allows them to travel back and forth. The pieces to be joined are fastened in the clamps, and the current turned on. The metal is heated at the joint, and gradually softens as the heating is continued, the pieces being forced together by means of a hand-lever, or automatically by the machine itself. When the weld is completed, the current is turned off, and the work taken from the clamps.

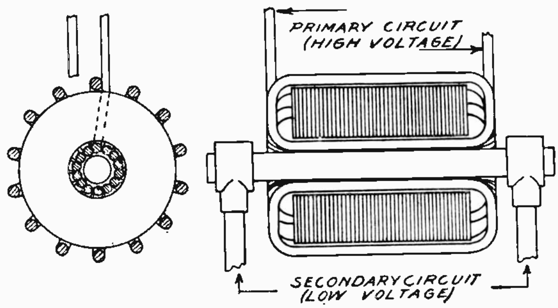


Fig. 5. Simple Transformer.

A simple machine which was used for some experimental work, is shown in Fig. 6. The current used in this particular case was taken from the lines of the Edison Company at 220 volts, and was reduced in the transformer to 5 volts. It will be noticed that the clamps are so shaped that the work may be instantly released when the weld is completed, taken from the machine, and the burr hammered smooth on an anvil if necessary.

No very great care need be taken as to the insulation on the machine itself, as, at the very low voltage used, there is very little chance of current leakage. The bed of this machine was cast iron; and contact was made by bringing the terminals of the transformer up through the base of the machine, and resting small blocks of copper on them, to which the pieces to be welded were clamped.

The principal factor of cost in a machine of this kind is the copper in the transformer. In the machine in question, the copper terminals were 1 by $1\frac{1}{2}$ inches in section; but, as the capacity of the clamps was far less than this, the terminal connections to the clamps were made only about one-quarter this size.

For purposes of experiment, it is possible to make a weld by simply clamping the pieces which are to be joined to the terminal wires of a transformer, by means of wooden hand-screws, and forcing

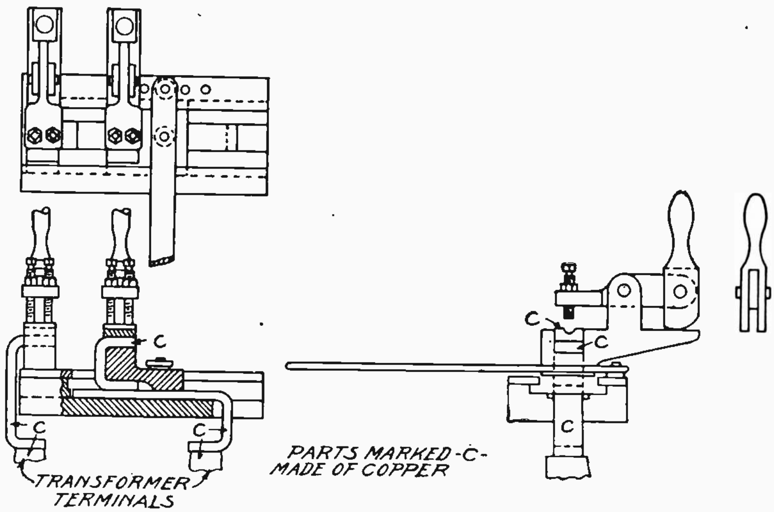
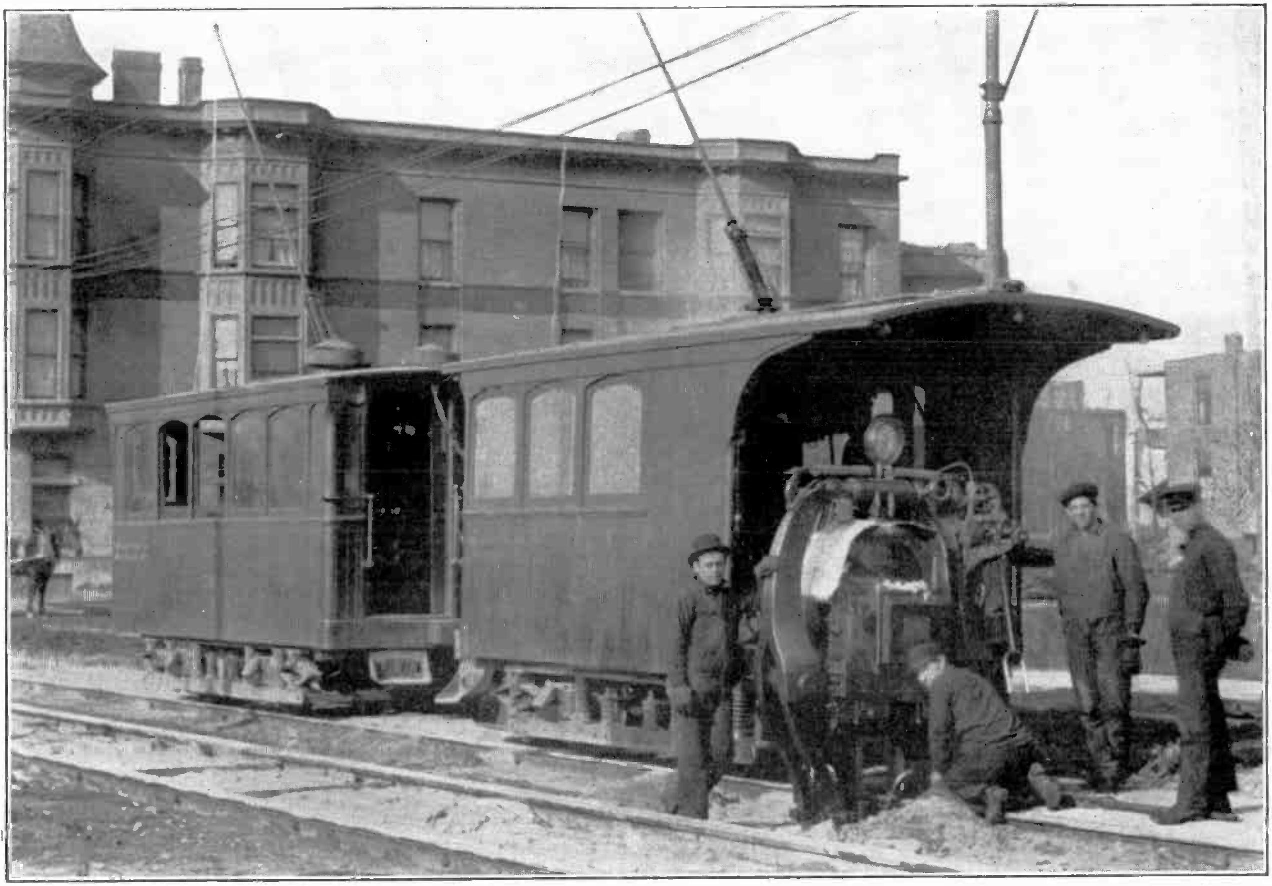


Fig. 6. Diagram of Simple Apparatus for Electric Welding.

the pieces together with the clamps. It is even possible to use iron clamps without danger to the operator, there being no chance of shock at such a low voltage. In fact, in designing a machine, there is no need to insulate the machine from the operator, for the reason given above. This however does not apply to the high-voltage side of the transformer, which should always be fully protected. On the operating side of large machines, a hand may be placed on each of the terminals when the full current is on, and no shock or sensation felt.

Fig. 7 shows a cut of a simple commercial welder. This is what is known as a hand-machine, as the turning on and off of the current,



ELECTRIC WELDING OF RAILS IN STREETS OF CHICAGO
Bar is Clamped to Rails and Welded by Current from Trolley.

and forcing of the pieces together, is done entirely by hand. As shown in the cut, the weld has just been completed, and the finished piece is still in the jaws. The machine is so arranged that by throwing the clamping levers when the weld is completed, the work may be instantly released. To adjust the clamps for different thicknesses of work, the adjusting screws are used; these are shown on top of the clamping jaws, and also just underneath the clamping levers at the back of the machine. The pieces are forced together by means of the long lever and hand-wheel at the right of the bed-plate. The hand-wheel is used for quick adjustment, and the lever for the final *squeeze* that does the welding.

This machine is largely used for straight and miscellaneous work; has a maximum capacity of 1.23 square inches of iron or steel, or .40 square inch of copper; and requires, at a maximum, 35 horsepower for 60 seconds.

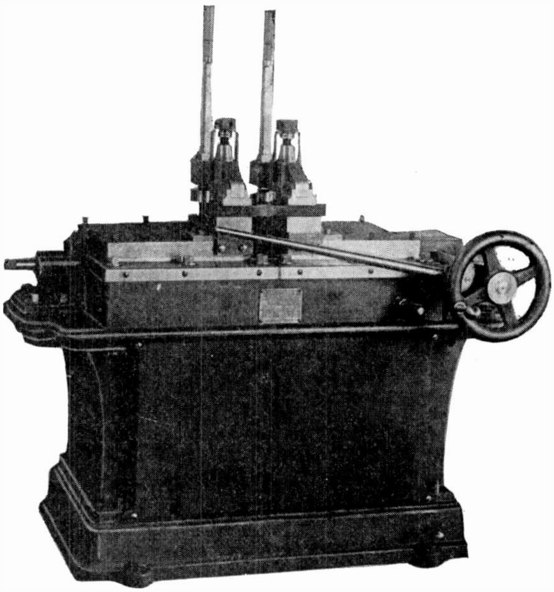


Fig. 7. Simple Commercial Welder.

The transformer is placed in the heavy bed of the welder, as in this way the conductors carrying the welding current to the jaws are made very short, to reduce the current loss to a minimum.

In operation, the pieces to be welded are placed in the clamps, and brought close together by the hand-wheel, the current being next turned on. In a few seconds the pieces become hot at the weld; and as soon as soft, they are forced together by the long lever, and the current turned off. On large work the piece is then instantly taken from the machine, and the joint smoothed up, either in the usual way on the anvil, or between suitable dies on a drop hammer. The work is done very rapidly, and the whole operation on a comparatively

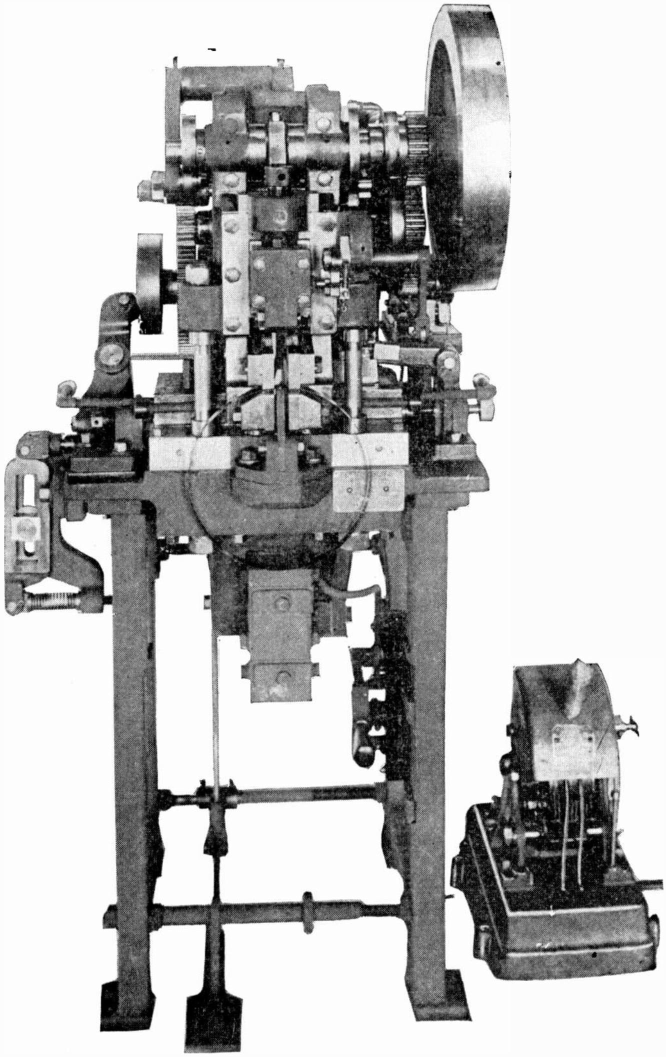


Fig. 8. Automatic Electric Welding Machine.

large piece may be done in two minutes. The time required on small work is only a few seconds, including the entire process.

For work where many pieces of the same kind are to be welded, a machine may be used which will work automatically. This is of decided advantage in addition to the speed, as the pressure on each weld may be kept uniform and controlled exactly, and the welds in this way made all the same. It has been found that welds which would be almost impossible to make on the hand-machine are easily made with the automatic, as the pressure control in the latter is much more exact. This advantage is most marked on metals which are very crumbly at high heats, and on small and delicate work.

A machine of this type is shown in Fig. 8. Some of these machines not only take care of the actual welding, but also have dies

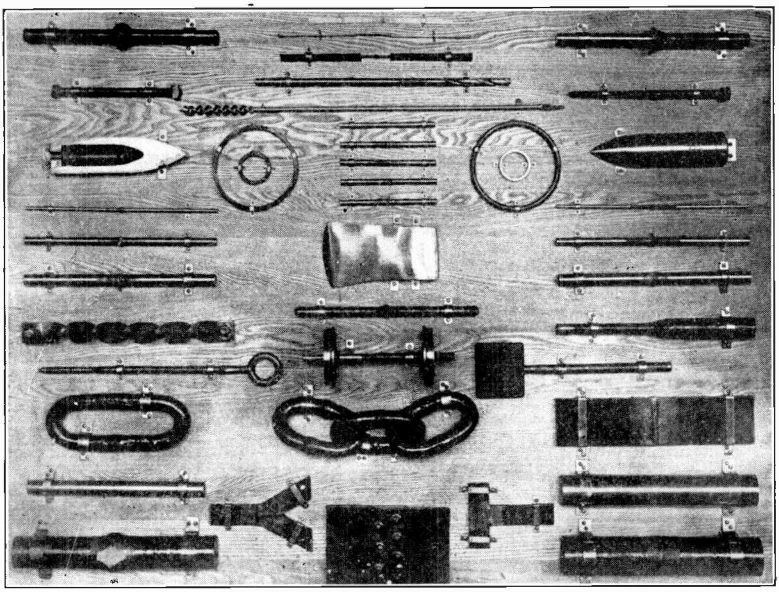


Fig. 9. Examples of Machine-Made Welds.

or jaws which press and form the joint to the same shape and dimensions as the bar stock, thus serving the combined purpose of heating and shaping.

One of the common uses that a machine of this sort is put to is that of making barrel hoops. These are made of wire about $\frac{3}{16}$ inch in diameter; and as they are intended for rough use, no effort is made to smooth up the joint. From 300 to 800 welds of this sort may be made per hour, and the machine operated by a boy. The average for wire hoops is about 500 per hour, according to figures given by the manufacturers of the apparatus.

Figs. 9 and 10 show examples of various kinds of welds made by this process—from small wires to large bars.

The shape of the piece has very little to do with the welding, so long as the pieces have the same section at the weld. I-sections and work of that character which it is impossible to handle in the ordinary way, can be worked as easily as round or rectangular bars. The weld

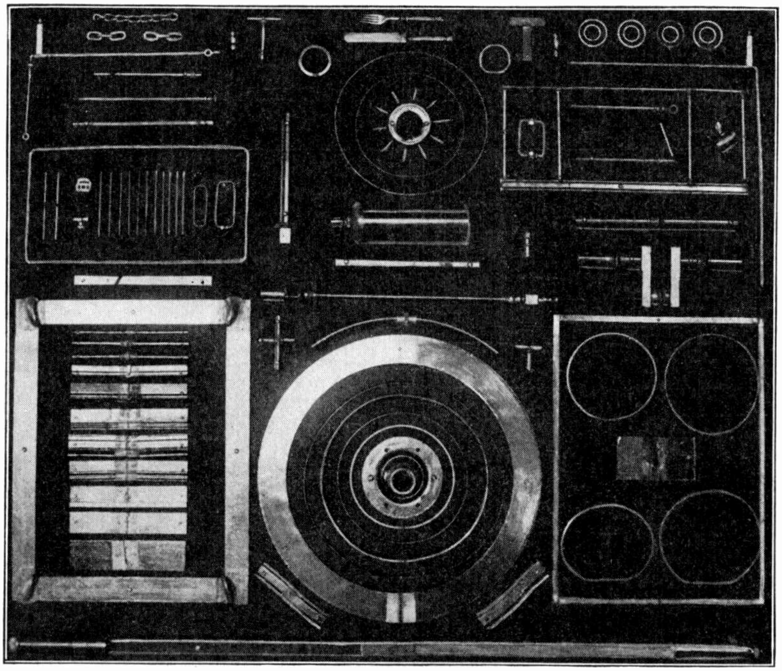


Fig. 10. Examples of Machine-Made Welds.

of a clincher rim, shown in Fig. 11, is a good example of the ease with which difficult work can be handled. The cut shows the piece with the burr still left on the weld, which is afterward smoothed or ground off, a uniform surface being left.

On small work where the joint is wanted smooth, the burr is generally removed with an emery wheel, unless the operation is performed in an automatic machine, in which case the burr is taken care of by the welder itself.

Practically all the welds made on the machine are butt welds; and while no particular preparation of the ends is necessary, still it is always best to see that they touch each other as near the center as possible.

Fig. 12 illustrates the action of the pieces in welding. In *A* are shown the pieces ready for the heating. It will be noticed that the ends are slightly convex in order to bring the centers in contact first. *B* shows the pieces as they appear when the weld is about half-completed, the shaded portion showing about the length that is ordinarily heated by the action of the current. *C* shows the completed weld, the shaded portion still representing the extent of the heating.

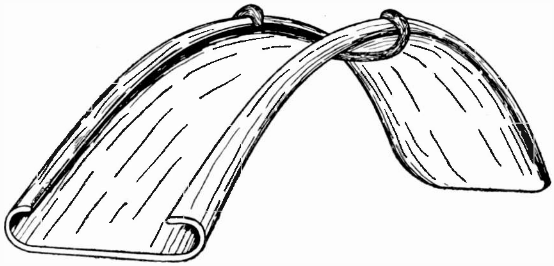


Fig. 11. Clincher Rim Weld.

One of the noticeable characteristics in connection with electric welding is the short distance from the joint that the work is heated. The actual heating effect of the current is confined almost entirely to the weld; but of course there is some heating by conduction which raises the temperature a short distance from the joint. This heating effect does not extend very far, as the time is so short that the heat does not have a chance to travel much. On a piece $\frac{1}{4}$ inch in diameter, the bar may be grasped with the bare hand within an inch of the weld immediately after the welding is completed.

On account of the above conditions, many machined and finished pieces may be welded without distortion, very little effort being required to refinish the part heated in welding.

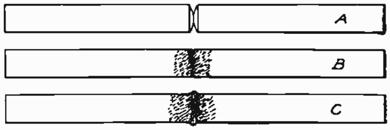


Fig. 12. Illustrating Action of Pieces in Electric Welding.

In welding in this way, it is always an advantage to have the pieces of as near the same section as possible at the weld. For instance, it would be a rather difficult matter to weld a bar of very small section directly against a bar of large cross-area. A method of handling work of this character is shown in Fig. 13, where it will be noticed that a sort of lug or projection has been left in making the main forging, to which the piece of smaller section is welded.

The difficulty of this sort of welding is largely due to the fact that the bar having the larger section will of course radiate the heat faster, with the result that the smaller bar will become overheated and burn long before the larger bar is hot enough to weld. This is overcome to some extent by so clamping the pieces that the piece having the larger section will project farther from the clamp jaw

Fig. 13. Illustrating Method of Welding Pieces of Different Cross-Section.

than the smaller one does. This will overcome a small difference of section; but when the difference is great, the larger piece should have its section reduced to that of the smaller for a distance of about one-quarter inch at least.

On heavy work it is necessary to force the pieces together with hydraulic pressure, it not being practicable to obtain the pressure with hand-levers. In fact, in some machines the gripping also is done in this way.

When welding tin, lead, zinc, etc., the pieces do not become hot enough to emit light or become incandescent, and the softening of the metal must be taken as an indication of the welding temperature. Lead pipe can be satisfactorily welded if care is taken in preparing the ends, which should have the edges beveled in order to reduce the section that is being heated.

Lead pipe of a comparatively large section can be handled, lead offering considerably more resistance to the passage of the current than either iron or copper. As a general rule, it is easier to weld electrically materials which have a comparatively high resistance than those of low resistance; thus copper requires more current than either iron or steel; iron or steel, than lead; etc.

One of the interesting applications of electric welding is the making of continuous cables of both steel and copper. This is easily done, and the strength is very little diminished by the process. Of course the cable is left solid at the point where the weld is made, as the metal is completely fused into one solid lump; but as this extends for a short distance only, scarcely equal to the diameter of the cable, it is no very serious objection.

Chain and Ring Welding. Chain links are welded by this method, although it would seem that the body of the link, being solid, would offer less resistance to the current than the joint, with the result that the current, following the path of least resistance, would heat the body of the link and leave the joint cold. This however is not the case, as the grips may be placed close to the joint, thus lowering the resistance across the weld and increasing the resistance through the solid metal.

Another fact is that while an alternating current follows the path of least resistance, it also tends to take the shortest path or the path of least counter-induction or self-induction, and will not go around a ring as easily as across the straight joint. The flow of current around the solid part of the ring may be still further checked by placing in the center of the ring or link a magnetizable iron core, effecting a greater counter-induction force.

Track Welding. This is one of the most important of the developments of the electric welding industry. Various methods of making rails continuous have been tried, but the most satisfactory seems to be that of electric welding. As nearly all of the street-railway and interurban work is now electric traction, the problem of a satisfactory track must be considered from the electrical as well as from the mechanical side. In other words, the track must not only present a smooth unbroken path for the wheels in order to have the cars run smoothly, but the rails must also be so bonded together as to make a continuous electrical conductor. The joints must have the same conductivity as the solid rail, or a greater conductivity.

One of the earlier ways of accomplishing this was to cast a chunk of cast iron around the joint, completely enclosing the rail with the exception of the head, for a distance of 8 or 10 inches. The objection to this was that the body of hot metal around the rail in the casting process so heated the head of the rail that is was annealed and softened enough to cause excessive wear, and was soon worn down enough in the immediate neighborhood of the joint to cause the cars to *bump* when passing over.

These objections were satisfactorily met by the electric weld; and this process is now almost universally used for rails buried in city streets, and to some extent on trackage on interurban lines.

Special apparatus is used for this work, and what is known as a *welding train* employed. The welding is generally done under contract by a firm having the special equipment for the purpose, and not by the railroad company itself. The contractors clean the ends of the rails to be welded; *shim* the joints where necessary; make the weld; and grind down the head of the rail to a smooth, even surface after the weld is made.

Welding Train. The welding train generally consists of four cars. The first car, taken in the order in which they operate, is the car carrying the sand-blast apparatus. The next two cars are the car carrying the welding machine proper, and the transformer car. The fourth car is the one carrying the apparatus for grinding the rail down to a smooth joint.

The operation of welding is briefly as follows

The street, around the rail, is opened up for a distance of about two feet each side of the joint, making a hole about four feet long and two feet wide each side of the rail. The old fish plates and bonds are then removed, and the sides of the rail cleaned with the sand-blast apparatus to remove all scale and dirt. If there is any opening between the rail ends, this is now filled by driving in shims made of thin *slices* of rail of the same section as that to be welded. The welding cars then take up the operation.

The plates to be welded to the sides of the rail are clamped in place, and the jaws of the welder are adjusted in position. The current is then turned on; and when the metal is hot enough, the weld is made by forcing the jaws of the welder together with hydraulic pressure.

When the weld is completed, the current is turned off; but the pressure is kept on the joint for a short time, in order to hold the plates in position while cooling. This operation is repeated until the three spots on the plates are welded to the rail. The welder then moves on to the next joint, and the grinding car completes the work by grinding off the top of the rail to a smooth, flat surface.

The sketch in Fig. 14 will give an idea of the sort of joint that is made by this method. A plate about an inch thick is welded each side of the rail, the welding being done at three spots only, at about the locations shown by the dotted lines, one at each end and one in the center.

Fig. 15 shows the diagram of a sand-blast car which carries a motor for running an air-compressor, the air-compressor itself, and the storage tank containing the sand under air pressure. The motor used in one car, fitted up for this purpose, and used in Chicago by the Lorain Steel Company, was of 18 horse-power; and 20 pounds pressure was carried on the sand tank. The sand was forced from the tank and through a flexible hose, and directed against the joint by a small nozzle. The work of cleaning the joints was quickly done, and the labor of only one man was required to take care of the car and apparatus.

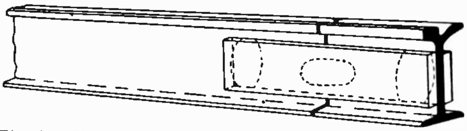


Fig. 14. Illustrating Process of Welding a Rail Joint.

As the current in most street-railway work is continuous, it is necessary to use a *rotary converter* to obtain power for the welding transformer. In the case mentioned above, the apparatus used consisted of a General Electric rotary converter. Current was taken from the trolley wire at about 600 volts, and delivered from the converter as alternating current, 40 cycles, at about 280 volts.

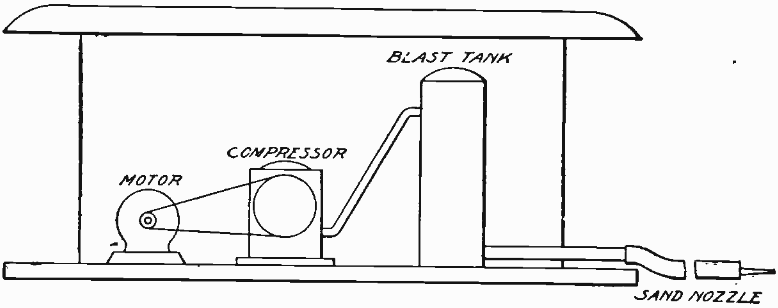


Fig. 15. Diagram of Sand-Blast Car.

From the converter the current was carried through a potential regulator of 60 to 65 kilowatts capacity.

At this voltage the current was carried to the welding transformer placed between the arms of the welding machine. This machine is shown in Fig.16, which illustrates the machine proper detached from the car. In Fig. 17 is shown a sketch of this welder, with a short explanation of the parts. The high-potential current is carried directly to the welding transformer, and the voltage is here reduced to about 6 volts. Probably the current used at the grips is about 20,000 amperes. In the car with the welder are also motors and fans used for circulating the water through the copper grips in order to keep them from being overheated, and also for cooling the circulating water. There are also motors for raising and lowering and shifting

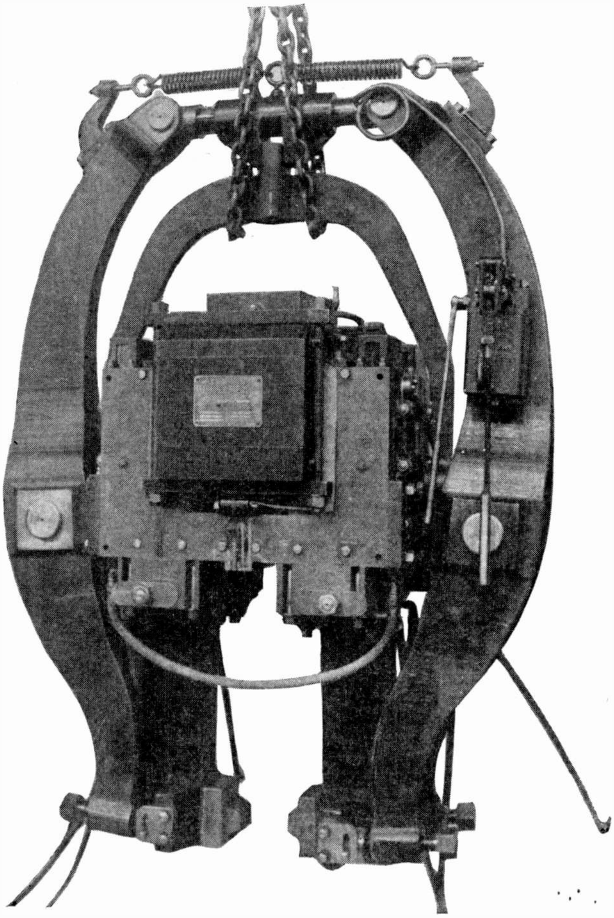


Fig. 16. Electric Welder.

the welding machine. The circulating water is cooled with a fan. The welding machine is carried on a sort of crane controlled by a long screw, and may be shifted to bring the grips in the proper place over the joint to be welded. The shifting of the welder is done mostly by power furnished from the motors in the welding car.

In Fig. 18 is shown a complete welding train in operation, the sand-blast car at the left, the grinder car at the right, and, in the center, the two cars containing the transformer, the regulating apparatus, and the welding machine proper. The welder may be tipped back or elevated to clear the rail while the car is being moved forward to position for another joint. The welder itself is shown separately in Fig. 19. Fig. 20 is a separate view of a sand-blast car; and Fig. 21, a separate view of a car for joint grinding.

Each of the cars of the welding train—with the exception of the transformer and welding cars, which are run together as one car—is equipped with an ordinary motor, and runs separately as a trolley car in moving from place to place.

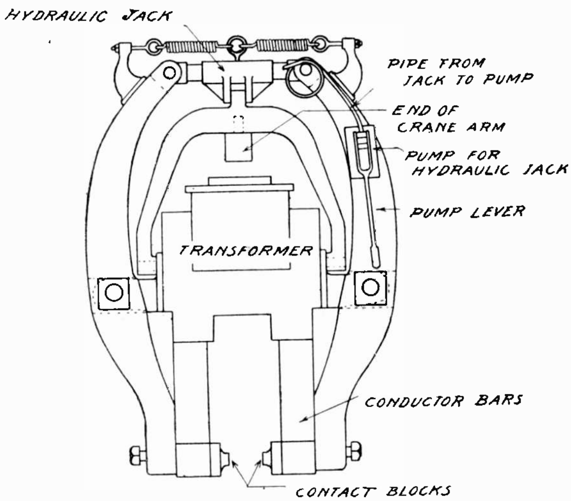


Fig. 17. Diagram of Welder.

In making the weld, the car is brought to position, and the plates adjusted. This must be done with care, or a bad weld will result, as will be noted later. Clamps are then put on to hold the plates in the proper position, the welding clamps are gripped over the plates, and the current turned on. The heating is watched; and as soon as the plates become red-hot, a flux is sprinkled on the joint. When the heating has continued far enough, the jaws are forced together with the hydraulic pump and plunger arrangement, between the upper ends of the arms. The pressure brought to bear on the joint is about 40 tons. The piston area is about 10 square inches; the pressure on the piston, about 4,000 pounds per square inch; and the leverage of the arms, about 2 to 1—making the direct pressure about as given above. Fig. 22 is a photograph of a completed weld.

The plate used on the side of the rail is shown in detail in Fig. 23.

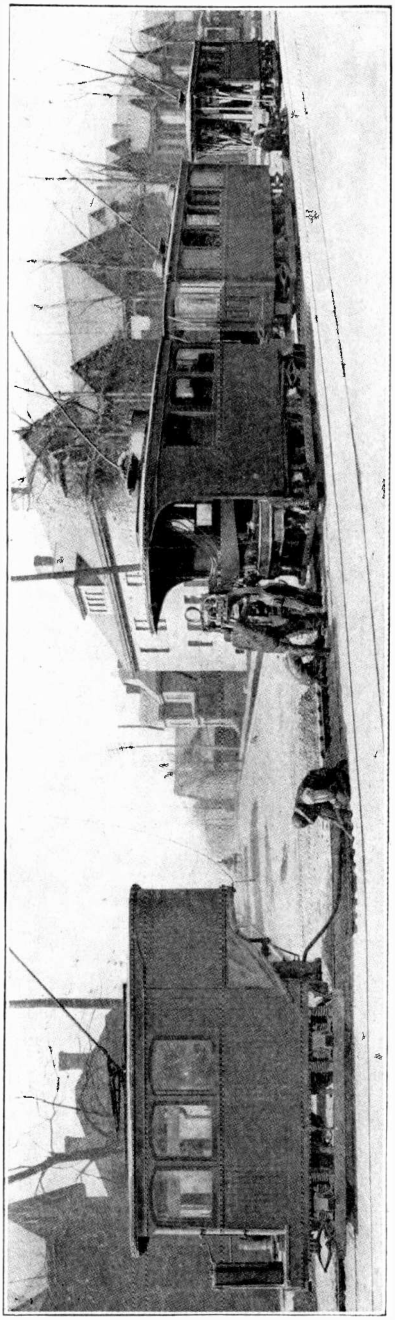


Fig. 18. Electric Welding Train in Operation.
Lorain Steel Company, Johnstown, Pa.

The dimensions are 22 inches by 4 inches by 1 inch, the last being the thickness. The plates are uniform in thickness, with the exception of three *contact-points* raised on them, one at either end and one in the center, the object being to concentrate the heating at these points. It will be noticed that these points are not flat, but are stepped, still further concentrating the effect of heating at the start of the welding process. When the weld is completed, these spots have been flattened out so far that the bar is brought in contact with the rail web. In a finished joint, there is about 30 square inches of welded surface on both sides of the rail.

Care must be taken to see that the ends of the plate are matched up on the two sides of the rail, or the twisting action of the welding pressure will cause the weld to crack open in cooling. On one occasion, in connection with work of this character, observation showed that defective welds were resulting, and it was discovered that the ends of the weld plates extended beyond the ends of the welding surfaces. In other words, instead of ending at the welding spot as shown in Fig. 23, the weld plates extended for a short distance beyond, as shown in Fig. 24. As this distance was not uniform, and as the plates were placed by bringing their ends even, the result was

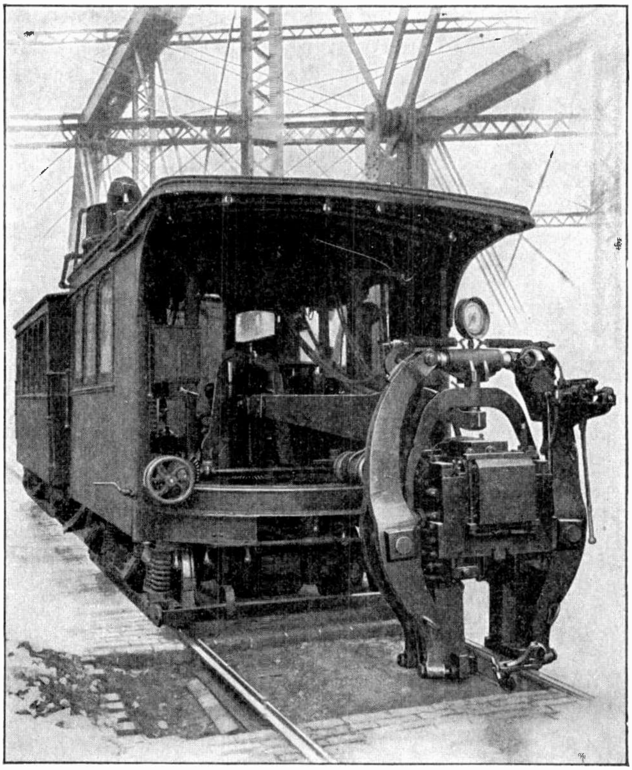


Fig. 19. Welder Car.
Lorain Steel Company, Johnstown, Pa.

that the welding spots were not brought opposite each other, and a sort of twisting action took place, causing the welds to crack open occasionally. When this was discovered, the ends of the plates were trimmed off to a uniform length, and no further trouble resulted.

The effect of placing with uneven ends is shown in Fig. 25, where the ends are placed in line, thus throwing the lugs out of true.

The *actual* time required for welding—that is, the time the current is on—is about $2\frac{1}{2}$ to $3\frac{1}{2}$ minutes for each point of contact, of which there are three at each joint; the variation in time being largely due to fluctuations in the line current, which, as it is taken from the trolley circuit, varies to some extent. On end welds, the clamps are kept on under pressure for three minutes after the weld is

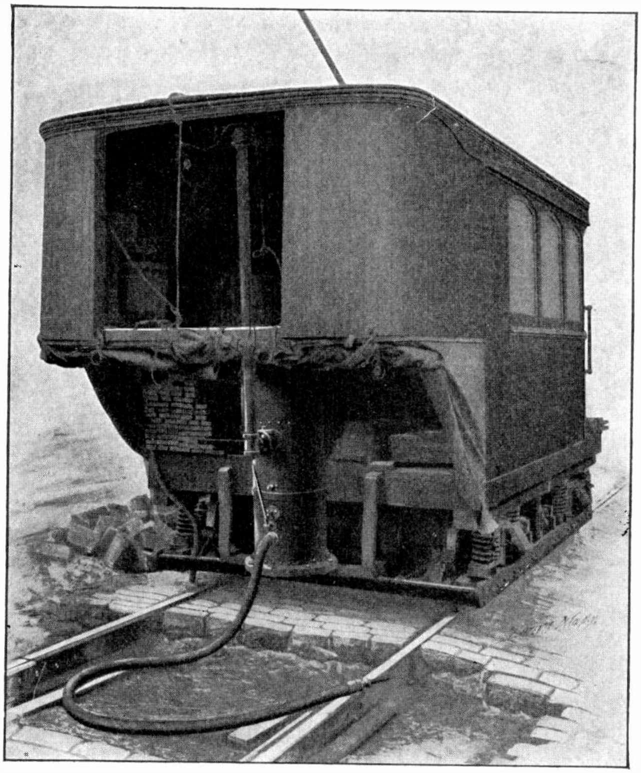


Fig. 20. Sand-Blast Car. Lorain Steel Company, Johnstown, Pa.

made and the current turned off. The center weld is clamped in this way only one minute. Such cooling under pressure was found necessary to insure good welds. When the clamps were released immediately after the current was turned off, it was found that frequently the weld would crack open in cooling, making a very large percentage of bad welds.

The heat is so localized that the head of the rail is never red-hot during the entire process, with the result that it is not softened, and

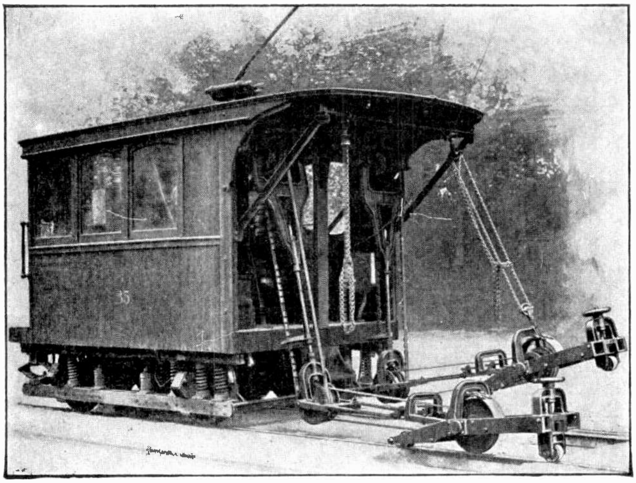


Fig. 21. Car for Joint Grinding.
Lorain Steel Company, Johnstown, Pa.

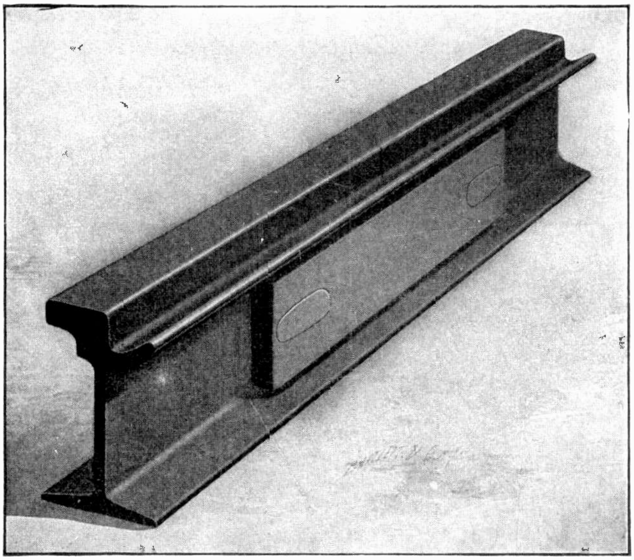


Fig. 22. Electrically Welded Joint.
Lorain Steel Company, Johnstown, Pa.

excessive wear does not take place at the joint, as is liable to be the case with the old method of cast welding.

The welds here illustrated were made under contract, the contracting company furnishing the welding train and men, the railroad company furnishing the current. The usual charge is $5.25 per joint, the welding company to replace any welds proving defective within one year. The percentage of good welds is over 99 per cent. This price seems to be practically universal but a slight difference is sometimes made in the terms for replacing defective joints, in some cases the welding company agreeing to pay back about twice the original cost of the weld for every defective joint.

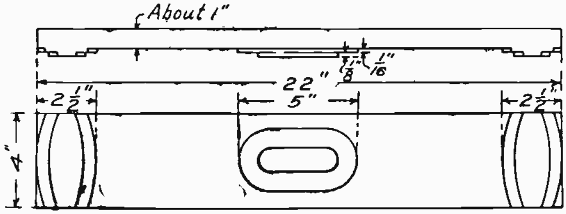


Fig. 23. Plate Used in Rail Welding.

The welds are finished by grinding with the portable grinding rig carried on a separate car. The arrangement of this car is shown in Fig. 26. A 5-horse-power motor is attached to each grinder, one on each side of the car. Each motor runs its own grinder only. The emery wheels are about 14 inches in diameter, with a 2-inch face, and are adjusted with the screws as shown. It requires from 5 to 10 minutes to dress the rail down to a smooth, even surface. The leveling is done with a straight edge. The grinder is so fixed that it may be moved back and forth on the rail, the grinding wheel being raised or lowered by means of the adjusting screw on the front end of the carriage. The jointed frame keeps the belts tight and allows the forward and back motion, at the same time preventing much movement sideways. One motor only at a time is used.

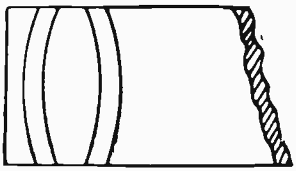
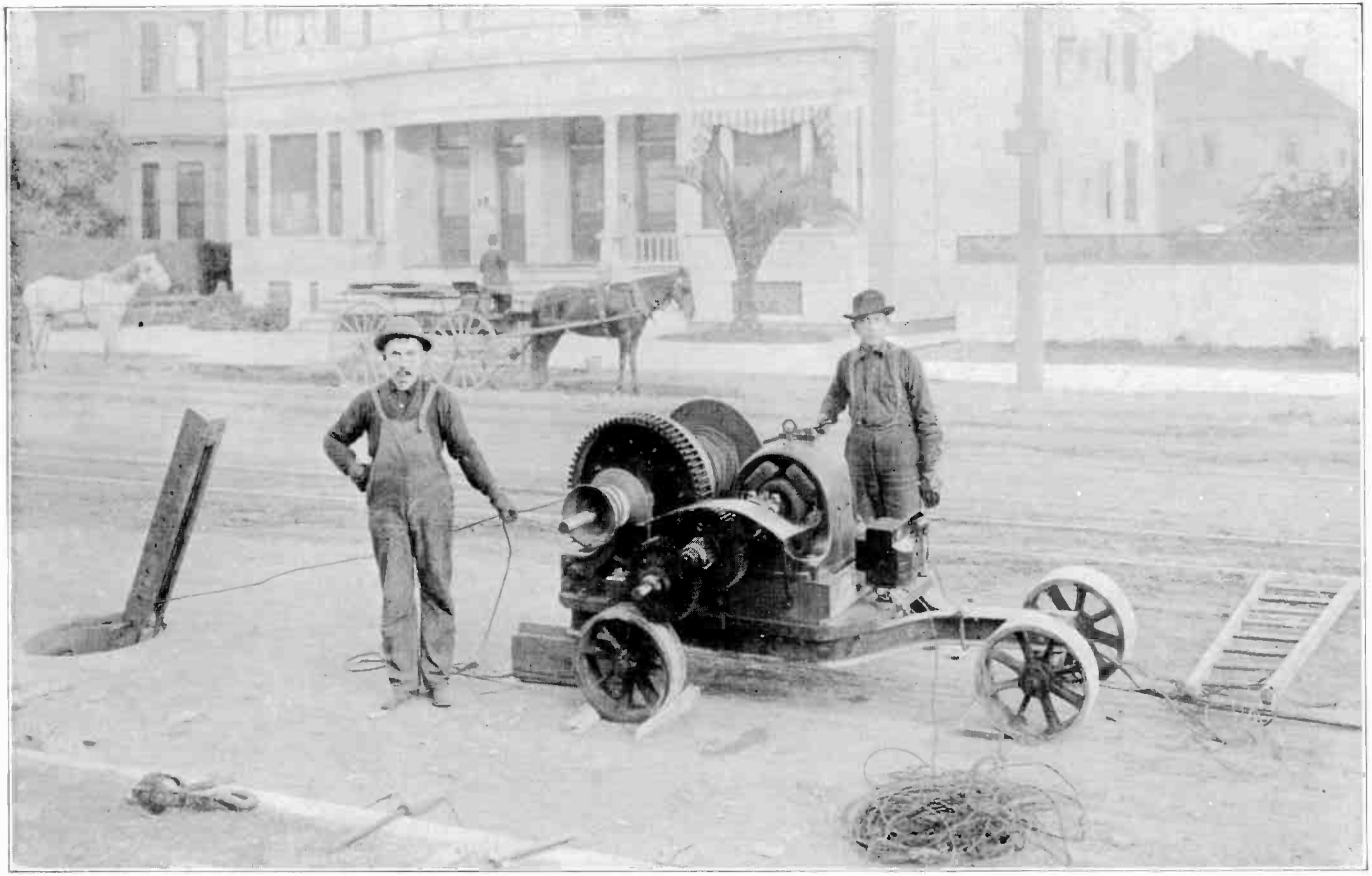


Fig. 24. Weld Plate Extending Beyond Joint.

There is another process of rail welding, in which a liquid flux is used. This process has been experimented with, but has not yet been perfected. A mould is clamped around the joint; the current is turned on; and the flux, which has previously been heated and melted in a crucible, is poured into the mould. Welding clamps



ELECTRIC WINCH FOR DRAWING CABLES INTO UNDERGROUND DUCTS similar to those used in the Thomson process are employed, and plates are welded to the side of the rail in much the same manner. This process, in fact, is much the same as the Thomson, except that a slightly higher voltage is used, a melted flux is employed, and the welding grips are surrounded by a mould to hold the molten flux in place. The inventors claim that less power is required, and that

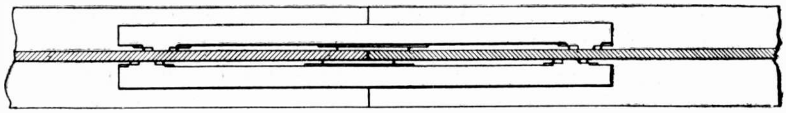


Fig. 25. Showing Effect of Uneven Placing of Plates.

work may be done more cheaply than by the Thomson method. In the experimental car used, the transformer for the final reduction in voltage was placed in the car itself, and the low-voltage current carried through wires to the welding grips. A large switchboard was provided in the front end of the car, equipped with means for changing the voltage at the grips, as a constant voltage was not used throughout the process.

Rail Welding Labor and Costs. The schedule given below shows approximately the labor required to run the welding train, including the cleaning of the joint with the sand-blast, shimming,

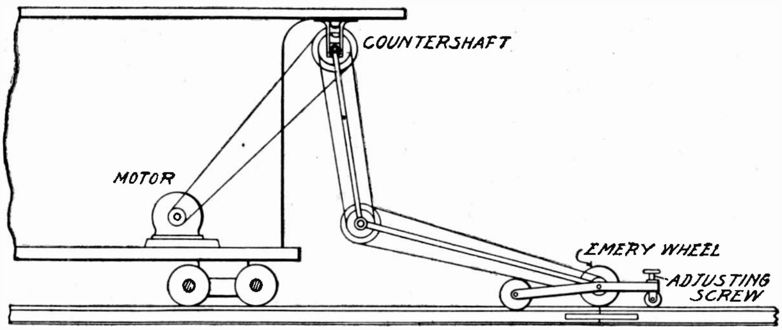


Fig. 26. Diagram of Grinder Car.

actual welding, and grinding of the finished weld. Two gangs are used, one day and one night; but only one foreman is used to look after both gangs. For one gang only, including the foreman who takes care of both gangs, the schedule of labor is as follows:

1 Foreman.
1 Sand-blast man.

1 Welder man.
2 " " helpers.
1 Dynamo man.
1 Grinder man.

This makes a total of 13 men for both day and night gangs, which force of men will make about 70 to 75 joints of three welds each per day.

The dynamo man is stationed in the transformer car, where instruments are provided for keeping track of the voltage, power used, etc. This man also keeps track of the time on the welding, signaling the welder when to release the grips after the weld is completed. The turning of the current on and off is done by the men at the welder.

The time on each joint is about 19 minutes, each weld requiring about 6 minutes, a minute more being taken to move from joint to joint.

Mr. P. Ney Wilson* gives the following data of some work done in New Jersey. The welding was done by the Lorain Steel Company, at a contract price of $5.25 per joint for the welding alone.

In figuring the cost to the railway company for opening the street around the joints, and relaying the pavement after the welding was done, the labor cost is taken as 15 cents per hour—or rather, the labor has been calculated to this average basis per hour. Rails were of 7-inch girder type similar to Cambria No 824; number of men employed, 98; joints per day, 64; data taken from about 3,000 joints; street opened up in each case, and returned to original condition after weld was made.

Cost per joint—(*average* results on over 3,000 joints):

Preparing joint, opening street, etc.		$2.277	
Material (saws, tools, etc.)		.188	
	Total		$2.465
Credit for scrap (old bond, etc.)			.912
	Net cost		$1.553
Replacing asphalt			.832
Contract price for weld			5.25
Net cost per joint completed			$7.635

The credit made above for scrap includes the amount realized from the selling of the old fish-plates, copper bonds, etc.

* *Engineering—Contracting*, March 20, 1907.

On some other work the same author gives the following:

7-in. girder rails, 60-ft. lengths, Penn. Steel Co. No. 238 and Cambria No. 824.

Pavement, Belgian block on sand foundation.

Average number of men employed, 103.7, at 15 c. per hour.

Cost of fitting joint for welding after deducting credit for scrap, $1.433

On another street where same rail was used in 30- and 60-foot lengths:

84.6 men, 15 c. per hour.

Average joints per day, 60.

Gross cost of fitting for each joint, $2.292.

Net " " " " " " $1.382.

This same joint was also used on some interurban work near Providence, R. I., where the rails were exposed to the air; but in this case an expansion joint was used about every 1,000 feet. The track was laid with T-rail, and was about six miles long.

Wire Welding. On telegraph wire, the Roebling Company are reported to make, on an average, about 600 welds per day. A large portion of the time, however, is taken in handling the heavy coils of wire.

Small wire loops and steel rings are made by the Thomson Company at the rate of from 1,000 to 3,000 per day of ten hours.

Direct and Alternating Current. On small work, direct current may be used; but for heavy pieces, there is a decided advantage in alternating current. The final results obtained are about the same whether direct or alternating current be employed; and in fact a storage battery may be used, if designed for very rapid discharge.

Nearly all welders are built for alternating current, the reason being that the heaviest current is carried on or near the surface of the conductor; and as it is here that the greatest radiation takes place, the useful heating effect of alternating current is thus greater than that of direct current of the same strength.

It is theoretically possible to weld sections of any size with a small current; but in practice it is found that the rapid radiation of heat from the surface of the metal must be taken into account. On large work, when a small current is used, a point is reached where the radiation will equal the heating effect of the current, and then the temperature remains constant. When this is the case, the remedy is to use a greater current strength.

Heating in Welder. The same process that is used in welding may be employed in any heating operation. Pieces are sometimes heated between the clamps of the welder, and upset to form a sort of ball or collar, as illustrated in Fig. 27. The same method is also used to fasten collars to shafts by a sort of riveting. The collar is made a loose fit on the shaft, and is slipped on into position, the shaft being then gripped in the jaws of the machine in such a way as to bring the collar midway between the two. The shaft is heated, and, when the pressure is applied, is upset tightly into the hole in the collar and against the sides, somewhat as shown in Fig. 28, thus firmly clamping the collar in place.

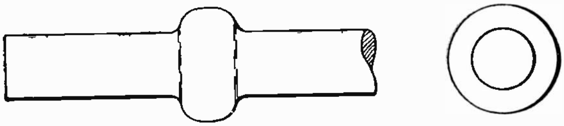


Fig. 27. Ball or Collar Formed at Joint of Electrically Heated Pieces.

Where it is desired to heat only the end of a bar, the submersion method may be used; but when the center of a bar is to be heated, the Thomson process is the better. In the latter case, the bar is gripped in the clamps in the usual way, with the part to be heated between the two jaws; the current is turned on; and the heating is continued until the metal is raised to the desired temperature, when the current is turned off, and the bar taken from the machine and treated in any way desired A bar may be heated at one end only, in a Thomson welder, by gripping the piece in one jaw and butting it against a much heavier piece held in the other jaw. The heating will be confined almost entirely to the smaller bar if there is a large difference in section between the two.

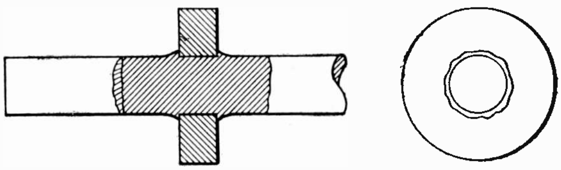


Fig. 28. Collar Fastened to Shaft.

Brazing and soldering may be done in this same way; but of course the amount of heat used is very much smaller and must be more carefully regulated. When preparing for brazing, the pieces may be placed together in exactly the right position, and brass provided for the joint in the shape of rolled or sheet brass placed over (or in) the crack between the pieces. The flux is added, and the heating done in the usual way.

Rail Bonding. A modification of the welding process is sometimes used for fastening bonds to the sides of rails, joined by the old fish-plate method, in order to make a continuous electrical conductor.

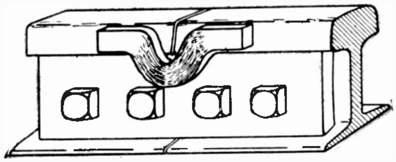


Fig. 29. Rail Bond Sweated against the Side of the Rail Head on Outside of Track.

In this work, the current required being very light, all of the apparatus is carried in one car. The work is really soldering, and not welding. The bonds are sweated against the side of the rail head on the outside of the track. Fig. 29 shows the shape and

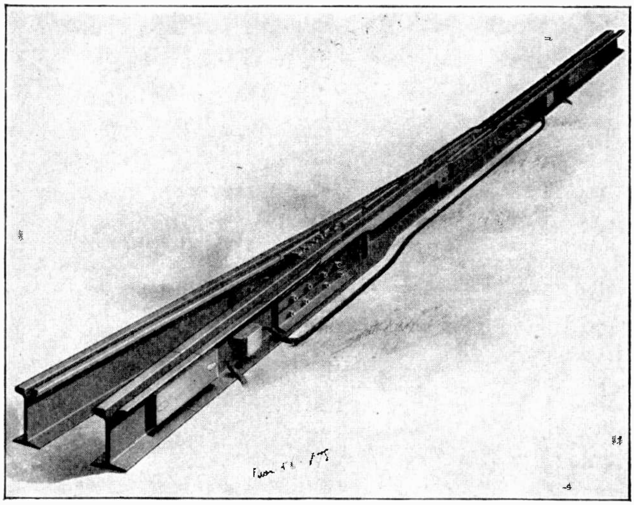


Fig. 30. Switch-Piece, Showing Method of Bonding around Same by means of Copper Cable with Ends Welded to Rail.

location of the bond used. The top of the bond is about flush with the top of the rail. The joint is sometimes touched up with a small portable hand-grinder, power for which is obtained from a wire fastened to a pole and hooked over the trolley wire. Fig. 30 illustrates the method of bonding a switch-piece.

Power Required for Welding; Miscellaneous Data. It is almost impossible to give the exact amount of power required for welding work of a given section, without taking into consideration the shape of the section and the time taken. Both of these elements influence the results to a large extent. It is possible, however, to state certain rough general rules, and to set forth the results of commercial work and experiments, which will serve as a guide for approximately estimating the amount of power and time required.

The shorter the time taken, the less current is taken in proportion, as the heat is radiated only at a certain definite rate, and consequently less energy will be lost during a short time.

Sir Fred Bramwell* gives data from the results of an extensive series of experiments. The electrical readings were reported by Sylvanus P. Thompson; and in the discussion, considerable data on American practice were given by Professor Kennedy. The data given in the above paper met with the approval of Elihu Thomson, and may be taken as probably representing good practice.

The particular form of electrical energy needed is large current and low pressure, as the pressure (voltage) has nothing to do with the heating property of the current, merely serving to force it through the metal.

Experiments on a number of welds with round iron $1\frac{1}{8}$ inches in diameter gave the following results:

Average time, $2\frac{1}{4}$ minutes, found by taking the total time, and dividing by the number of welds made.

Actual time the current was on, about 26 seconds for each weld.

About 23.6 horse-power was required, this being the total load on the engine and including the engine, dynamo, and transformer losses.

Table II, compiled by S. P. Thompson, gives the results from readings taken between generator and welder, thus including the loss in the machine and welding transformer only. *Average* results are given, but the individual readings did not vary much from the average.

Exact proportions between power required and cross-sectional area cannot be given, as radiation has considerable to do with the power absorbed, and a thin rectangular bar will radiate heat faster than a round one of the same area.

* Proceedings of the Institution of Civil Engineers of Great Britain, Paper No. 2460.

TABLE II

Data of Welding Operations

Size of stock	1⅛ in. diam. Wrought Iron	¾ in. diam. Steel	2½ in. by 1⅛ in. Wrought Iron
Time current was on (seconds)	32	16	28.5
Power used (kilowatts)	13.17	11.4	24.98
Power used (horse-power)	17.5	15.2	33.4
Area of section (square inches)	1.00	.44	2.81
Horse-power used per square inch	17.5	34.5	11.8

Kennedy gives the following as American practice:

Standard projection of each piece from jaws of welder, distance equal to diameter, making distance between jaws of welder equal to twice diameter of work.

Standard time for 1-inch bar, 40 seconds; other sizes in proportion.

Length of part heated, to vary about as the diameter.

Horse-power to vary about as the square of the diameter, horse-power per square inch to remain constant.

As the result of a series of experiments the horse-power per square inch is given as follows:

1-inch bar, wrought iron	20.0	Horse-power
¾ " " " "	19.3	"
½ " " " "	20.4	"
1 " " steel	23.4	"
¾ " " "	20.5	"
½ " " "	19.6	"

This makes the horse-power per square inch practically constant; but it will be noted that no account is taken of the time, which may be varied in such a way as to make the horse-power always constant.

The above data gives enough information to enable the making of a fairly accurate estimate of the amount of power required in any particular case.

Another method of estimating, given by Mr. Hermann Lemp in *Engineering Magazine*, is based on the assumption that it takes about 7 horse-power-minutes to raise one cubic inch of metal to the welding temperature. This is practically the same for copper, brass, and iron—with the distinction, however, that for metals which conduct heat easily, a shorter time and correspondingly greater current strength must be used to prevent excessive loss from radiation and conduction. When the pieces are both short and wide, making the conduction by the clamps great, from 10 to 15 horse-power-minutes per cubic inch are required.

Axle and Tire Welding. The figures given in Table III are based on data given by Mr. Fred P. Royce in *The Iron Age.*

TABLE III

Axle and Tire Welding

Size Stock	Power Used	Time	Area in Sq. In.	Power Used per Sq. In.
AXLE WELDING				
1 -in. round	25 H.P.	45 sec.	.785	32.0 H.P.
1 -in. square	30 "	48 "	1.000	30.0 "
1¼-in. round	35 "	60 "	1.227	28.5 "
1¼-in. square	40 "	70 "	1.563	25.6 "
2 -in. round	75 "	95 "	3.142	24.0 "
2 -in. square	90 "	100 "	4.000	22.5 "
TIRE WELDING				
1 -in. by 3/16 in.	11 H.P.	15 sec.	.198	58 H.P.
1¼-in. by ⅜ in.	23 "	25 "	.470	49 "
1½-in. by ⅜ in.	20 "	30 "	.561	36 "
1½-in. by ½ in.	23 "	40 "	.750	31 "
2 -in. by ½ in.	29 "	55 "	1.000	29 "
2 -in. by ¾ in.	42 "	62 "	1.500	28 "

The radiating effect of the thin flat section is well illustrated by the 1 in. by $\frac{3}{16}$ in. tire, where 58 H. P. per square inch was required to make the weld; while with the comparatively heavy 2 inch by ½ inch tire, the power was much less, being only 29 H. P. per square inch.

It will be noticed from Table III, that a greater amount of power per square inch is required to weld pieces of small area than those of larger section.

A safe rule to follow on average work would be to allow about 40 H. P. per square inch on pieces of from .05 square inch in cross-section to about .75 square inch; while above this size, from 30 to 20 H. P. would seem to be about right, depending on the shape of the section, 30 H. P. to be used for flat sections, and 20 H. P. for sections approximately round or square.

TABLE IV

Power and Time Requirements for Electric Welding of Round Iron or Steel Bars and Heavy Iron Pipe

ROUND IRON OR STEEL

Diameter	Area	H. P. Applied to Dynamo	Time in Seconds
¼ in.	.05	2.	10
⅓ "	.10	4.2	15
½ "	.20	6.5	20
⅝ "	.30	9.	25
¾ "	.45	13.3	30

EXTRA HEAVY IRON PIPE

Inside Diameter	Area	H. P. Applied to Dynamo	Time in Seconds
½ in.	.30	8.9	33
¾ "	.40	10.5	40
1 "	.60	16.4	47
1¼ "	.79	22.	53
1½ "	1.10	32.3	70
2 "	1.65	42.	84
2½ "	2.25	63.7	93
3 "	3.	96.2	106

TABLE V

General Table of Power and Time Requirements for Electric Welding of Iron, Steel, and Copper

Iron and Steel			Copper		
Area in Square Inches	Time in Seconds	H. P. Applied to Dynamo	Area in Square Inches	Time in Seconds	H. P. Applied to Dynamo
0.5	33	14.4	.125	8	10.
1.	45	28.0	.25	11	23.4
1.5	55	39.4	.375	13	31.8
2.	65	48.6	.5	16	42.
2.5	70	57.0	.625	18	51.9
3.	78	65.4	.75	21	61.2
3.5	85	73.7	.875	22	72.9
4.	90	83.8	1.	23	82.1

General Tables of Power and Time Requirements. The data in Tables IV and V are given by the Thomson Electric Welding Company, and may be taken to represent current practice on commercial work.

It will be noted that the power as given is the power required to run the *dynamo*, and thus includes all losses in dynamo, transformer, and welding machine proper.

COMMERCIAL WELDING

Electric welding has developed so far now that there are companies organized to do commercial welding on a large scale. In fact, many articles which are ordinarily very expensive to produce may be made very cheaply by this welding process. Cap screws, for instance, are now being made by a welding process, in place of the usual method of turning down the body from stock the size and shape of the head. By the old method, the shank of the bolt was turned down from bar stock of the same section as the head. When the shank was long, this necessitated an enormous loss of material. By the electric method, the head is made with a short stub for a shank, about a quarter-inch or so in length, and to this short stub is welded the finished shank in any length desired. Ordinarily cap screws are made of a sized stock which leaves a very small head, in order to save stock; but when the electric method is used, any sized head may be welded to the desired shank without loss of stock.

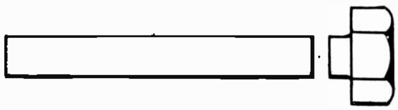


Fig. 3.. Cap Screw.

In Fig. 31 is shown a sketch of a cap screw made in this manner, showing the parts before they are put together. The welding of course raises a burr, which may be removed easily by grinding or by taking a finishing cut in a lathe.

This method of welding has almost developed a new industry, as many parts are now made from forgings, which were almost impossible to make that way before on account of the enormous cost of the dies. Thus the cost of making the automobile forging shown in Fig. 32 would be almost prohibitive if forged in one solid piece; but by making in several pieces and then welding, the work is much simplified and the cost greatly reduced.

In Fig. 33 is another piece of work—a valve-stem for a gas engine—the making of which is much simplified by electric welding. If this piece were to be forged solid, it could of course be made in dies by drop forging; and while this is perfectly practicable when lots of several thousand are made at once, if only a few hundred or a

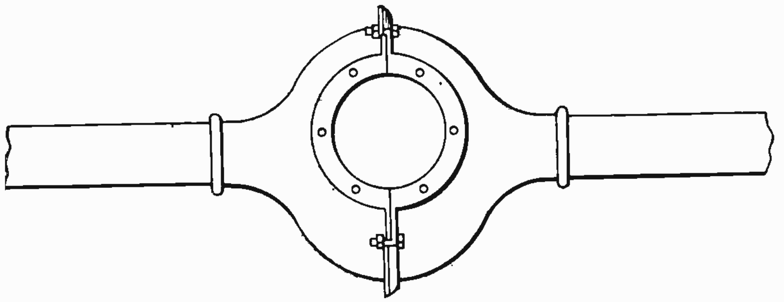


Fig. 32. Automobile Forging Made of Separate Parts Electrically Welded Together.

few dozen are required, the welding process greatly simplifies the matter. The separate pieces may be made on the screw machine, and then welded and a cut taken to smooth up the stem.

Still another sort of weld is shown in Fig. 13 where the work is shown after welding but before the burr has been removed.

Fig. 11 shows a weld in a section of clincher rim, a piece of work which it would be almost impossible to weld by any other method.

The applications of electric welding are almost unlimited, and in some fields have made possible work which otherwise might be impossible to accomplish. Many tools require a very hard cutting edge and a very tough shank; these may be obtained by welding a high-carbon steel for the cutting part of the tool to a low-carbon machine-steel shank. High-speed or air-hardening steel may be used in the same manner. This not only saves on the first cost; but a better tool is the result, as there is less chance of breakage in the shank.

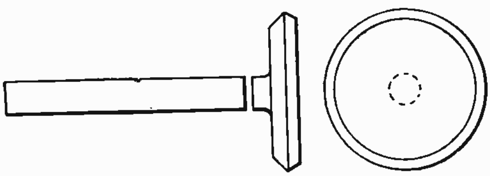


Fig. 33. Gas-Engine Valve-Stem.

Action of Various Metals in Electric Welding. Mr. Elihu

Thomson* gives some interesting data regarding the action of various metals in the electric welder:

Tin can be welded with ease; also antimony and bismuth.

Aluminum requires precautions; but welds can be made, and, when done right, the results are good. Hand electric welding is not good for aluminum; but with automatic machines, almost uniformly good results are obtained.

Brass requires much greater current strength than wrought iron, although the specific resistance of cold iron is almost the same as that of brass. As the heat of the metal rises, however, resistance increases only slightly with brass and German silver, while the increase with iron is large.

Brass seems to soften hardly at all when heated, passing almost immediately from solid to liquid, and, if too great pressure is used, will crumble and make a rather poor joint.

Some bronzes—notably aluminum bronze—show some plasticity before fusion.

Copper is a good conductor, and radiates heat easily. About one volt is required across terminals, and welding should be done rapidly in order to lose a minimum amount of energy through radiation.

As a general rule, a flux should be used on metals whose oxides melt at higher temperatures than the metals. Brass should be fluxed, copper not. Covering action of flux is useful in most cases. No flux is required on soft iron; but heat which welds soft iron would ruin steel, so that flux is required on steel.

RECENT APPLICATIONS

One of the most recent and interesting applications of electric welding is that of making the side joints on ordinary hot-water tanks such as are found attached to kitchen stoves.

The following cuts and descriptive matter, for which the author is indebted to E. A. Suverkrop and the *American Machinist* is not only of interest on account of the process used, but also as giving a comparison of cost and strength between this and other methods of doing this sort of work.

The work described is done at the works of the John Wood Manufacturing Co., Conshohocken, Pa., where 800 to 1,000 boilers are made every twenty-four hours.

†The raw material in the shape of plates cut to size and varying in thickness from No. 16 to No. 9 Birmingham wire gauge—these are the thicknesses of the plates used for the boilers having electrically welded seams—are manufactured in the same town to special analysis.

*Transactions of the Institute of Mining Engineers.

†E. A. Suverkrop, *American Machinist*, Feb. 25, 1909.

The requirements for this purpose demand an open-hearth steel possessing anti-rusting properties. It must be low in carbon, the analysis calling for 0.12 per cent, and the sulphur content must not exceed 0.03 per cent, while the tensile strength varies between 55,000 and 58,000 pounds per square inch.

The first operation is the rolling of the plates into cylindrical form which is done on the usual boiler rolls which are, of course, of a diameter to suit the work, the boiler shells ranging in diameter from 7 to 16 inches, and up to 70 inches in length. From the rolling operation the shells pass to the sand-blasting room where the usual low-pressure sand-blasting apparatus is used to remove the scale back on either side of the seam for about an inch and a half. The object of this is to give clean metal free from scale for the weld and also to facilitate the passage of the electric current, scale being a partial insulator of electricity. The plant which supplies current for the two welding machines consists of two 60-kilowatt Thomson alternating generators, specially wound for the purpose, delivering the current to the primary circuit at a voltage varying from 250 to 350, heavier work requiring the greater voltage, while for thinner work the primary voltage is reduced. The Thomson process of electric welding is used with modifications made necessary by this particular class of work. These modifications have been developed at this plant and are embodied in the two machines, built by the Standard Welding Company, Cleveland, O., shown in Figs. 34, 35, 36, and 37.

The machines are approximately 9 feet high, 6 feet wide, and 20 feet long over all. The machine proper consists of a heavy cast-iron base *B* upon which are mounted the pressure rolls or spools *A*, one on each side, and between which the boiler shell *C*, Fig. 36, passes during the welding operation. These rolls are made in pairs for the various sizes of boilers, are easily changed from one side to another, and are mounted so as to adjust to or from the center.

In front of the machine is a stake *D* which carries a horizontal bar *E*, upon the end of which is a head *F*, shown in Fig. 35, carrying three rollers, one roller on the top immediately below the two copper electrodes *G*, and the other two at an angle of about 120 degrees. These two lower rollers hold the boiler shell against the pressure rolls *A*, while it passes through the machine. Behind the machine, Fig. 35, is a device similar in construction to the regulation draw

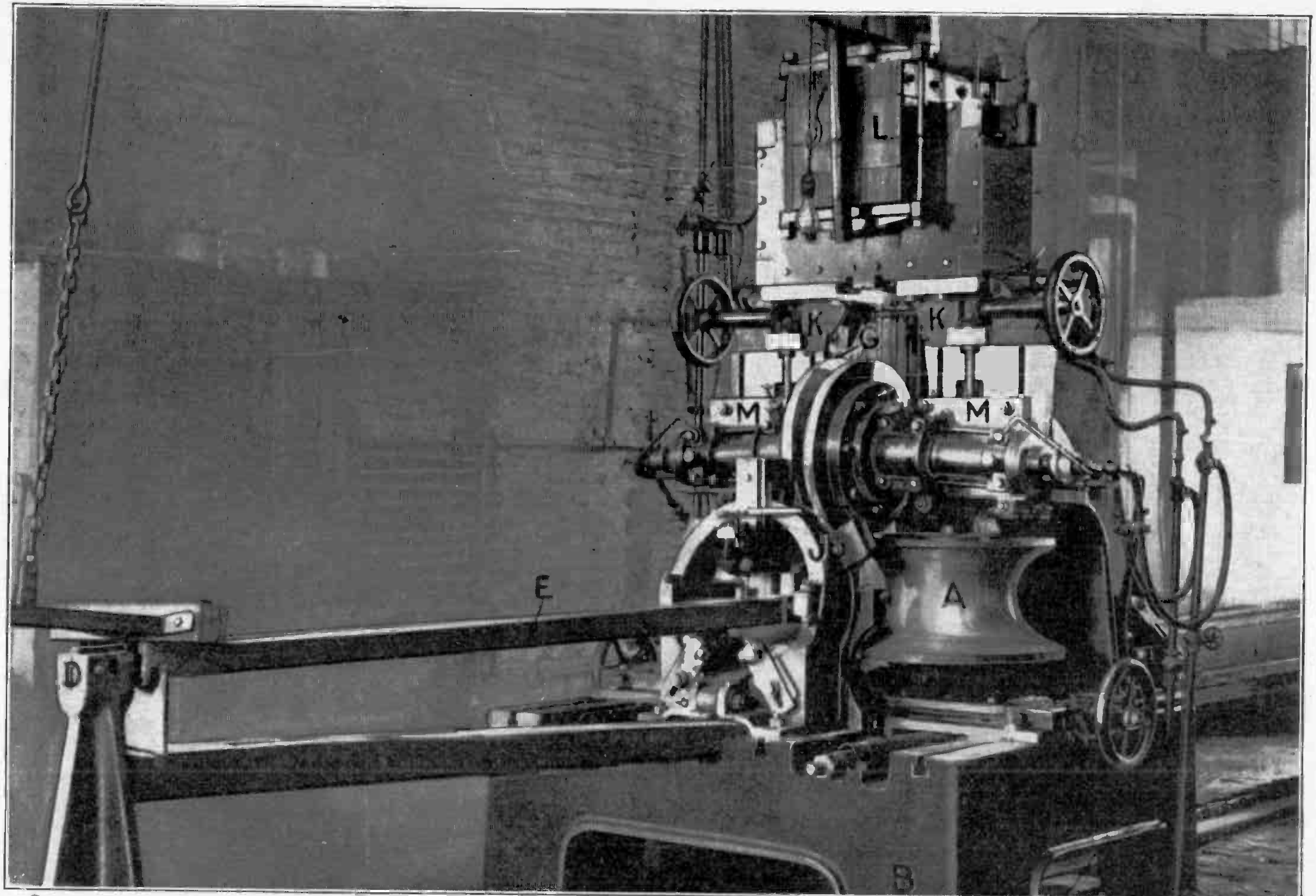


Fig. 34. Front of Electric-Welding Machine.

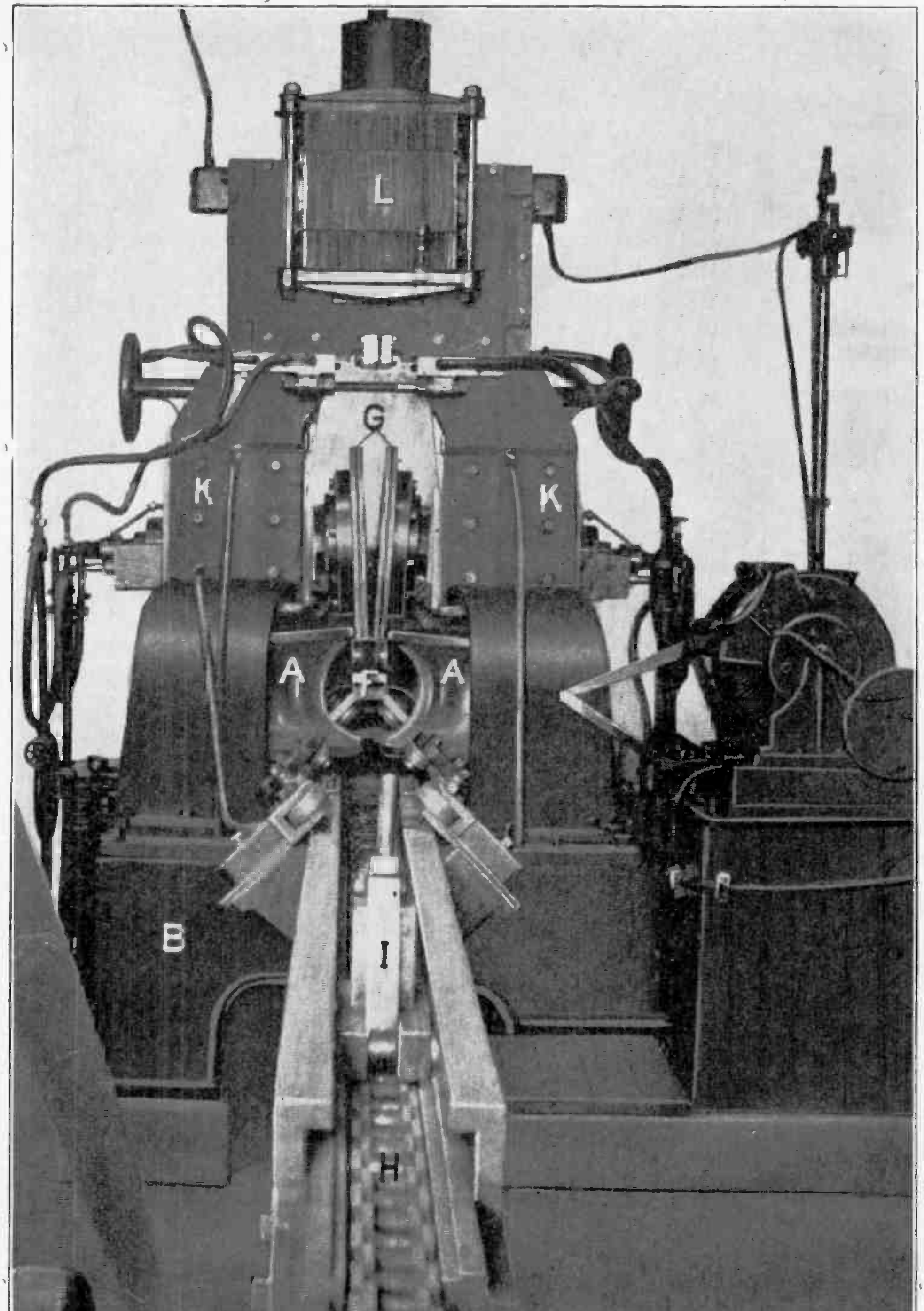


Fig. 35. Rear View of Electric-Welding Machine.

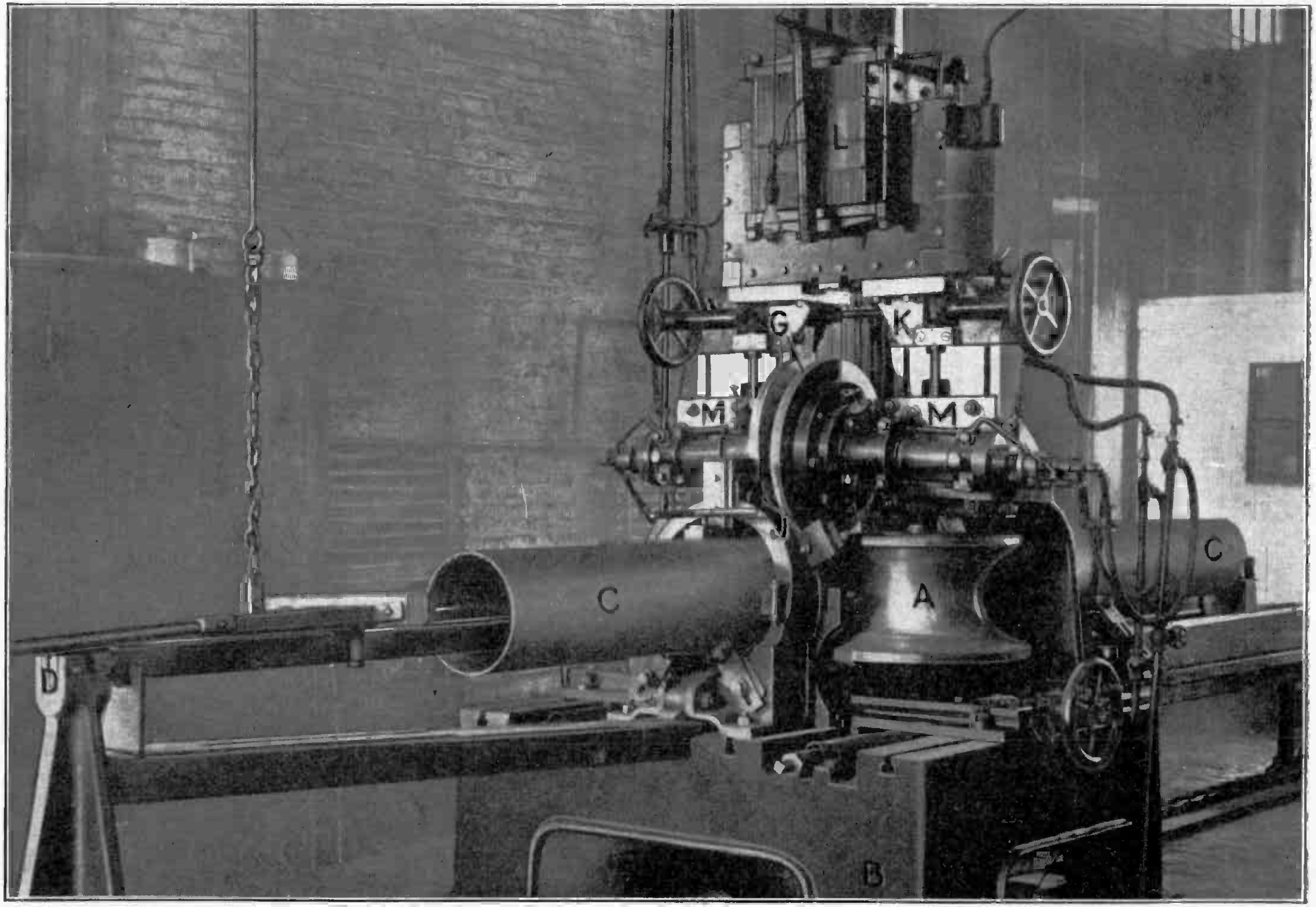


Fig. 36. Electric-Welding Machine with a Shell in Starting Position and One at Finished Position.

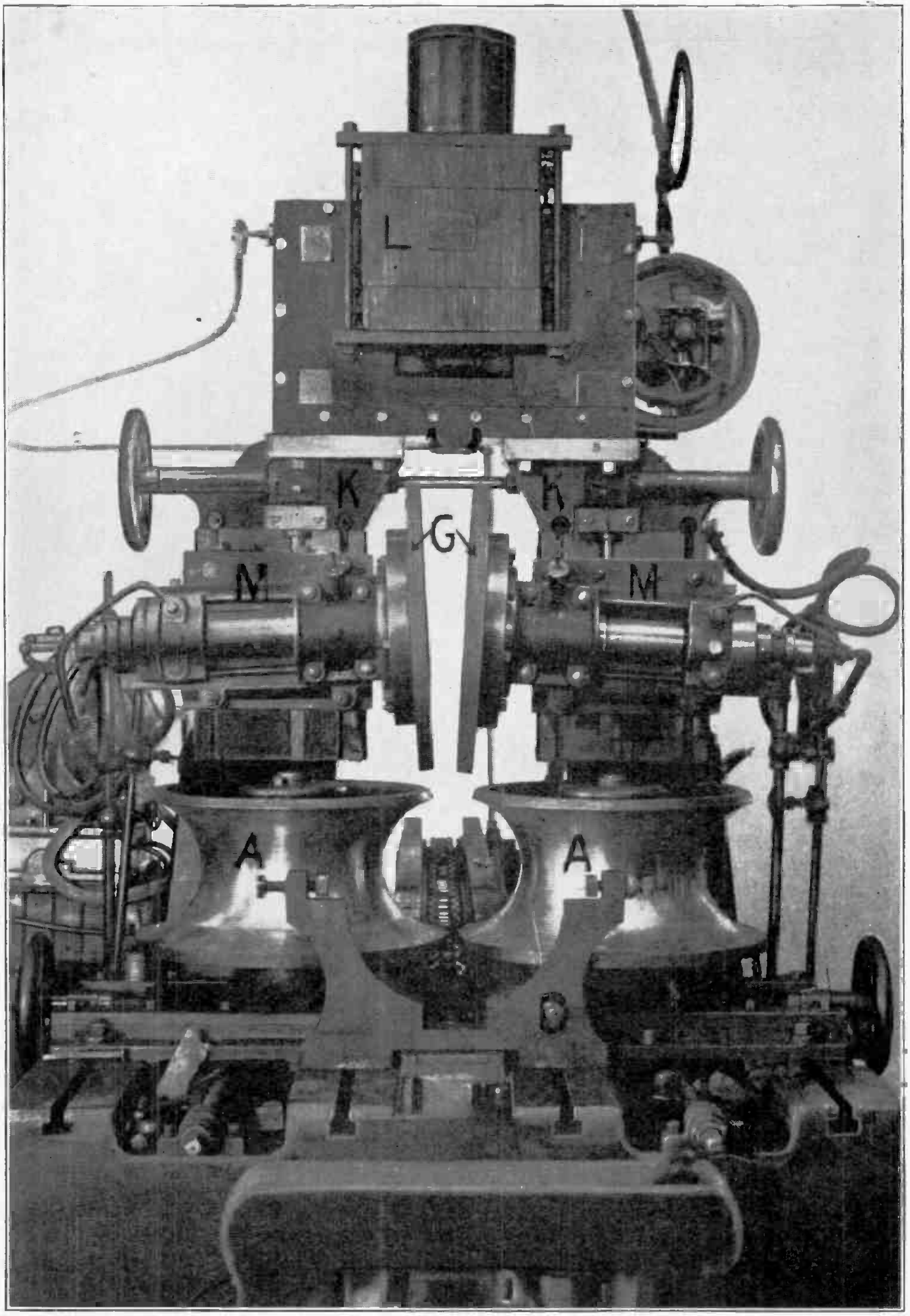


Fig. 37. Front of Electric-Welding Machine with Yoke Removed.

bench, and having an endless chain *H* carried on pulleys at either end of a planed guide between which the chain runs.

The chain is attached to a carriage *I* provided with a gripping device which grips and draws the boiler shell between the pressure rolls during the welding operation. In front of the machine and secured to the base is a yoke *J*, Figs. 34 and 36, through which the boiler shell passes on its way to the pressure rolls and welding electrodes. The object of this yoke is to guide the shells and keep the joint exactly equidistant from each electrode during the welding operation, as the success of the weld depends to a great extent on the seam being guided in a straight line and half way between the electrodes. The yoke is provided at the top on the side next the machine with a thin blade of steel—not visible in the half-tone—which locates the boiler shell by the edges which pass one on either side of it. The yoke and other controls for the boiler shells are all within easy access of the operator.

Owing to the extreme flexibility of these thin boiler shells the adjustments and movements of the electric welding machines must of necessity be very exact and under instant and absolute control; a boiler shell 6 feet long taking but 22 seconds to weld from end to end does not permit of cut-and-try methods of adjustment.

Mounted on the base is the main frame *K* of the machine which carries at the top the transformer *L*, which is of the Thomson type. The primary circuit varies as previously stated, from 250 to 350 volts, depending on the character of the work; the transformer steps it down to from 25 to 45 volts, this also being governed by the character of the work.

The current is led from the transformer to the rotary electrodes *G* secured by bolts to gun-metal spindles approximately 4 inches in diameter, which run in gun-metal boxes in the heavy gun-metal saddles *M*. The saddles *M* are insulated from the cast-iron frame *K* of the machine by sheet mica, approximately $\frac{3}{16}$ inch thick.

The spindles which carry the electrodes are hollow to permit a circulation of cooling water which passes through the transformer and both spindles of each machine. The piping and valves show plainly in all the views. The cooling is necessitated by the heavy amperage, in the neighborhood of 24,000 amperes being required for electric welding.

The current passes from the saddles to the spindles or *vice versâ* at the point of contact, and among these points of contact are the two bearings. When the bearings become worn, slight sparking is liable to occur which has the tendency to make the bearings cut. But in spite of this sparking and the fact that gun metal and gun metal do not run well together, these bearings run from 12 to 14 months without renewing. When it does become necessary to renew the bearings, the spindle is so made that a new sleeve of gun metal can be driven on the spindle proper after the worn one is removed and the half bearings in the saddle and cap are readily replaced.

The electrodes *G* are copper disks secured to a flange on the spindle ends by tap bolts from the back. They are $1\frac{1}{4}$ inches thick, and about 26 inches in diameter. The spindles are inclined at such an angle that the electrodes, where they are nearest to each other, are about $\frac{1}{4}$ inch apart. This is at the point in contact with the boiler shell, and at this point the welding is performed. On the opposite side the disks are about $2\frac{1}{2}$ inches apart.

The operation of the machine is as follows: The rolled boiler shells are lifted into the front of the machine with the seam up, as shown in Fig. 36, passed through the yoke, the small blade mounted on the yoke passing between the edges at the seam and locating the shell so that it will pass through with the seam equidistant between the two electrodes. The shell is then gripped by the clamp on the carriage *I*, Fig. 35, at the back of the machine and the draw bench started. This draws the shell backward between the pressure rolls and under the electrodes. The moment the seam strikes the electrodes, the current is switched on and the weld starts. As no instruments are used to determine the heat at point and time of weld, I cannot give any exact figures but a reasonable guess would place the temperature at about 2,800° F. The two edges are pressed together by the pressure rolls and the semi-fluid metal forms on the outside of the seam in the shape of a half-round bead running the full length of the welded shell.

From putting one 5-foot shell in until the putting in of the next, the elapsed time is about one minute, the actual welding taking but 22 seconds. The shell is red hot for a space only about $\frac{3}{8}$ inch in width, and the blue color caused by the heat extends for less than an inch on each side of the weld. During the welding operation one can put one's finger on the shell 2 inches back from the red-hot weld and not feel that it is warmer than the surrounding atmosphere.

Owing to the shape and pressure applied to the shell by the electrodes and the roller on the inside of the shell, the finished product as it comes from the welder is out of round, being approximately as shown in Fig. 38, *A* being the weld, *A B* and *A C* are flat. The shells after leaving the welding machine, and previous to putting in the upper head, are rounded up to make them nearly true cylinders. This job is done very rapidly on a special machine built in the works.

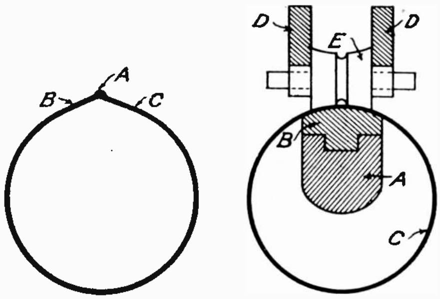


Fig. 38. Fig. 39.
Section of Shell and Rounding-Up Machine.

This rounding-up machine—shown partly in section in Fig. 39—has a horizontal stake *A* with a planed surface on top to which various sized dies *B* can be readily fitted, the dies conforming to the inside curvature of the boiler shells *C* and being of a length greater than the longest boiler shell.

On either side of and above the stake are a pair of guides *D*, and at the front and back of the machine are a pair of idlers over which travel two parallel endless chains which are driven by a $7\frac{1}{2}$ horse-power motor. These carry a rounding-up roll *E* conforming to the outside curvature of the boiler. The operation is as follows: The boiler shell is placed on the die on the stake with the welded seam up. The clutch is then thrown in and the rounding-up roller *E* is drawn by the chains on either side along the seam, guides *D* on top forcing it against the outside of the distorted boiler shell. One pass is sufficient to bring the shells to perfect cylindrical shape.

So far only the electric-welded shells have been referred to, but as I wish to compare them with riveted and oxyacetylene welded shells, I will state briefly the methods by which these two varieties of shell are produced. The sheets for the riveted shells are punched in the flat at both ends, but two strokes of a multiple punch being necessary. The rivets used are $\frac{3}{8}$ inch in diameter and $\frac{3}{4}$ inch pitch. The sheets are then rolled to cylindrical shape, riveted, and then the seam is brazed. This takes about five minutes of time and 1½ pounds of brass at 13½ cents a pound.

The subsequent operations on these boilers are practically the same as those on the electric welded ones. The oxyacetylene flame has been described so many times that a repetition is not necessary here. The John Wood Manufacturing Company has a complete installation with two complete generating plants for oxygen and one for acetylene. They use it for welding heads to shells where this is ordered, but it requires too much space to apply to long seams.

Many tensile and vibratory tests have been made of electric welds made by this concern in various ways, plain butt welds, heavy butt welds—in which the plates were forced together so that a large amount of molten steel was raised on either side—and lap welds.

The percentage of defective welds made with the electric welding machine is about 0.1 per cent. In not one single case has an electric weld pulled apart at the weld. No piece tested has shown

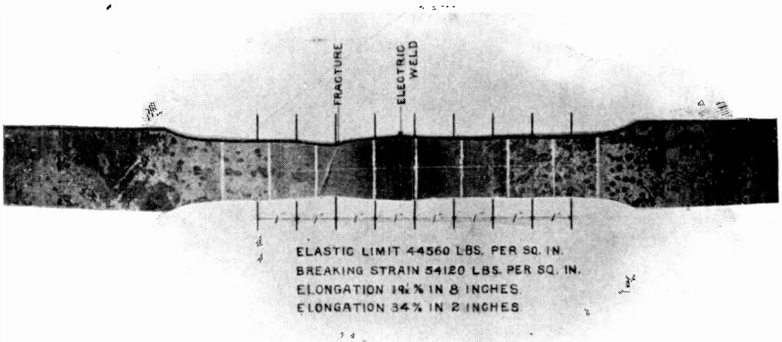


Fig. 40. Typical Electric-Welded Test Bar.

any crystallization either at the weld or at any place within the influence of the heat. All test pieces pulled apart at a point beyond the influence of the heat.

The oxyacetylene-welded test pieces show a crystalline fracture, and, while the sectional area in the gas weld is increased 50 per cent, one of the test pieces failed partly in the weld. The tensile strength of the gas weld is good, but it does not stand up well under the vibratory test. The riveted and riveted and brazed seams invariably pull apart at the rivets. Fig. 40 shows a typical test bar, the fracture occurring beyond the influence of the heat.

Table VI shows a series of tests giving about average results. The plain riveted and riveted and brazed seams both failed at the

TABLE VI

Tests of Riveted, Riveted and Brazed, Gas-Welded, and Electric-Welded Seams

Test No.	Section, Orig.		Area, Orig.	Elastic Limit, Per Sq. In.	Ultimate, Per Sq. In.	Elongation. Per Cent In.		
						8″	2″	
1	2.66	0.084	0.223	43,230	45,520	2.5	7.0	Plain riveted
3	2.82	0.100	0.282	37,450	56,210	13.8	15.0	Riveted and brazed
5	2.30	0.085	0.195	45,800	59,640	17.0	26.0	Gas welded
7	1.923	0.081	0.156	42,570	50,130	2.0	5.0	Electrically welded
10	1.922	0.080	0.154	47,670	64,420	20.5	36.0	

rivet holes. The gas weld failed partly at the weld and then the fracture ran at an angle. The electric welds failed beyond the part heated by the electrodes.

Comparing the costs of the three methods of making the longitudinal seams, taking the electric weld as 1, the gas weld would be about 7.5, and the riveted and riveted and brazed seams about 10.

REVIEW QUESTIONS

REVIEW QUESTIONS

ON THE SUBJECT OF

ELEMENTS OF ELECTRICITY AND MAGNETISM

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1. Explain, from the standpoint of induced magnetization, the process by which a magnet attracts a piece of soft iron.

2. What are the differences in the magnetic behavior of soft iron and hard steel?

3. What is meant by a magnetic line of force?

4. What reasons have we for thinking that magnetization is a molecular phenomenon?

5. State how you would test the sign of an unknown charge of electricity by means of the gold-leaf electroscope.

6. Describe the process of charging an electroscope by induction.

7. In charging an electroscope by induction, why must the finger be removed before the removal of the charged body?

8. If you hold a brass rod in your hand and rub it with silk, the rod will show no sign of electrification; but if you hold the brass rod with a piece of sheet rubber and then rub it with silk, you will find it electrified. Explain.

9. Why is a pith ball attracted to an electrified rod and then repelled from it?

10. What differences can you mention between magnetism and electricity?

11. Explain the principle of the condenser.

12. Explain the principle of the lightning rod.

13. Why is the capacity of a conductor greater when another conductor connected to the earth is near it than when it stands alone?

14. Why cannot a Leyden jar be appreciably charged if the outer coat is insulated?

15. If the potential difference between the terminals of a cell on open circuit is to be measured by means of an instrument consisting of a coil and magnet, why must the coil have a very high resistance?

16. How much current will flow between two points whose P. D. is two volts, if they are connected by a wire having a resistance of ten ohms?

17. If a voltmeter placed across the terminals of an incandescent lamp shows a P. D. of 110 volts, while an ammeter connected in series with the lamp indicates a current of .5 ampere, what is the resistance of the incandescent filament?

18. If a certain Daniell cell has an internal resistance of 2 ohms and an E. M. F. of 1.08 volts, what current will it send through an ammeter whose resistance is negligible? What current will it send through a copper wire of 2 ohms resistance? Through a German silver wire of 100 ohms resistance?

19. A Daniell cell indicates a certain current when connected to a galvanometer of negligible resistance. When a piece of No. 20 German-silver wire is inserted in the circuit, it is found to require a length of 5 ft. to reduce the current to one-half its former value. Find the resistance of the cell in ohms, No. 20 German-silver wire having a resistance of 190.2 ohms per 1,000 ft.

20. Why is a Daniell cell better than a bichromate cell for telegraphic purposes?

21. Why is a Leclanché cell better than a Daniell cell for ringing door-bells?

22. If the internal resistance of a Daniell cell of the gravity type is 4 ohms, and its E. M. F. 1.08 volts, how much current will 40 cells in series send through a telegraph line having a resistance of 500 ohms? What current will one such cell send through the same circuit? What current will 40 cells joined in parallel send through the same circuit?

23. What current will the 40 cells in parallel send through an ammeter which has a resistance of .1 ohm? What current would the 40 cells in series send through the same ammeter? What current would a single cell send through the same ammeter?

REVIEW QUESTIONS

ON THE SUBJECT OF

THE ELECTRIC CURRENT.

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1. (*a*) Explain what is meant by electromotive force. (*b*) What is its unit of measurement, and by what value is it represented?

2. (*a*) What is necessary to cause an electric current to flow? (*b*) What is meant by the strength of a current? (*c*) What is its unit of measurement, and by what value is it represented?

3. What is the unit of resistance and by what value is it represented?

4. Upon what three general factors does resistance depend?

5. What length of copper wire 2 millimeters in diameter will have the same resistance as 12 yards, 1 millimeter in diameter?
Ans. 48 yards.

6. State Ohm's law.

7. Two wires, whose resistances are respectively 28 and 24 ohms, are placed in parallel in a circuit so that the current divides, part passing through each. What resistance is offered by them to the current? Ans. 12.92 + ohms.

8. Fifty Grove's cells (E. M. F. = 1.8 volts) are in series, and united by a wire of 15 ohms resistance. If the internal resistance of each cell is .3 ohm, what is the current? Ans. 3 amperes.

9. (*a*) What is the unit of quantity of electricity? (*b*) Define the ampere-hour.

10. What is the power in watts when 4000 joules of work are done in 50 minutes? Ans. 1.33 + watts.

11. How many horse-power are equivalent to 83 kilowatts?
Ans. 111 + horse-power

12. What is a shunt circuit?

13. A current of 18 amperes flows in a circuit whose resistance is 116 ohms. What is the voltage? Ans. 2088 volts.

14. The resistance of 312 feet of a certain wire is 2.08 ohms. What would be the resistance of 240 feet of the same wire? Ans. 1.6 ohms.

15. A total current of 56 amperes passes through a divided circuit having the resistance of its branches equal to 28 and 4 ohms respectively. What is the current in each branch?

Ans. In the 28-ohm branch, 7 amperes.
In the 4-ohm branch, 49 amperes.

16. What is the value of the current when 4 ampere-hours are delivered in a circuit in 20 minutes? Ans. 12 amperes.

17. (*a*) Define the joule. (*b*) Define the watt.

18. A 220-volt circuit supplies a current of 18 amperes. What is the power in kilowatts? Ans. 3.96 K. W.

19. If the resistance of a certain wire is 2.3 ohms per 1000 feet, how many feet of the wire will be required to make up a resistance of 17.8 ohms? Ans. 7739 + feet.

20. What is the resistance of a wire having a diameter of .2 inch if the resistance of the same length of similar wire having a diameter of .04 inch is 64.2 ohms? Ans. 2.56 + ohms.

21. Define specific resistance.

22. The resistance of a circuit is 1.8 ohms and the voltage is 110. What is the current? Ans. 61 + amperes.

23. A circuit contains a voltaic cell generating an electromotive force of 1 volt. Its electrodes are connected by three wires in parallel of 2, 3, and 4 ohms resistance respectively. The resistance of the cell is $\frac{1}{13}$ ohm. What is the current?

Ans. 1 ampere.

24. Eight cells each having an E. M. F. of .9 volt and an internal resistance of .6 ohm are connected in parallel, and the external resistance is 3.4 ohms. Find the current.

Ans. .26 ampere (approx.).

25. What quantity of electricity will be conveyed by a current of 40 amperes in half an hour? Ans. 72,000 coulombs.

26. The resistance of a circuit is 10 ohms, and the current is 33 amperes. What is the power in watts? Ans. 10,890 watts.

27. How many watts are equivalent to 14 horse-power?
Ans. 10,444 watts.

28. Five conductors having resistances respectively equal to 14, 3, 20, 31 and 8 ohms are joined in series, and the E. M. F. applied to the circuit is 50 volts. What is the current?
Ans. .65 amperes.

29. (*a*) Define conductance. (*b*) Define conductivity.

30. What is the resistance of 10 feet of annealed gold wire .001 inch in diameter at 32° F., if the resistance of an inch cube of the substance at 32° F. is .8079 microhm? Ans. 123 + ohms.

31. A copper wire has a resistance of 13.5 ohms at 43° F. What is its resistance at 57° F? Ans. 13.91 + or nearly 14 ohms.

32. What must be the resistance of a 220-volt circuit if the current is to be 70 amperes? Ans. 3.14 + ohms.

33. The E. M. F. applied to a circuit is 582, and the current is 8 amperes. A number of lamps connected in the circuit require a total drop of 522 volts. Find the resistance of the remaining portion of the circuit. Ans. 7.5 ohms.

34. A circuit is made up of six wires connected in parallel and having resistances of 72, 60, 21, 36, 40 and 210 ohms respectively. Find their joint resistance. Ans. 7.3 + ohms.

35. When a cell, which has an internal resistance of 1.39 ohms and an E. M. F. on open circuit of 1.32 volts, is supplying a current of .29 ampere, what is its available E. M. F.?
Ans. .92 volts (approx.).

36. With a current of 20 amperes how much time will be required to deliver 4,000 coulombs. Ans. 3 minutes, 20 seconds.

37. The voltage of a circuit is 103 and the current is .5 ampere. What energy is expended in a minute and a half?
Ans. 4635 joules.

38. The resistance of a coil of platinoid wire at 98° C. is 3014 ohms. What resistance would the coil have at 18° C.?
Ans. 2962 ohms (approx.).

39. What is the resistance of 28 feet of No. 6 (B. & S.) pure copper wire at 90° F.? Ans. .0118 + ohm.

40. If a resistance of 116 ohms be inserted in a circuit, and it is desired to maintain a constant current of 9.6 amperes, how much must the voltage of the circuit be increased?
Ans. 1113 + volts.

41. When a current of 14 amperes flows in a circuit whose resistance is 54 ohms, what energy in kilowatt-hours is expended in half an hour? Ans. 5.292 kilowatt-hours.

42. Explain the difference between the kilowatt and the kilowatt-hour.

43. What number of calories will be developed by a current of .14 ampere flowing through a wire of 4 ohms resistance for 5 minutes? Ans. 5.6 + calories.

44. The voltage applied to a circuit in which three wires are connected in parallel is 107. Find the current in each branch if the separate resistances are respectively 43, 9 and 25 ohms.

Ans. In 43-ohm branch, 2.4 + amperes.
In 9-ohm branch, 11 + amperes.
In 25-ohm branch, 4.2 + amperes.

45. How many horse-power are equivalent to 1048 watts? Ans. 1.4 + horse-power.

46. If the resistance of 1 foot of annealed silver wire .001 inch in diameter at 32° F. is approximately 9.02 ohms, what is the resistance of 4 miles of the wire .01 inch in diameter at a temperature of 90° F.? Ans. 2137 + ohms.

47. Twenty large Leclanche cells (E. M. F. = 1.5 volts, resistance = 0.5 ohm each) are in a circuit in which the external resistance is 10 ohms. Find the strength of current which flows (*a*) when the cells are joined in series; (*b*) when all the cells are in parallel; (*c*) when there are 2 files each having 10 cells in series; and (*d*) when there are 4 files each having 5 cells in series.

Ans. Amperes (*a*) 1.5; (*b*) 0.149; (*c*) 1.2; (*d*) 0.706.

48. How many kilowatts are equivalent to 150 horse-power? Ans. 111.9 K. W.

49. If a current of 9.3 amperes flows when the voltage of a circuit is 110, how much resistance must be inserted in the circuit to reduce the current to 3.4 amperes? Ans. 20 + ohms (approx.).

50. A current of 26 amperes is flowing in a circuit which has a voltage of 500. What is the equivalent power in mechanical units? Ans. 17.4 + horse-power.

REVIEW QUESTIONS

ON THE SUBJECT OF

ELECTRICAL MEASUREMENTS

PART I.

1. What is the distinction to be made between fundamental and derived units? Give examples of each.

2. Describe briefly the different types of galvanometers and explain wherein they differ and the advantages of each.

3. Voltmeters and ammeters are really *galvanometers*. Why do they fall into this class and to which type do they belong?

4. Explain the *lamp and scale* and the *telescope and scale* methods of reading galvanometer deflections.

5. Describe the control magnet as used with needle galvanometers and explain its function.

6. Describe and explain the electrodynamometer and the wattmeter. How do they differ?

7. Describe the rheostat. What materials may be used for the resistance?

8. How do resistance coils differ from the rheostat mentioned in Question 6? What material is generally used for accurate resistance units and why?

9. Describe and explain the use of shunts for galvanometers.

10. Explain the Wheatstone's bridge. Describe the two usual forms of the bridge.

11. Make the usual "diamond" diagram of the connections of a bridge and find the value of X when $M = 1{,}000$, $N = 10$, and $P = 3{,}247$.

12. Describe a good method for measurement of a low resistance.

13. Describe good methods for measurement of a fairly high resistance.

14. How do you measure a *very* high resistance?

15. Describe the method for finding the place where a telephone line is grounded.

16. Describe a good method of measuring the resistance of a cell.

17. Describe the potentiometer method of measuring the e. m. f. of a cell. Why is this method best?

18. What is a standard cell and what are the requisites of such a cell?

19. Describe the Weston standard cell. Does its e. m. f. rise or fall with rise of temperature, and how much per degree Centigrade?

20. Describe the lead storage cell. What is its e. m. f. when charged, and when discharged? What materials are used for the positive and the negative plates and for the solution?

REVIEW QUESTIONS

ON THE SUBJECT OF

ELECTRICAL MEASUREMENTS

PART II.

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1. Describe the ballistic galvanometer and explain why its period of swing should be long.

2. Describe a condenser, mentioning materials used, method of connection, etc. What is the *unit of capacity* in which condensers are rated?

3. Make a diagram of connections for the direct-deflection method of comparison of capacities of condensers.

4. Describe and explain either the bridge method or the method of mixtures for comparison of capacities of two condensers.

5. If in question 4, $R_1 = 2{,}100$, $R_2 = 1{,}000$, $C_1 = 0.2$, what is C_2?

6. Describe the alternating-current method of determination of the capacity of a condenser.

7. What is *self induction?* What is *impedance* and how is it expressed in terms of resistance and inductance?

8. Describe the alternating-current method of measuring an inductance.

9. What is a *variable standard of self inductance* and how is its inductance varied?

10. Describe the bridge method of comparison of two self inductances, one being variable.

11. Show how a capacity is compared with a self inductance by the condenser method.

12. What is *mutual induction* and why is it so called?

13. Describe the ballistic galvanometer method of measuring mutual inductance.

14. How is the constant of the ballistic galvanometer determined?

15. Describe the alternating-current method for mutual inductance.

16. What is supposed to happen to a piece of steel to make it a magnet? How are magnets made? What materials are decidedly magnetic?

17. What is the *line of no variation?* What is *magnetic dip?* About how much is the magnetic dip in Chicago?

18. Describe one method of measuring magnetic dip.

19. Describe the magnetometer method of measuring the horizontal component of the earth's magnetic field.

20. What do you understand by **B**, **H**, and μ? How are Φ and B related?

21. What is *magnetomotive force?* What is *reluctance?* What is *hysteresis?*

22. Describe either the divided bar method or the ballistic method of measuring magnetic flux.

23. Draw a hysteresis curve and explain a method of getting the necessary data for such a curve.

24. Describe Professor Ewing's magnetic hysteresis tester and explain its use.

REVIEW QUESTIONS

ON THE SUBJECT OF

ELECTRIC WIRING

1. Explain the three-wire system of wiring.

2. In case a test shows excessive leakage, or a ground or short circuit, how would you locate the trouble and remedy it?

3. Describe the construction and use of outlet-boxes.

4. What is the principal difference between alternating and direct-current circuits, so far as concerns the wiring system?

5. Compare the advantages of the two-wire and three-wire systems of wiring.

6. Under what general heads are approved methods of wiring classified?

7. A single-phase induction motor is to be supplied with 25 amperes at 220 volts; alternations 12,000 per minute; power factor .8. The transformer is 200 feet from the motor, the line consisting of No. 4 wire, 9 inches between centers of conductors. The transformer reduces in the ratio $\frac{2{,}500}{250}$, has a capacity of 30 amperes at 220 volts, and, when delivering this current and voltage, has a resistance-E. M. F. of 2.5 per cent, and a reactance E. M. F. of 5 per cent. Calculate the drop. (Use table and chart.)

8. What are the distinctive features of the different kinds of metal conduit?

9. Suppose power to be delivered, 300 K. W.; E. M. F. to be delivered, 2,200 volts; distance of transmission, 15,000 feet; size of wire, No. 00; distance between wires, 24 inches; power factor of load, .7; frequency, 100 cycles per second. Calculate line loss and drop in per cent of E. M. F. delivered. (Use table and chart.)

10. In installing A. C. circuits, what requirements are insisted on as to the placing of conductors in conduits?

11. Describe the manufacture, use, and special advantages of the different kinds of armored cable.

12. Describe three different methods of testing? Which is to be preferred?

13. What conditions determine whether a two-wire or three-wire system of wiring should be used?

14. In locating cut-out cabinets and distributing centers, what requirements should be fulfilled?

15. What is "knob and tube" wiring? Explain its use and discuss its advantages or disadvantages.

16. How far apart should exposed-wiring insulators be placed?

17. What tests should be made before an electric wiring equipment is finally passed for acceptance? Give reasons.

18. What regulations govern the use of fibrous tubing?

19. What is meant by mutual induction?

20. What are the advantages and disadvantages of overhead linework as compared with underground linework?

21. Describe and illustrate by sketches proper methods of supporting and protecting exposed-wiring conductors.

22. Discuss the advantages of running conductors exposed on insulators.

23. Illustrate by diagram, proper and improper methods of grouping conductors of two two-wire circuits.

24. What dangers are inherent in the use of moulding? What precautions should be taken to avoid them?

25. Describe the proper methods of laying out branch circuits, (*a*) in fireproof buildings; (*b*) in wooden frame buildings. Give sketches.

26. What methods of installing wiring are best adapted for the following classes of buildings, (*a*) fireproof structures; (*b*) mills, factories, etc.; (*c*) finished buildings; (*d*) wooden frame buildings?

27. What is skin effect? Its bearing on the problem of wiring?

28. In selecting runways for mains and feeders, what precautions should be taken?

29. Describe the method of laying (1) vitrified conduit; (2) fibre conduit.

30. Give sketches showing proper and improper methods of guying poles.

REVIEW QUESTIONS

ON THE SUBJECT OF

ELECTRIC WELDING

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1. What are the three general methods of electric welding?

2. Make sketch of simple electric crucible.

3. Describe method of heating metal electrically in a bucket of strong brine.

4. What are some of the serious objections to welding in a forge fire that are overcome in the electric welding process?

5. Describe and explain the action of the current in automatically raising all parts of the joint to the same temperature when welding by the Thomson process.

6. Why is it economical to use as low a voltage as possible when welding by the Thomson method?

7. Why is it difficult to weld a piece of small cross section to one of larger section?

8. What are the particular advantages of electric welding of rails on electric traction roads?

9. Describe a welding train for track welding.

10. What is the cost for power (approximately) for making a welded joint in a rail such as described in the text? Assume that the grinding and sand blast apparatus are running practically continuously and just keep up with welder, and that the cost of current is 3 cents per K. W. hour.

11. What would be the cost of electrically welding rails 7″ girder type per mile of new track, at the usual contract price per joint, 60′ rails to be used and no allowance to be made for street work?

12. How can a bar be heated at one end only, in a Thomson welder?

what would be the power required to weld a wrought iron bar $1\frac{3}{4}''$ in diameter.

14. What are the advantages of using an automatic welder when working with metals such as brass, which crumble easily when heated?

15. If 150 welds per day of 8 hours are made in steel bars 2″ square, what is the cost per weld for power and labor? Calculate the cost of power as applied to dynamo. Assume power required as shown in Table IV, calculate 10% loss in dynamo, cost of labor as 35 cents per hour, and cost of current delivered by dynamo as $3\frac{1}{2}$ cents per K. W. hour.

16. What is the advantage of using alternating current, rather than direct, for welding by the Thomson process?

17. Describe Arc method of cutting a steel beam in two.

18. What is the difference between the Direct and Indirect methods of welding?

19. What is the cost per gross for labor and power for welding steel rings made of $\frac{1}{2}''$ round stock under the following conditions? Labor cost, 30 cents per hour; power cost, 3 cents per H. P. hour delivered to dynamo; time and power to be taken as given in Table IV, and *total* time for each ring to be assumed as twice the length of time that current is used for welding.

20. What is the elementary electrical principal on which all electric heating and welding is based?

21. What is the electric blowpipe?

22. Describe a high voltage method of welding.

23. What is the difference between a "hand" electric welding machine and an "automatic" welder?

24. What voltage should be used in welding copper?

25. Why does the electric current tend to travel through the part to be welded rather than around the solid metal, when welding a small ring or link on a Thomson welder?

26. Why does it require a larger horse power in proportion to weld a thin small section than a heavy thick one?

27. Should a static transformer or a rotary converter be used on rail welding when the current comes from the trolley circuit?

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