A PRIMER
OF ELECTRONICS

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A PRIMER
OF ELECTRONICS

BY

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A PRIMER OF ELECTRONICS

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To My Father

ROBERT W. CAVERLY

FOREWORD

There are today, in the electrical industry, thousands of men and women who, not being engineers, know little or nothing about the products with which they deal. This book is written for them—the salesmen, store clerks, stenographers and, in fact, all persons who would like to know a little of the basic principles behind some of the common electrical devices in everyday home and commercial use. A deliberate effort has been made to remove the complex technical aspects with which electrical engineers and physicists must deal and which quite naturally make the non-technically trained person shy away.

Man has crossed the threshold of a vast realm in which electricity will serve him to an almost inconceivable extent. Electric light and power, the telephone and the radio are firmly established in the lives of everyone. Television for all homes is receiving its final grooming and is ready to come out of the laboratories. These accomplishments are accepted by the average person, without thought or understanding.

We hear a great deal today about electronics. No one knows to what extent electron tubes and devices will affect our lives in the near future. The war brought many of them out of the laboratories and into practical use as vital weapons. Soon they and many others will find practical uses to ensure peace and bring untold wonders into the fields of communication, education, entertainment and commerce. Hints of what is to come are found every day in the magazine advertisements of electrical manufacturers.

The thread of electronics has been woven through the entire text, so that even though some fields through which the reader passes may seem irrelevant, this thread will serve as a guide line to bring him back to the purpose for which the story is written—to give the average man a basic understanding of how that infinitesimal servant the electron works for him.

DON CAVERLY.

MARBLEHEAD, MASS.,
November, 1943.

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A PRIMER OF ELECTRONICS

AUTHOR'S NOTE

At the outset it might be well to note that previous teachings explain electric current as flowing from positive to negative. This explanation has been the basis of certain established fundamental rules governing the direction of electromagnetic forces and of motor or generator rotation. However, with the development of an understanding of electrons as basic negative charges, it becomes evident that they must flow in the opposite direction —toward positive—so that current flow is generally thought of as going in one direction, but electron flow in the other. Therefore, in order to avoid confusion the author has chosen to refer to current flow rather than to electron flow, so that the old rules can be applied for clearer explanations. The reader may, if he wishes and if it is not confusing, remember that the electrons are flowing the other way whenever the direction *of electric current flow is mentioned in Parts I and II. In Part IV, electron flow is described more in detail.*

Part I

ELECTRIC CURRENT

CHAPTER 1

What Does Electronics Mean?

Once upon a time not so long ago, there was a sales meeting. The group of men present were discussing what all business groups discuss—the future progress of their company and what they, as salesmen, would be called upon to sell. The company they represented to the buying public manufactured light sources and equipment, radio tubes and other types of vacuum and gaseous discharge tubes for communication, detection and similar purposes.

The word *electronics* popped up frequently until finally someone asked, "Just what is *electronics?* If we are going to deal with electron tubes and devices utilizing them, we need to know a great deal more about them."

The word *electronics* has received a tremendous amount of attention during the past few months, and it may be destined for some abuse by being applied where it does not appear to belong. On the other hand, a simple candle could technically be called an electronic device since it involves electrons in motion and a consequent physiochemical change. It would seem, however, that the science of electronics may deserve a category of its own, even though there appears to be no sharp dividing line between an electronic and a non-electronic device.

The word *electron* is a noun applied to the basic element of electric charge. The American Standards Association defines an electron as " . . . the natural, elementary quantity of negative electricity," and electronics as " . . . that branch of science and technology which relates to the conduction of electricity through gases or in vacuo."

Perhaps, then, we can more properly apply the word *electronic* to a device or tube which is deliberately designed to make use of electron emission, rather than to one in which the electronic characteristics are more or less incidental. Within the electronic category would come radio tubes, fluorescent lamps and a great many other vacuum or gaseous discharge tubes in the field of communications, surgery and general industry.

Basic Substance—the Electron.

All substances are composed of atoms—infinitesimally small particles of matter, something less than a hundred-millionth of an inch in diameter. They are not necessarily solid spheres or cubes, but rather might be considered as little knots of balanced energy. They have a central kernel or nucleus which is made up of a preponderance of positively charged particles around which negative charges, called *electrons*, rapidly revolve in much the same way that the planets revolve around the sun. This theory of atom structure was developed by Dr. Niels Bohr, a Danish scientist, who first brought it to the attention of physicists in 1913.

These inconceivably small whirling systems make up all matter. The fundamental difference between one element and another is in the number of electrons revolving around the nuclei of its atoms. A hydrogen atom, for instance, has only one electron revolving about its nucleus, whereas a helium atom has two; carbon, six; oxygen, eight; and so on for each of the elements thus far discovered. A mercury atom has 80 electrons swarming around its nucleus, and a few other elements have still more. The smallest unit of an element or compound which retains the identity or character of the solid or fluid substance, is a cluster of atoms called a *molecule*. The water we drink, for instance, is composed of two parts of the element hydrogen and one part of the element oxygen; that is, its molecule consists of two hydrogen atoms and one oxygen atom. It is expressed chemically as H_2O.

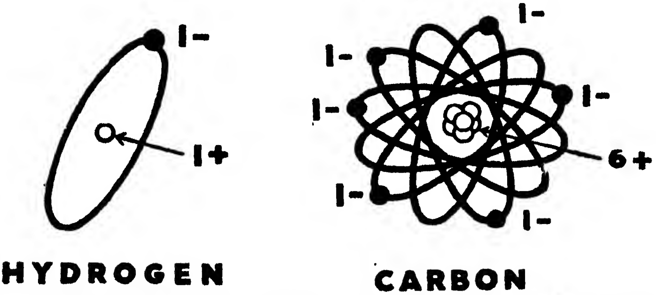


FIG. 1.—Atomic structure, as seen in the simple atom of hydrogen, left, where one electron revolves around one positively charged nucleus of one proton, and in the complex carbon atom, right, where six electrons swarm about a nucleus of six protons.

The charge of each individual electron is always the same, regardless of its source. In an ordinary electrically neutral atom, the total positive charge of the nucleus or core is equal to the total negative charges of the planetary electrons around it. Although this book adheres, for the sake of simplicity, to the theory that electrons are pure or basic negative charges, the true nature of the electron is not definitely established. They have weight and mass, but their solid form, if any, is not clearly understood. One ounce of electrons would contain about 30 billion billion billion of them.

The Theory of Electric Current.

Since all substances are made up of atoms, all must contain electrons because they are a part of the atoms.

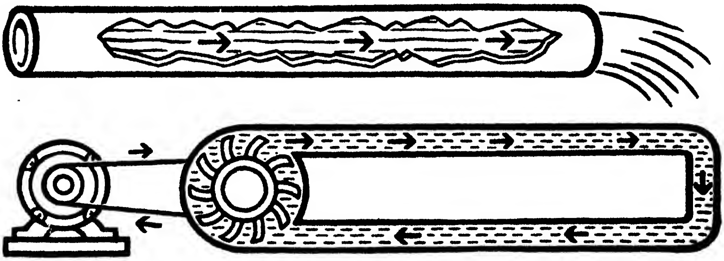


FIG. 2.—Electrons flowing along a conductor may be compared to the action of water flowing through a pipe. Direct current flows like water from a centrifugal pump, through a continuous loop of pipe back to the pump.

However, there are also in all materials varying amounts of so-called *free electrons*, which are not bound tightly to atoms, but which are free to move about in all directions from one atom to another. The fact that their speed may be stimulated by the application of additional energy, such as heat, will be touched upon later. In certain kinds of atoms some of the electrons can be moved relatively easily from atom to atom. Such substances are called *electrical conductors* and include copper, aluminum, iron and many other metals, compounds and liquids. In other atoms, the electrons are more tightly bound to the atom. Therefore, such substances as rubber, mica, paper and oil are non-conductors because they greatly impede the flow of electricity.

Thus in a copper wire, electrons move at random in every direction within the metal. When in addition to this motion there is a definite drift of electrons along the conductor, an electric current is said to be *flowing*. This flow of electric current may be compared to the flow of water in a pipe. The force that starts these electrons moving in one direction is called an *electromotive force* (E.M.F.) and will be considered more in detail later.

Direct current always flows in the same direction. Its flow may be compared to the flow of water from a centrifugal pump—through a continuous loop of pipe and back to the pump.

Fig. 3.—The *discovery* of electricity by Thales about 2,500 years ago was based on the ability of amber, when rubbed with flannel, to pick up various light-weight objects.

Early Observations and Natural Electrical Phenomena.

The Greeks had a word for electricity. It was *elektron*, which translated means amber. Thales of Miletus, an ancient Greek philosopher, is said to have been the first to observe that an amber rod, when rubbed, would attract straws and other light objects. This simple experiment performed 2,500 years ago marks the first time man became aware of electricity. Today, every woman is familiar with a similar phenomenon when her silk slip clings to her dress, and all office workers know how a sheet of paper sticks to the surface of the desk if it is rubbed vigorously a few times and how it will even crackle when lifted from the desk.

When a glass rod is rubbed with dry flannel, friction transfers some electrons from the flannel to the glass rod. The rod becomes *negatively* charged because it has acquired a surplus of electrons, and the flannel becomes *positively* charged because of a deficiency of them. If the same thing is done again with another rod and flannel, it will be found that the rods, if suspended on a cord (and insulated from the ground), will tend to repel each other, as will the two pieces of flannel, but that the rods and flannel are attracted to each other. Thus we find a fundamental law of electricity—that like charges repel each other and unlike charges attract each other. In other words, matter resents being thrown out of balance electrically and seeks to regain balance by discharging a surplus of electrons to other matter having a deficiency of them or at least a more nearly neutral electronic state.

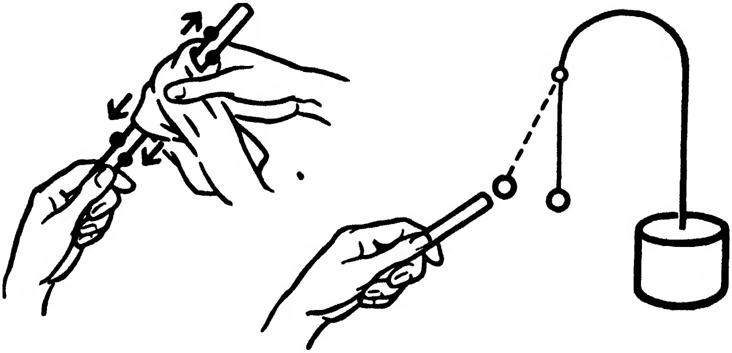


FIG. 4.—A glass rod, when rubbed with dry flannel, becomes negatively charged because it has acquired a surplus of electrons. The rod will then attract a pith ball, right, or it will repel a similar negatively charged rod.

There are a great many visible examples of electronic discharges in everyday life. When a lump of sugar is broken, a cat's fur rubbed or a roll of friction tape unrolled, sparks can be seen if the room is dark enough. The friction creates an electronic discharge in each instance. Another example which has caused discomfort and surprise to thousands of people is the result of scuffing feet along a dry rug and then touching a radiator or another person with a finger tip. The friction of scuffing charges the body with an excess of electrons, which are promptly discharged with a spark upon contact with a non-charged object.

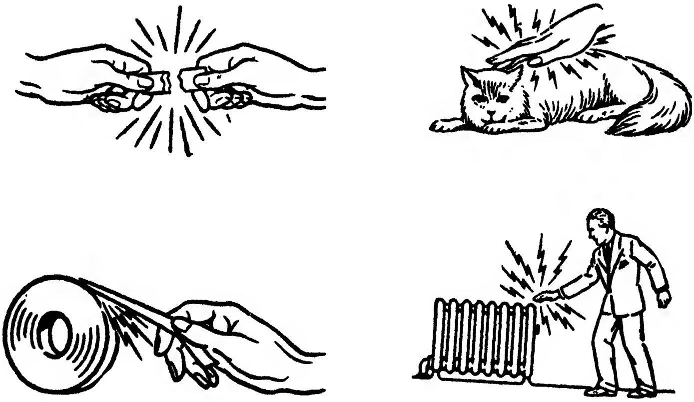


Fig. 5.—Above are illustrated familiar examples of electronic discharges which are seen in everyday life. Friction causes the spark.

Measurement of Electric-current Flow—the Ampere.

It has already been pointed out how the flow of current is somewhat like the flow of water in a pipe. Water flow can be measured in gallons per second. Electric-current flow can be measured if we determine the total quantity of electrical charge moved and the time involved in moving it.

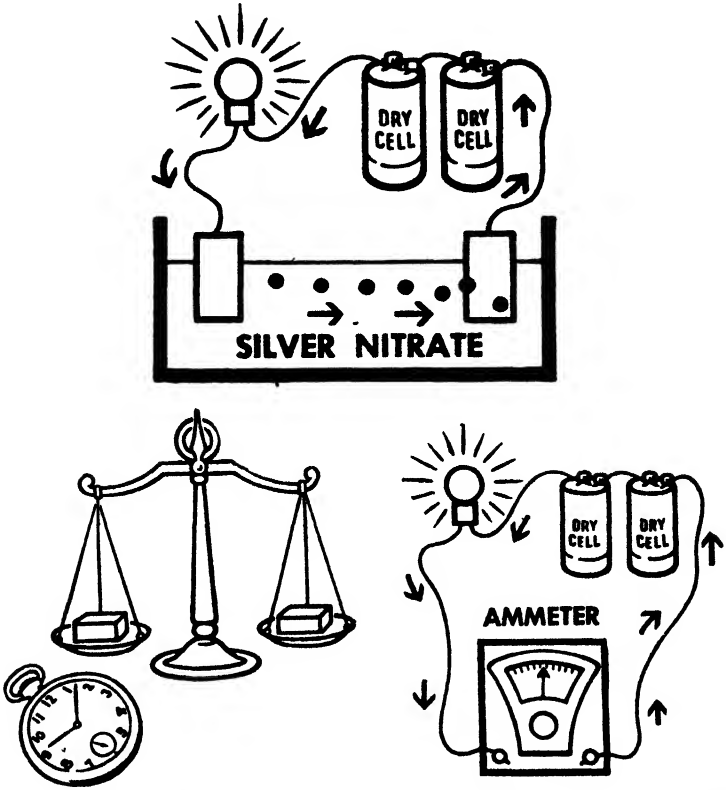


Fig. 6.—Electricity is measured by the quantity per second passing through a conductor. The unit of quantity is an ampere, established in the laboratory by using a silver nitrate solution, scales and a measure of time, top and left. Commercially, an ammeter, right, measures the quantity of electricity passing through a circuit.

The flow is measured in terms of its effect upon certain chemicals. The quantity of electricity which will deposit 0.00118 gram of silver in a standard silver nitrate solution is known as the *coulomb*. This unit was named in honor of the famous French physicist Charles A. de Coulomb.

The total quantity of charge in coulombs may be determined by weighing the negative plate before and after the time interval of current flow and dividing this weight in grams by 0.00118. Then by dividing the number of coulombs thus obtained by the total number of seconds for which the current flowed, the number of coulombs per second can be obtained. And coulombs per second equals *amperes* (named in honor of André Marie Ampère, also a French physicist).

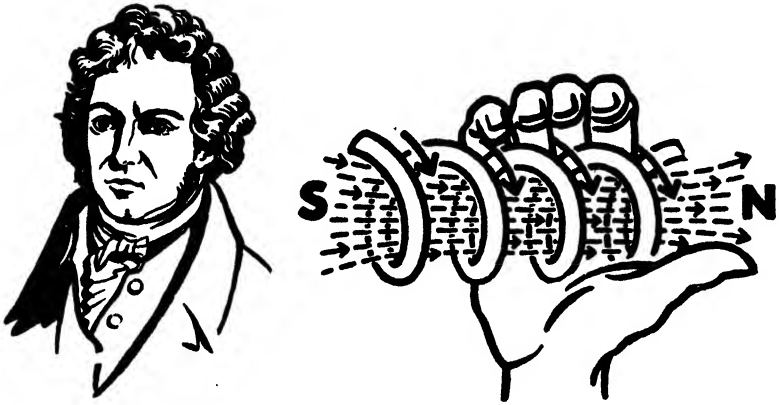


FIG. 7.—André Marie Ampère, left, discovered the right-hand rule, shown at right, which establishes that when a coil is held in the right hand, and the current flows in the direction of the fingers, the thumb always points to the north pole of the magnetic field which is set up in the coil.

Of course such a method of measuring current is inconvenient and could not be used today except experimentally; so the ammeter has been developed. It is connected in series with the load, and the current is read directly in amperes on the scale of the instrument.

Measurement of Electrical Pressure—the Volt.

In discussing current flow in the preceding paragraphs, no account was taken of the electrical pressure forcing it.

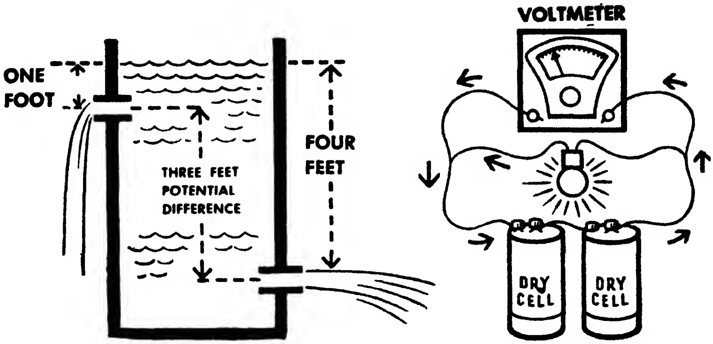


FIG 8.—In both the flow of water, left; and the flow of electricity, right, pressure is measured by the difference in potential. The voltmeter measures that there is a 3-volt difference in potential between the ends of the lamp circuit.

Of course, some sort of pressure is necessary if it is to flow at all. The unit of such electrical pressure is called the *volt*, named for Alessandro Volta, an Italian scientist.

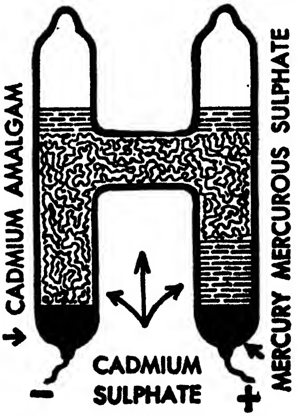


FIG. 9.—The Weston Normal cell provides a constant and known voltage (1.0183 at 20° Centigrade) which is used as a standard in measuring the *legal* volt.

An understanding of voltage may be clearer if the water analogy is used again. If two holes of the same diameter are punched in a water tank, one near the top and one near the bottom, the water will flow more rapidly from the lower hole than from the upper one. The reason for this is the difference in fluid pressure at the bottom and top of the tank. Obviously, the weight of water or pressure is greater at the bottom; so the water is forced out more rapidly. The difference in the two pressures is called the difference in *potential*, and it can be easily measured.

Electrical pressure or voltage is measured in much the same way. In Fig. 8, two 1.5-volt dry-cell batteries are shown connected in series with an incandescent lamp. The voltmeter would show a reading of 3 volts, which means that the difference in potential or electrical pressure between the two ends of the lamp circuit is 3 volts. Electromotive force is the difference in potential which causes a current of electrons to flow in the circuit, giving rise to a continuous current. Thus, the batteries are like the tank of water being slowly emptied to maintain a constant E.M.F. between the lamp terminals.

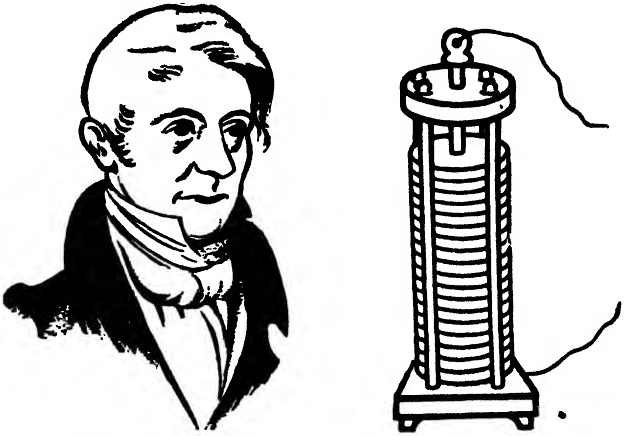


Fig. 10.—Alessandro Volta, born in 1745, made many contributions to electricity, including Volta's pile, right, the first battery. The *volt*, unit of electrical pressure, was named for him.

One *volt* is the electrical pressure or E.M.F. required to produce a current of one *ampere* through a conductor against a resistance of one *ohm*. The ohm, a unit of resistance to current flow, will be discussed shortly.

In electrical calibration work it is essential to have a cell of known and constant E.M.F. The Weston Normal Standard cell has been employed as the International Standard for E.M.F. ratings because of its extraordinary constancy of E.M.F. Its E.M.F. in standard form at 20° Centigrade is 1.0183 volts. Therefore, the legal volt may be defined as 1/1.0183 of the voltage generated by a Standard Weston cell.

The first battery was devised by Volta and was called the *voltaic pile.* It consisted of a pile of alternated discs of silver and zinc, separated by brine-soaked cloths. Modern dry-cell batteries utilize a similar principle.

Resistance to Current Flow—the Ohm—Its Measurement.

All movement of matter (except a falling body in a perfect vacuum) is opposed by the resisting force of friction. In the water pipe, the interior walls of the pipe resist the flow of water. In an electrical conductor, a resistance opposes the flow of current through the conductor.

The quantity of flow per second (amperes) which can be forced through a conductor is directly proportional to the push it receives (volts) and is inversely proportional to the resistance it encounters (ohms). This is known as Ohm's law and is expressed as

$$E = IR, \quad \text{or} \quad I = \frac{E}{R} \quad \text{or} \quad R = \frac{E}{I}$$

where E equals volts, I equals amperes, and R equals ohms.

In electrical circuits it is frequently necessary deliberately to cut down the flow of current. This is done with resistances or *resistors*, as they are often called.

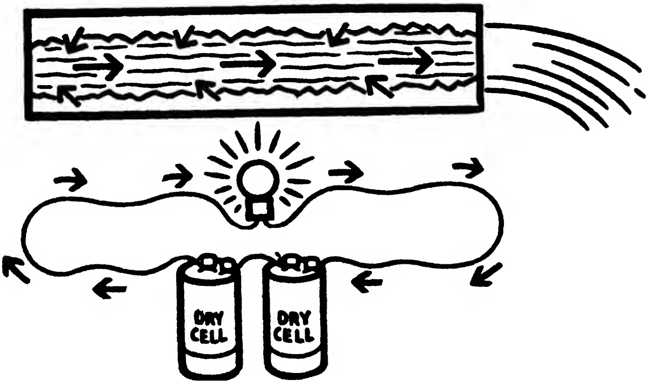


FIG. 11.—An electrical conductor has resistance which interferes with the flow of electrons. It may be compared with the friction of the interior of the pipe against the flow of the water.

Such resistors may be simple coils of fine wire, carbon or graphite rods or other devices which will satisfactorily reduce the flow of current through the circuit.

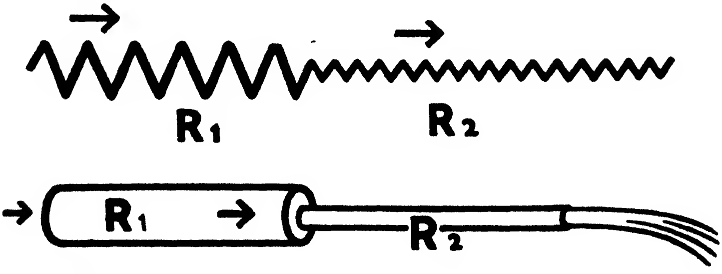


FIG. 12.—When two or more resistors are connected in series, the total effective resistance will be the sum of the separate resistances.

When two or more resistors are connected in series (end to end) so that the same current flows through first one and then the other, the total or combined effective resistance of all is equal to the sum of the individual ones. If the water-pipe example is used again, it will be seen that the action of electrical resistances in series is like the water resistance in two pipes of different sizes coupled end to end; that is, the total resistance to the water flow is equal to the sum of each pipe's resistance. This might be expressed as

$$R_t = R_1 + R_2, \text{ etc.}$$

when R_t equals the total, R_1 the first resistance, R_2 the second, and so on, for any number. Also, the voltage or pressure required to push the same amount of current through the series of resistors is equal to the sum of the pressures required to push it through each one of them. In other words, if R_1 requires 50 volts to push 10 amperes through it, and R_2 requires 70 volts to push 10 amperes through it, then both together will require 120 volts. Furthermore, if that much pressure (120 volts) is not available, 10 amperes of current flow will not be able to get through, and Ohm's law will have to be applied to find out just how much will get through.

On the other hand, if, for instance, only 110 volts is available and a current flow of 10 amperes must be obtained for some reason, resistance can be taken out gradually until it is found that the 10-ampere current is getting through. This is the principle of rheostat operation.

To summarize briefly, the current (amperes) in all parts of a series circuit is the same, but the pressure (voltage) required to force a given current through is proportional to the amount of resistance offered.

If resistors are connected in parallel (side by side), the pressure or voltage drop across each of them is obviously the same regardless of the size of the resistors. However, in this case the total current flow will be equal to the sum of the current flow in each individual resistor.

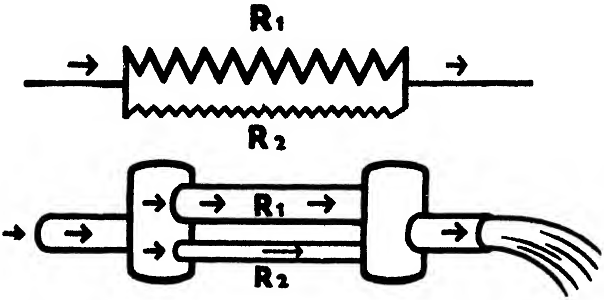


FIG. 13.—When two or more resistances are connected in parallel, the effect is similar to that shown with the two sizes of water pipes. The flow of both the current and the water is reduced because of the two paths through which they must flow.

It will also be inversely proportional to the resistance offered by each resistor and can be expressed as

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2}, \text{ etc.}$$

With the two water pipes connected in parallel, the resistance to the flow of water is reduced because in this arrangement it passes through two pipes simultaneously instead of through first one and then the other as in the case of series connection.

CHAPTER 2

Conductor Characteristics and Resistance.

The resistance to the flow of current offered by any conductor is affected by any one or a combination of four principal factors, namely the length of the conductor, its diameter or cross-sectional area, the type of material it is and its temperature.

First, the resistance of any given type of conductor varies directly with its length. In other words, the longer the wire, the greater its electrical resistance in the same proportion. Second, the resistance of any given type of conductor varies inversely with its cross-sectional area, which means that if the cross-sectional area is doubled, its resistance to the flow of current is cut in half because twice as much room is allowed for it to pass along the wire. Third, different materials offer different amounts of resistance. Since silver has the

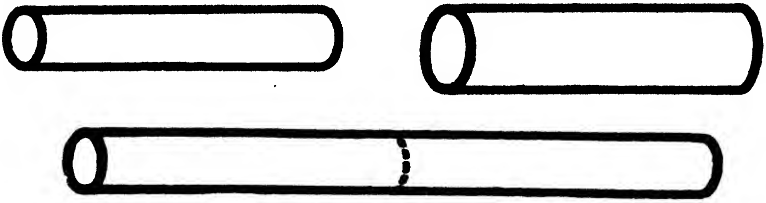


FIG. 14.—The resistance of any given conductor varies directly with the length and inversely with the cross-sectional area. One unit area of unit length, as above left, will have twice the resistance of a unit length of two unit areas as above right, and one-half the resistance of a unit area of two unit lengths as shown in the center. Thus, the larger the wire, the less the resistance.

lowest resistance of all metals, it is established as the basis for comparison with all others with a relative resistance of 1. Fourth, when the temperature of a conductor is raised, it speeds up the random movement of the atoms in the conductor. In all pure metals this *increases* the resistance to current flow. In carbon and

STANDARD WIRE TABLE

GAUGE	DIAMETER	OHMS PER 1000 FT.	POUNDS PER 1000 FT.
18	.040"	6.39	4.91
20	.032"	10.16	3.09
22	.0253"	16.15	1.94
24	.0201"	25.69	1.22
26	.0159"	40.86	0.77
28	.0126"	64.96	0.48
30	.0100"	103.30	0.30
32	.0079"	164.26	0.19
34	.0063"	261.23	0.12
36	.0050"	415.24	0.08
38	.0039"	660.37	0.05
40	.0031"	1049.7	0.03

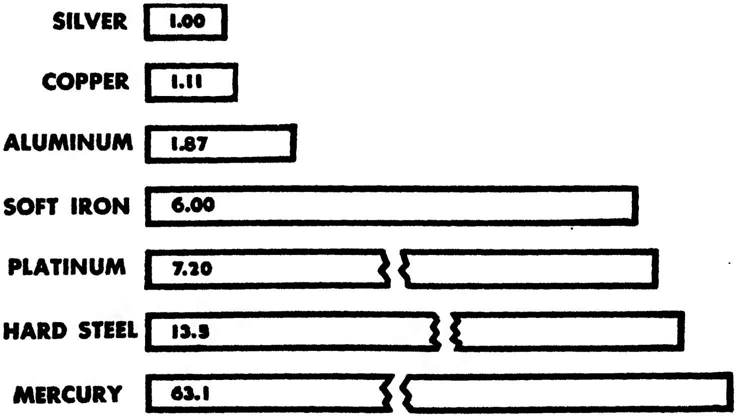


FIG. 15.—The variation of resistance to the size of copper wire has been worked out in this table, top chart. The relative electrical resistance of various conductors is shown below.

a few other substances, however, the resistance decreases as the temperature rises.

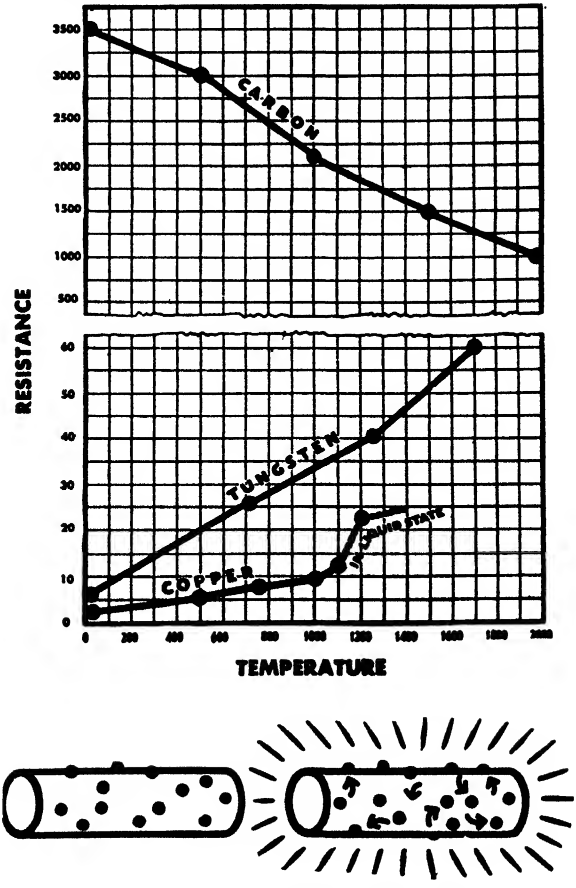


Fig. 16.—The resistance of a conductor varies with the temperature of that conductor, as shown in the chart. The cause is a speeding up in the random movement of the atoms, as shown (temp. is in °C. and resistance in ohms-cm.).

The standard or legal unit of resistance (the ohm) is defined as the resistance at 0° Centigrade of a column of mercury weighing 14.4521 grams, 106.3 centimeters high, with a uniform cross-sectional area of 1 square millimeter.

The Unit of Electric Power—the Watt.

Thus far, none of the units of current-flow measurement discussed has covered the capacity of that flow to do work. The ampere is simply a measure of the amount or quantity of current flow, the volt a measure of the pressure behind it and the ohm a measure of the resistance to flow which must be overcome.

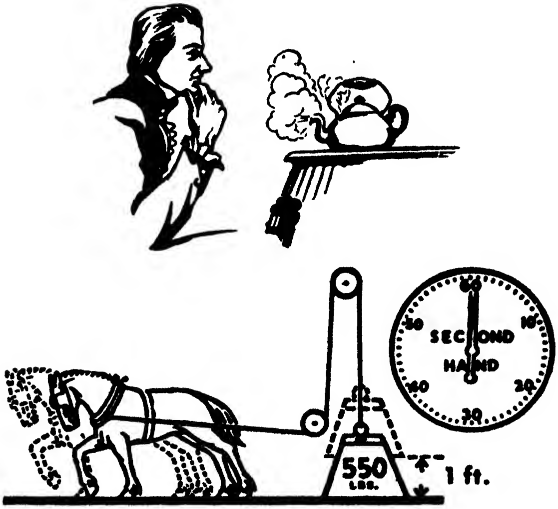
The time rate of a man, a horse, or a machine to do work (overcome resistance) is called *power*. The average man can lift or raise about 90 pounds a distance of 1 foot in about 1 second. This combination of weight, distance and time would be called 1 *manpower*. Even if he lifted this weight in two or three pieces of 45 or 30 pounds each, respectively, but lifted them a foot each and all in 1 second, he still would be accomplishing 1 manpower of work. If he weighed 180 pounds and stepped up four steps, each 1 foot high, and did it in 1 second, he would accomplish 8 manpower of work.

James Watt, a Scotch engineer for whom the *watt* unit of electric power was named, found by repeated tests and studies that the average horse can lift 550 pounds at the rate of 1 foot per second. Watt first evaluated and defined the horsepower while developing the first practical steam engine, and his evaluation that

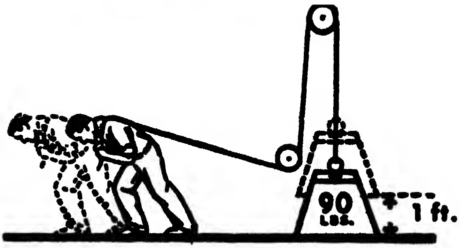
$$1 \text{ HP (horsepower)} = \frac{\text{pounds lifted} \times \text{feet per second}}{550}$$

is the basis of mechanical-power measurement today.

Electric power, however, is measured somewhat differently. The work that a stream of water can do does not depend entirely upon the size of the stream,



HORSEPOWER



MANPOWER

Fig. 17.—James Watt, of steam-engine fame, first defined horsepower—the moving of 550 pounds to a height of 1 foot in 1 second. It is compared, above, to manpower, the moving of 90 pounds to a height of 1 foot in 1 second.

or entirely upon the pressure behind it, but rather upon the combination or product of these two factors. Similarly, the work done by a flow of current does not depend wholly upon the volume or quantity of that flow, or wholly upon its pressure, but rather upon the product of the two. Thus it can be seen that electric power equals the current in amperes times the pressure (or E.M.F.) in volts. This is expressed as

$$P = EI, \qquad \text{or} \qquad \text{watts (power)} = \text{volts} \times \text{amperes}$$

(For direct current. Alternating-current characteristics will be discussed later.)

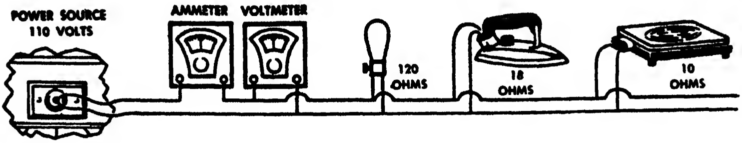


Fig. 18.—Graphic illustration of how to compute power in watts.

$$I = \frac{E}{R} \qquad\qquad P = EI$$

I lamp $= {}^{110}\!/_{120} = 0.916$ ampere
I iron $= {}^{110}\!/_{18} = 6.11$ amperes
I grill $= {}^{110}\!/_{10} = 11.0$ amperes
I = current, amperes
E = E.M.F., volts

P lamp $= 110 \times 0.916 = 100.76$ watts
P iron $= 110 \times 6.11 = 672.10$ watts
P grill $= 110 \times 11.0 = 1210.0$ watts
R = resistance, ohms
P = power, watts

The watt unit of power measurement is the amount of power required to maintain a current flow of one ampere at a pressure of one volt. Since the watt is a relatively small unit of power, the kilowatt (KW), which is 1,000 watts, is used where larger units of power measurement are desirable. The watt-hour and kilowatt-hour (KWH) are units of *power-time* measurement and are used to determine the amount of power used over a period.

Although horsepower is the unit of mechanical-power measurement and watt the unit of electric-power measurement, there is a numerical relationship between the two. One horsepower is equal to 746 watts.

Energy—Potential and Kinetic.

Since energy is the ability to do work, and since power is the time rate of doing work, it is obvious that there is a relationship between power and energy in that power may also be defined as the time rate of expending energy. Therefore, a brief analysis of energy may be included at this point.

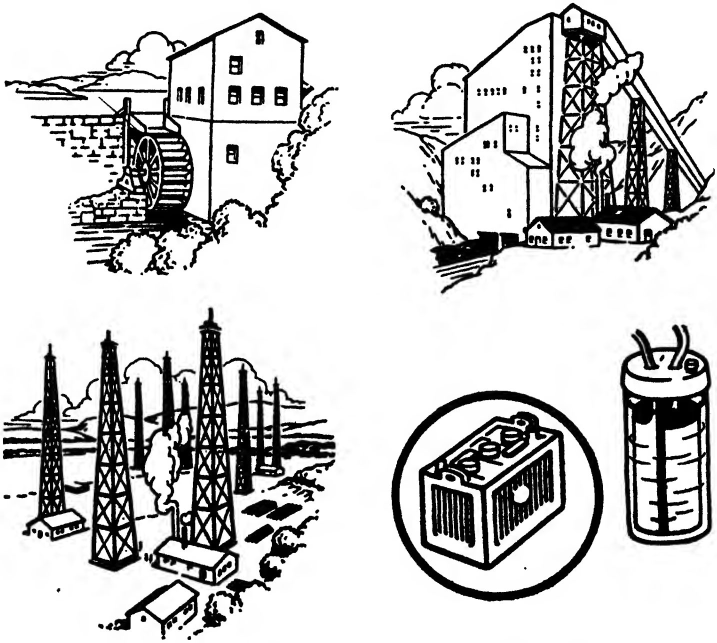


Fig. 19.—Potential energy is common in everyday life—the weight of the water above the wheel, the coal from the mines, the oil from the wells. Also, in electricity, the storage battery when *charged* holds potential energy.

Potential energy is just what its name indicates. It is energy which is stored up and ready for release under the right conditions at any time. The storage of water behind a dam is a typical example of potential energy. It is ready to turn the mill wheel and do useful work when the gate is opened.

Coal, oil and natural gas, hidden deep in the earth, are also examples of potential energy. Created millions of years ago from vegetable and animal matter under terrific heat and pressure, these three fuels are tremendously important today as sources of power when burned in Diesel-engine generators or in the boilers of the great steam-turbine power plants.

The storage battery is another illustration of potential energy. Gaston Planté, the inventor, found that two plates of lead placed in a dilute solution of sulphuric acid would become *charged* if connected for a short time to a voltaic cell. Thomas A. Edison spent many years developing and perfecting a slightly different type of storage battery. At present, storage batteries are the heart of automobile-ignition systems and have countless uses in industry and transportation. Today the charging is accomplished with a low-voltage direct-current (D.C.) generator, and the potential energy stored is in the form of chemical energy.

One other form of potential energy which might be mentioned is that evidenced in a flat spiral steel spring which is wound tight. In this case the potential energy is the result of displacement of the steel molecules (mentioned on page 3). In a relaxed condition the steel molecules are in what might be called a normal relative position. But when the spring is wound, these little particles are forced out of place, and their tendency to return to their original positions supplies the potential energy of a tightened spring.

This example of the wound spring is an ideal place to turn to the consideration of *kinetic energy* because while the spring is unwinding, either rapidly or slowly as in a clock, it is a source of kinetic energy.

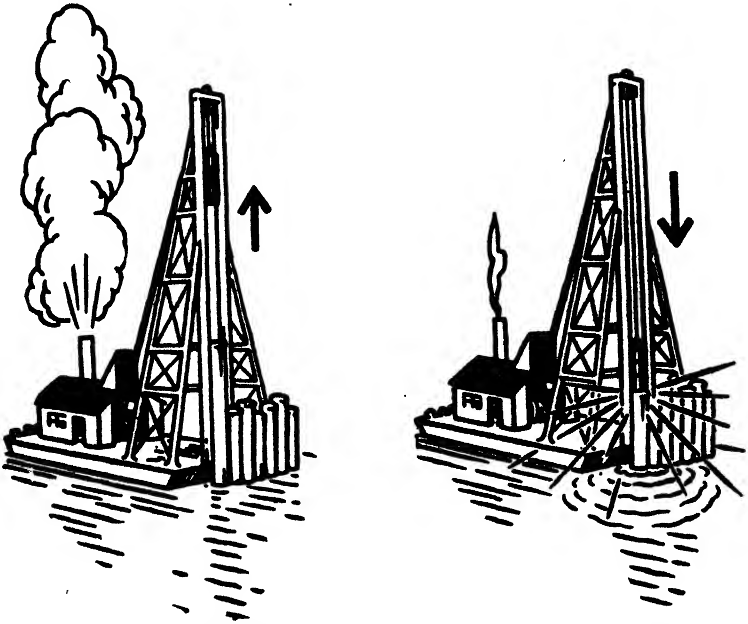


FIG. 20.—Kinetic energy is energy in motion, as in the pile driver above. The turbine that drives an electric generator imparts the same kind of energy.

Kinetic energy is energy in motion. In a pile driver, for instance, potential energy is present while the weight is held at the top, but, upon release, this energy has been transformed from potential to kinetic as the weight falls to drive the pile into the river bottom.

The energy in explosives results from the relative positions of atoms rather than from molecules as in the steel spring. Here the atoms which were in their "normal" positions in the solid form of the explosive are suddenly and violently disarranged when the solid undergoes an abrupt chemical change by becoming a gas. The consequent large increase in volume is what we call the *explosion*. Thus the potential energy of the solid (or liquid) explosive becomes kinetic energy during a split second, whereas the clock spring may require days to unwind.

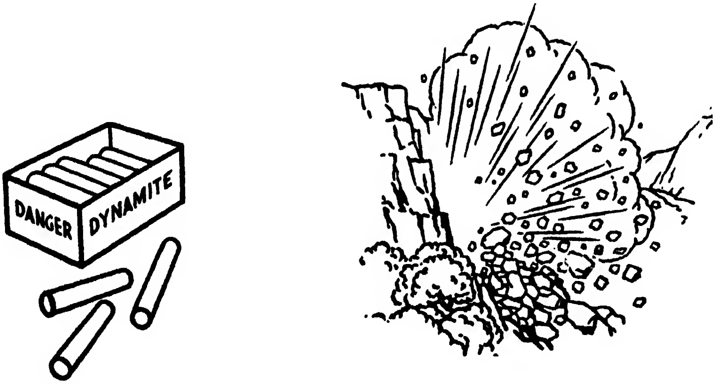


FIG. 21.—In its solid or liquid form, an explosive has potential energy. The explosion is a rapid transformation of that potential energy into kinetic energy.

As far as is known, or at least within the scope of present average human conception, energy, like matter, can neither be destroyed nor created. This law of the conservation of energy is one of the great scientific generalizations. If it is true that energy can be changed only in form or from one location to another, then there is no more energy in the universe today than there was in the beginning—and no less.

Part II

MAGNETISM

CHAPTER 3

Magnetic Force.

No one knows exactly what magnetism is. It is a force which is related in some way to electronic flow and one which can be manufactured, or at least made evident at will, as well as accurately controlled. It is present in thousands of devices in everyday use and is as important in the consideration of electricity as electronic flow itself. The earth is a gigantic magnet with north and south poles the same as the little U-shaped steel bars with which all children are familiar.

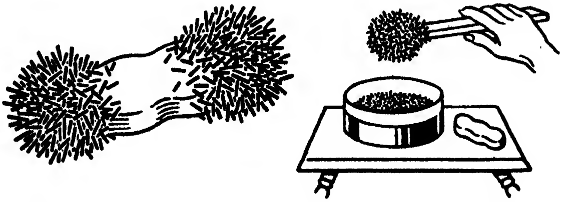


FIG. 22.—Magnetic iron, or *lodestone*, was the first known magnet.

Magnetic force has been known for thousands of years. It is said to have been discovered near the city of Magnesia in Asia Minor, when *magnetite* iron ore was found to have the ability to attract other particles of iron. Early navigators used elongated pieces of the ore as compasses and called them *leading stones*, from which the name *lodestone* is derived. When a steel bar is rubbed on lodestone it becomes *magnetized* and will attract iron. Just what happens when a steel bar is magnetized is not yet clear. Some scientists' theory of magnetism is that the steel is composed of a great many small magnetized particles which point in every direction under normal conditions, but which, when rubbed with lodestone or otherwise magnetized, all turn in the same direction and thus magnetize the steel bar.

FIG. 23.—The theory of magnetism—a steel bar (left) becomes magnetized (right), and the tiny particles all point in one direction.

Magnetic lines of force have a very definite and consistent pattern, which is called a *magnetic field.* If a piece of paper is placed over a bar magnet and iron filings are sprinkled on the paper, they will arrange themselves to coincide with the pattern of the field. These lines of force are, of course, imaginary ones along which the attractive or repulsive force of the magnet acts. Their direction is generally assumed to be from the north pole to the south pole and back through the interior of the magnet, forming closed loops called the *magnetic circuit.*

Like *unlike* charges of electricity (a negative and a positive), *unlike* magnetic poles attract each other; *like* magnetic poles repel each other, as do two positive or two negative electrical charges. The intensity of attraction and repulsion is a function of the pole strengths of the magnets.

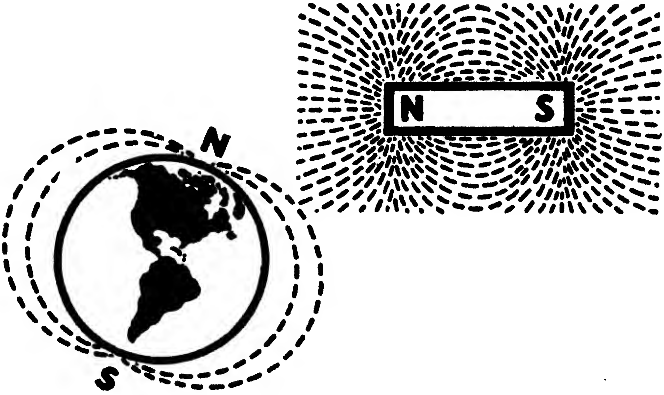


Fig. 24.—The arrangement of magnetic fields to the north and south poles of a permanent magnet, also to the earth.

Electromagnetism.

The similar characteristics of current flow and magnetic lines of force have been indicated in the discussion above. Actually, current flow can be used to produce a magnetic field, or a magnetic field can be used to generate a pressure or E.M.F. (voltage), which will cause current flow. As a matter of fact, any conductor through which current is flowing has magnetic force around it and at

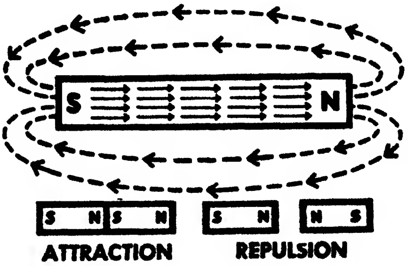


Fig. 25.—Magnetic lines are imaginary lines along which the attractive or repulsive force of the magnet acts.

right angles to it. One way of remembering this relationship is to visualize the operation of driving a screw into a wall. The direction of current flow would be the same as the movement of the screw into the wall—away from the body—whereas the magnetic lines of force around the conductor carrying the current would be in the direction of the twist of the screw driver—clockwise to the person facing the wall.

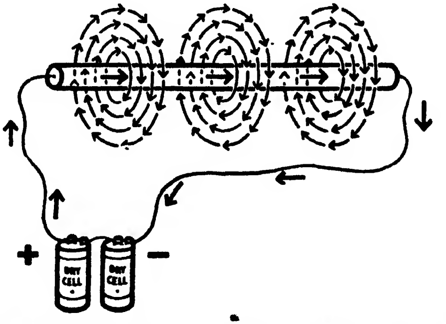


FIG. 26.—The magnetic field of a straight current-carrying conductor is around the conductor and at right angles to it.

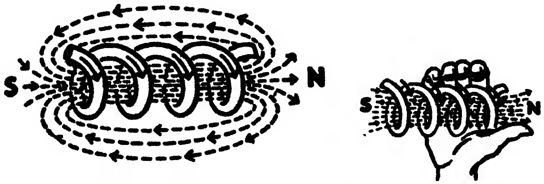


FIG. 27.—When an electric current flows through a coil of wire, the regions or spaces inside and outside the coil become magnetized.

If a conductor is coiled, the space within, as well as around, the coil becomes a magnetic field, and an iron bar within the space becomes an electromagnet when current flows through the coil. It will be recalled that Ampère discovered the right-hand rule (illustrated on page 10), which tells us that with a coil held in the right hand and the current flowing in the direction of the curled fingers, the thumb always points to the north pole of the magnetic field established within the coil by the current it is carrying.

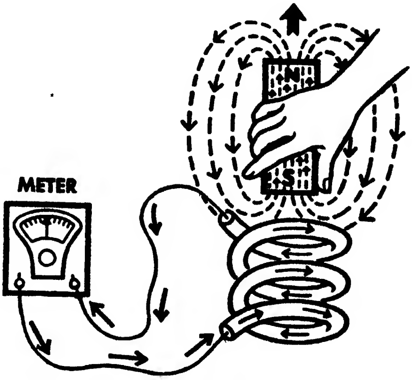


FIG. 28.—Moving a permanent magnet within a coil of wire causes a current to flow in the electric circuit. This principle is the basis for electric generators.

The other equally important relationship between current flow and magnetic force seems to be the reverse of the production of a magnetic field described above. When a conductor is moved across a magnetic field an E.M.F. is generated which causes current to flow in the conductor if the circuit is closed. To express the same idea another way, if a permanent magnet is plunged into a coil of wire (or removed from it), the magnetic lines

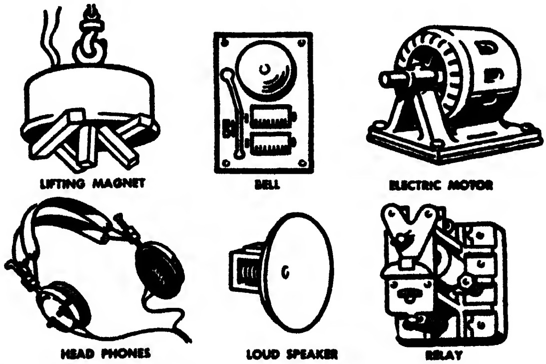


FIG. 29.—There are many practical uses of electromagnetism.

of force "cut" the wire and induce an E.M.F. or pressure (voltage) which causes current flow in the circuit. Such voltage exists only while the magnet is in motion within the coil and ceases when it is completely removed. This is the basic principle behind the great electric generators in power plants.

Generation of Electric Power.

Although there are many practical uses of electromagnetism, the most important one is, of course, in the generator.

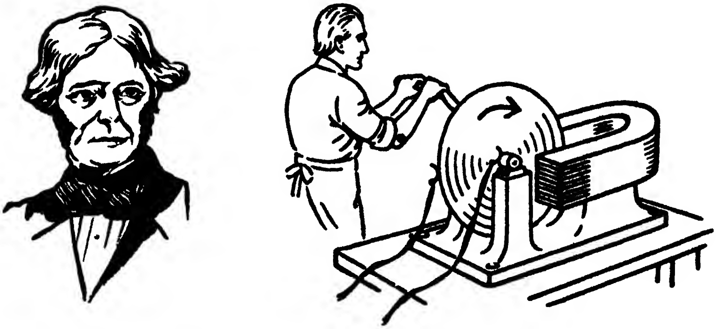


Fig. 30.—The world's first generator, built by Michael Faraday, had a copper disc in the field of a permanent magnet. Manpower supplied the kinetic energy.

Michael Faraday, an English scientist, constructed the first electrical generator. It was a simple device as compared with today's massive machines and consisted of a copper disc about 1 foot in diameter which was rotated between the poles of a permanent magnet.

A man supplied the kinetic energy necessary to turn the disc. In modern power plants this energy is provided by falling water (hydroelectric generators), by steam produced in boilers using coal or oil as a fuel (steam turbines) or by internal-combustion engines (Diesel generators).

The turning copper disc in Faraday's device cut the lines of force of the magnet, and an electric current was generated which flowed from the disc through contact brushes at its rim and shaft and thus into the conductors of the circuit.

There are three forces involved in the simple generator described above: first, the physical force provided by the man turning the disc; second, the magnetic lines of force between the poles of the magnet; third, the E.M.F. or voltage generated in the disc which caused the flow of electric current. The definite relationship between the directions in which these three forces are exerted is best described in another right-hand rule, called *Fleming's rule.*

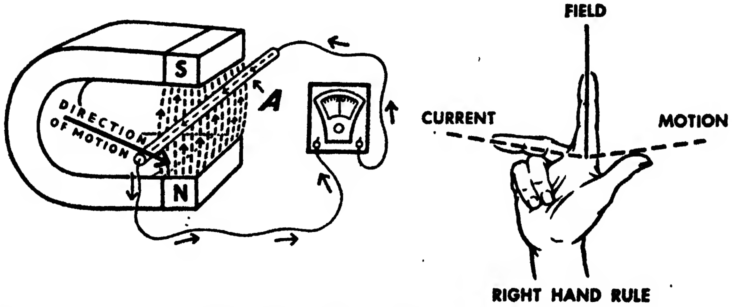


Fig. 31.—The elementary principle of generation of electrical current by cutting the lines of force. The right-hand rule shows the method of determining the direction of the current flow.

It has been previously pointed out that a conductor must be in motion through a magnetic field if a flow of current is to be set up within it. If this conductor (*A* in Fig. 31) is moved in the direction indicated with respect to the north and south poles of the magnet, then current will always flow in the direction shown by the arrows. Fleming's rule demonstrates this relationship by stating that if the conductor is moved in the direction of the thumb, and the forefinger points the direction of the magnetic force (toward the south pole), then the current in the conductor will flow in the direction of the extended second finger—all fingers to be at right angles to each other.

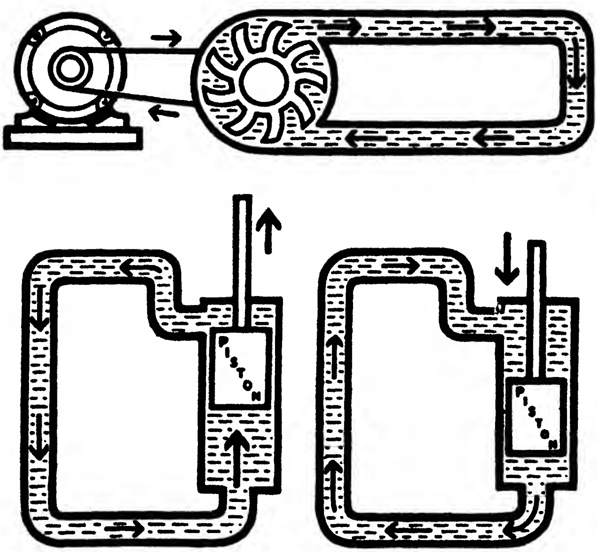


Fig. 32.—Direct current, in a manner similar to the water from a centrifugal pump, above, flows continuously in one direction. Alternating current changes direction periodically, as does the water in the closed pipe circuit below.

It has already been explained that when electrons flow along a conductor in one direction only, *direct current* is said to be flowing. This may be compared to a closed pipe circuit through which water flows continually from a centrifugal pump.

Alternating current, on the other hand, changes or alternates its direction at definite intervals. It might be compared to a closed pipe circuit in which water is constantly circulated back and forth by a valveless reciprocating pump.

Thus far, the source of pressure or E.M.F. (voltage) has been generally considered as a battery of established potential. It has just been pointed out, however, that when a magnetic field is cut by a conductor, current will be caused to flow in that conductor in a direction determined by its relative motion through the lines of magnetic force. Therefore, it is obvious that current can be produced in a loop of wire being turned in the field of a magnet so that the loop cuts across the lines of magnetic force. This is similar to Faraday's generator except that a loop of wire is used instead of a copper disc.

Alternating-current Generators.

As previously explained, the direction of induced E.M.F. in the wire loop is dependent upon the direction of its movement through the magnetic lines of force. It can be seen from position *A* (Fig. 33) that as the loop is turned counterclockwise, the right-hand half of the loop cuts upward through the lines of force. By applying Fleming's rule it is found that the current flow will be in the direction indicated by the straight arrow, or toward the reader. On the other hand, the left half of the loop (shaded half) cuts downward through the magnetic field, and the flow will be in the opposite direction. But since the loop is a continuous one, the current flows on around and out through the brushes into

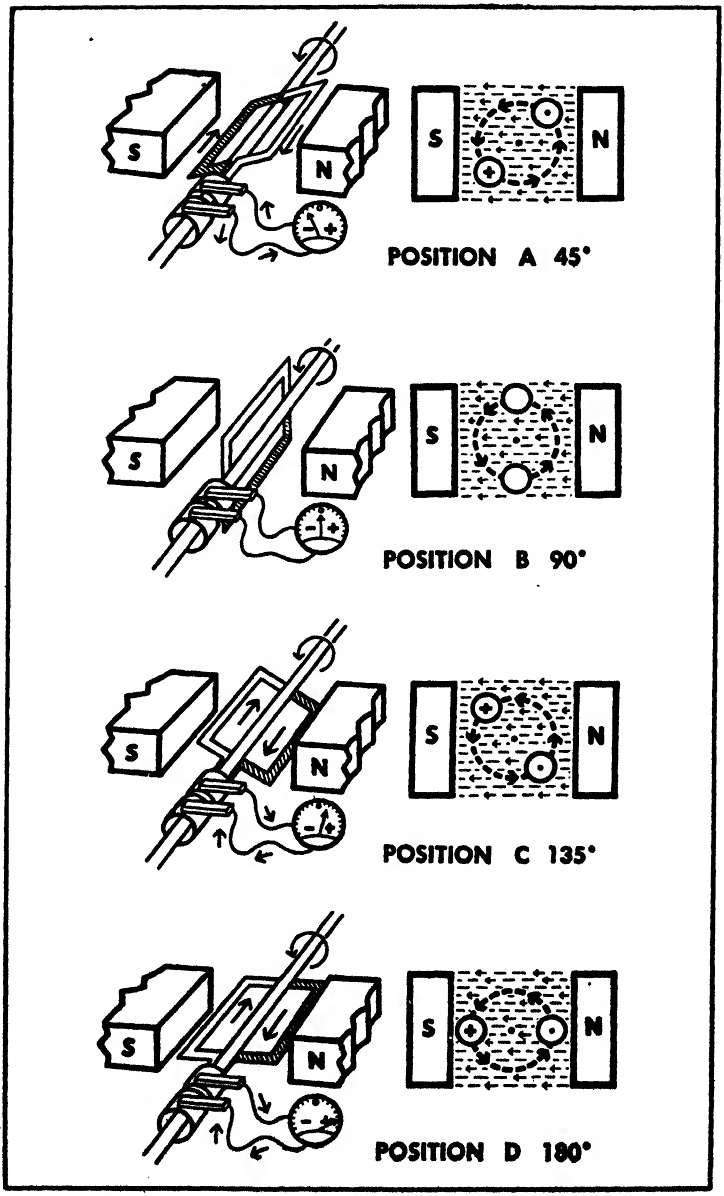


Fig. 33.—Demonstrating the principle of alternating current.

the circuit and back again. Now when the loop reaches position *B*, no lines of force are being cut, and so there is no E.M.F. (voltage) generated at this point.

As the loop continues to turn, position *C* is reached, and it can be seen that the half of the loop which was cutting downward on the left (shaded half) is now cutting upward on the right, so that current now must flow in the opposite direction through that half as well as through the other half. Thus we have a complete reversal of current flow direction in 180° of rotation—or alternating current being generated.

Since at position *B* there was no E.M.F. being generated, it follows that at position *D* the maximum value of E.M.F. will be found since in that position the loop is cutting the greatest number of lines of force. This maximum value is reached gradually as the loop approaches a horizontal position, *D*. Also, the minimum or zero value is reached gradually as it cuts fewer and fewer lines of force and eventually is in a vertical position, *B*.

A curve can be plotted for the rise and fall of the generated E.M.F. This curve is called a *sine wave*. Figure 34 shows this wave form of a modern A. C. generator. The positions *A*, *B*, *C* and *D*, just described, are shown at 45, 90, 135 and 180°. The strength of the E.M.F. generated at these positions is indicated above and below the zero value represented by the center horizontal line. Thus the strength of the E.M.F. is zero at *B* and maximum at *D*, and it is negative at *A* and positive at *C* or *D*.

When the voltage has gone from zero to one maximum value and back to zero again, and then to the other maximum (in the opposite direction) and back to zero—in other words completed one whole wave from 0 to

360°—it has completed a *cycle.* The number of cycles completed in one second is called the *frequency.*

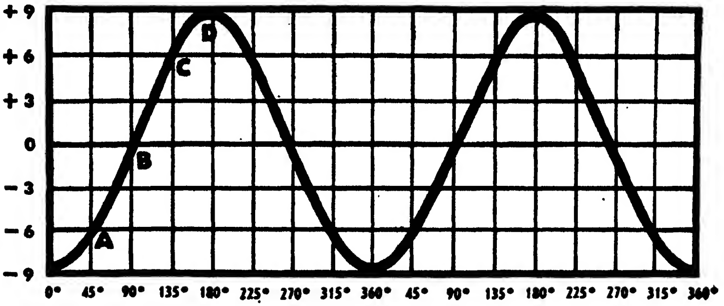
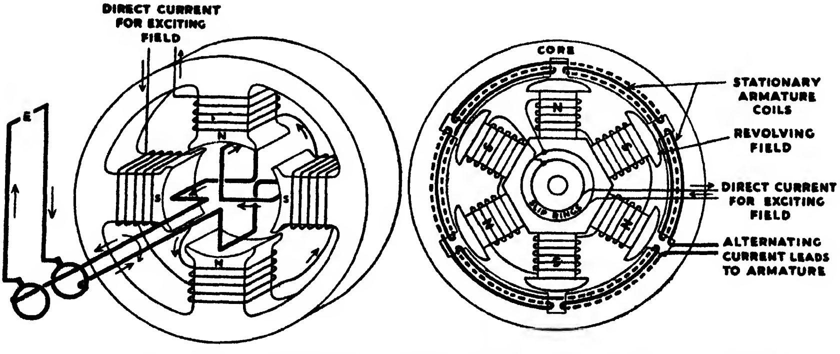


Fig. 34.—Curves of alternating voltage.

The large present-day A.C. generators involve the same principle of the wire loop except that many wire loops are used and the process is reversed; that is, the magnets revolve inside the wire loops (armature windings), and the magnets instead of being permanent magnets are electromagnets, the magnetic field being created by passing an "exciting" current through the coils of the electromagnets. Alternating currents are



Figs. 35 and 36.—Illustrating simple generator windings. (*Courtesy of Fairbanks, Morse and Co.*)

usually generated at a frequency of 60 cycles per second, although 25 and 40 are not uncommon.

Phase Relation.

It has just been shown how the simple-loop A.C. generator produces its E.M.F. in the form of a single rising and falling wave. It is called, therefore, a *single-phase* generator.

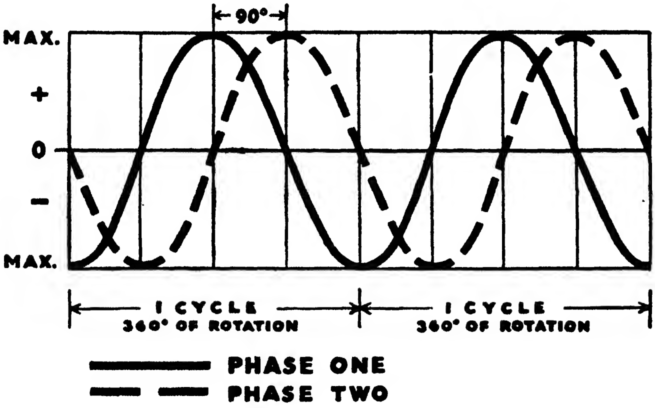


FIG. 37.—Sine waves of a two-phase A.C. generator.

If two separate loops at right angles to each other are used, and the E.M.F. generated pushes electrons out through separate sets of brushes, it is obvious that the resulting two sets of waves would not coincide, because the loops would be cutting the magnetic lines of force at different times. In other words, when one is at its peak E.M.F., the other is at zero, which means that a quarter of a cycle later the opposite condition will exist, or that phase 1 follows phase 2 by a quarter cycle. A generator of this type would be called a *two-phase* alternator.

When three single-phase windings are placed on the same shaft with the windings brought out through their respective slip rings and brushes, the voltage waves will

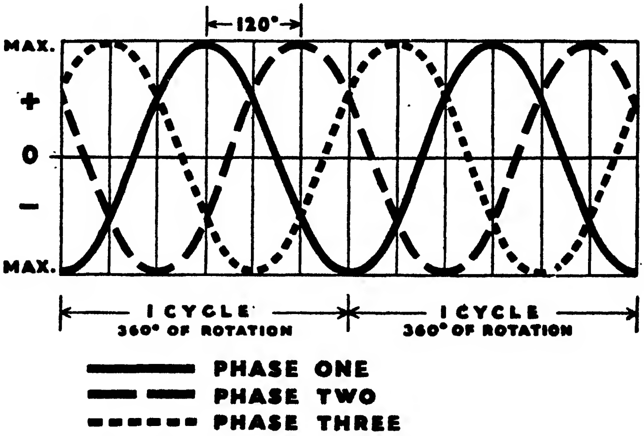


Fig. 38.—Sine waves of a three-phase A.C. generator.

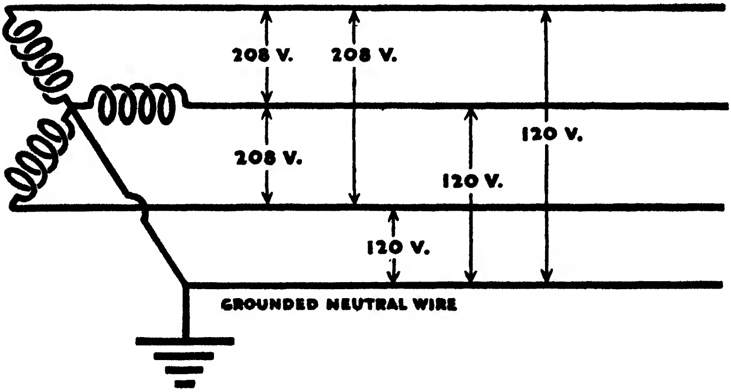


Fig. 39.—The four-wire, three-phase distribution system.

occur a third of a cycle apart as shown in the diagram. This manner of generating three-phase current is used to a very large extent throughout the country. Actually, six separate wires are not used since it is possible to connect all the phases together in such a way that only three wires will serve the purpose.

When a fourth grounded (neutral) wire is introduced into the system, a three-phase, four-wire system results, with approximately one-half as much voltage existing between any one of the phase wires and the ground, as between two phase wires.

Although a greater number of phases is possible in a generator, there is no economic justification for such equipment except in very specialized applications.

Direct-current Generators.

A D.C. generator actually produces its E.M.F. (voltage) in the same way that an A.C. generator does. The direct or unidirectional current is obtained by a method of carrying it away from the machine. This method involves the reversal of connections at just the precise instant when the current being generated is changing its direction. In other words, if in position *B* of the simple-loop-generator diagrams (Fig. 33) the connections to the meter are reversed, the meter would still show negative instead of positive at positions *C* and *D*. But when the shaded half reached the top in a vertical position, the connection would have to be changed back again to keep the current still flowing in the same direction.

In a D.C. generator this changing is done as the generator revolves by means of a device on the shaft called a *commutator*. The brushes in contact with the commutator are so placed that the current is always carried away in the same direction.

It might appear that, although the current is direct in a generator of this type, there will be a decided pulsation due to the rise and fall of E.M.F. values. This would be true in the simple-loop generator, but in modern multipolar machines, the design of the armature overcomes this pulsation.

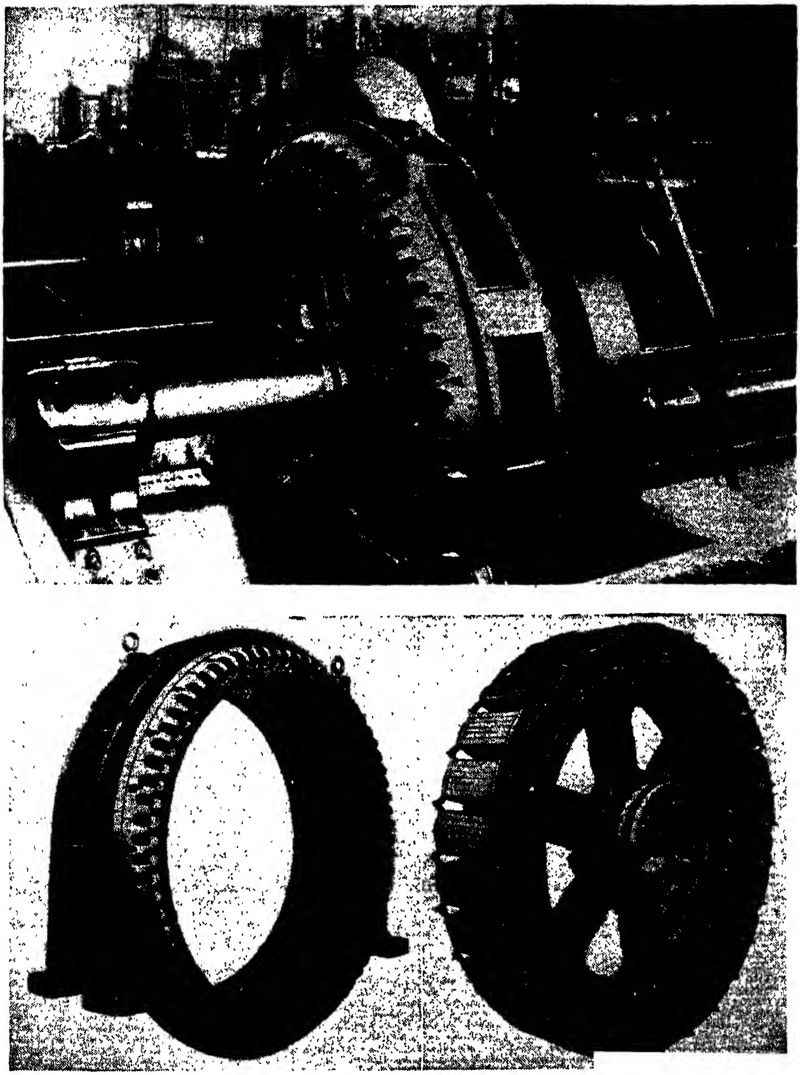
Volumes can and have been written on the design and various winding methods of generator armatures and fields. They are a study in themselves and an involved one. Therefore, further discussion in this book would be out of place, since it is intended here to present only the primary factors and uses of magnetism.

Motors.

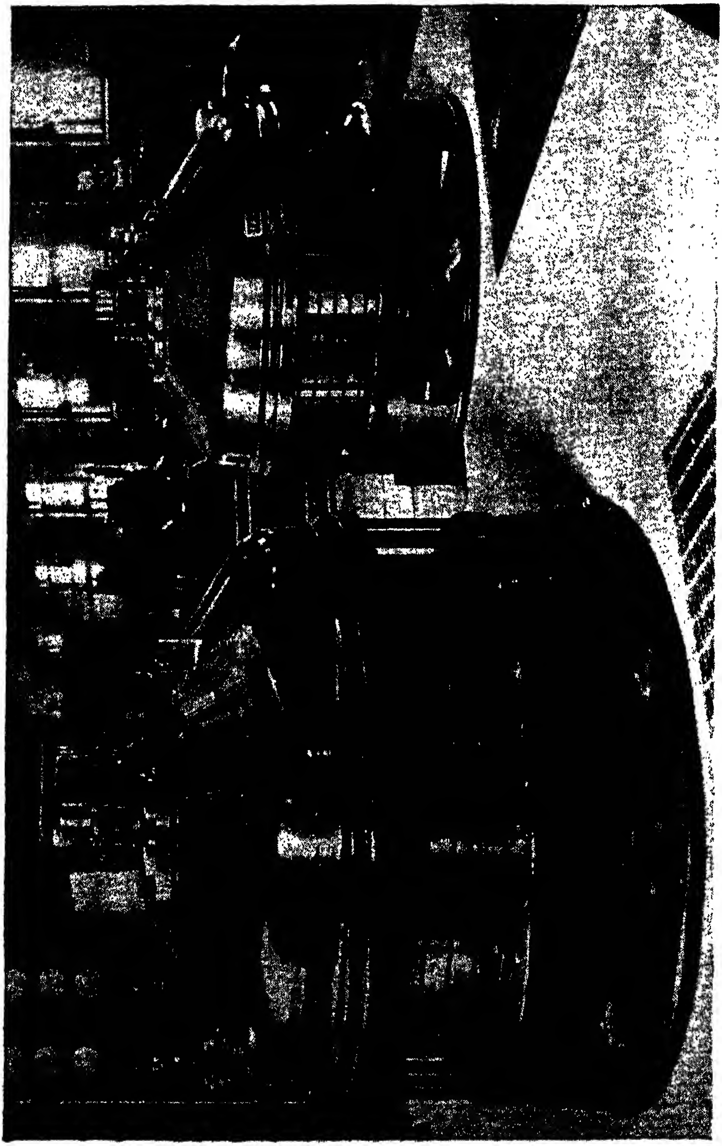
Basically, an electric motor reverses the process of a generator. If, instead of turning the wire loop through a magnetic field and allowing the generated current to flow out of it, we connect the loop to a source of E.M.F. (a battery or generator) and push the current flow through it, the loop will turn by itself; that is, it will turn until it reaches the vertical position *B* (Fig. 33). At this point it can go no farther because to do so would be contrary to the various forces involved—the magnetic lines of force between the poles of the magnet, the direction of the current flow resulting from the electromotive force (E.M.F.) from the battery and the directional force of the turning loop.

If the polarity is reversed (connections reversed) and the loop started gently, it will immediately flip around another 180°, where it will stop again for the same reasons noted above.

In a D.C. motor this changing of connections is done automatically, as the armature revolves, by means of a split commutator on the shaft, which reverses the direction of current flow at each half revolution. The



Top, Diesel-driven A.C. generators of this type are widely used throughout industry. Lower left, complete stator core of a 845KVA-257-R.P.M. alternator similar to that shown in the top photograph. Lower right, the rotor of a large generator showing the field poles and windings. (*Courtesy of Fairbanks, Morse & Company.*)



Two of a group of 250-horsepower, 167-R.P.M. three-phase, 25-cycle 6300-volt, vertical-shaft, synchronous motors directly connected to pumps in a municipal sewage-disposal plant. *(Courtesy of Fairbanks Morse & Company.)*

momentum of the armature as it revolves, carries it past the "dead point" so that a continuously running D.C. motor results. The motor will run as long as current is forced through its armature via the alternating device or commutator on the shaft.

There is a motor rule for determining the direction of rotation of a motor which is exactly the same as Fleming's rule except that the left hand is used instead of the right.

There are many types of motors for both A.C. and D.C. operation, the differences between them being primarily in the methods of winding the armature and field coils, in the number of poles and in a few other factors. The selection of the best type of motor for any particular application is governed by the kind of service required. Some applications require high speed, some a constant slower speed, others a readily controlled variable speed and still others great turning power. Sometimes a motor is desired with a combination of two or more of these factors plus other additional ones, and new and better types are constantly being developed.

Like the study of generators, a complete study of motors would require hundreds of pages. Therefore, the discussion here must be limited to the basic magnetic principles and laws involved in motor rotation.

Counter E.M.F.

Lenz, a physicist of the nineteenth century, proved that electromagnetically induced currents (currents generated in a conductor cutting through a magnetic field) have such a direction that their own magnetic fields (produced in turn by the current flow) tend to oppose the motion which produces them. In other words, the forces which make the wire loop turn in the simple motor create other forces around the loop which oppose its motion. It is a sort of a conflict between the generating and the motor characteristics of the device. This opposing voltage, generated in the loop by virtue of its cutting magnetic lines of force, pushes a current flow in the opposite direction to the other current flow, which is deliberately forced into the loop from a battery or generator in order to make it turn.

The voltage applied from the outside source is usually called the *impressed E.M.F.*, whereas the voltage generated in the loop (armature) is called the *counter E.M.F.* The difference between the two may be called the *net E.M.F.*

This is important in motor operation because as a motor gains in speed, its counter E.M.F. becomes greater as more and more magnetic lines of force are being cut. This, in turn, means that the net E.M.F. becomes less and less, with the result that less current flows in the motor circuit. Thus a motor requires less current when running full speed than when starting.

To compensate for this difference in starting and running currents, starting boxes, which are variable resistors or rheostats, are frequently placed in a motor circuit. It is obvious that if the full line voltage is impressed on the motor while starting, and before any counter E.M.F. (counter voltage) is generated by the rotating armature, the coils might be seriously damaged or burned out. Therefore a gradual application of voltage by means of the starting compensator as the motor gathers speed will eliminate such damage.

CHAPTER 4

Transformers.

Since a conductor moving through magnetic lines of force will have an E.M.F. (voltage) set up within it, the strength of which will depend upon the number of lines of force being cut, it follows that any change in magnetic lines of force around a stationary conductor will also generate or *induce* an E.M.F. in that conductor.

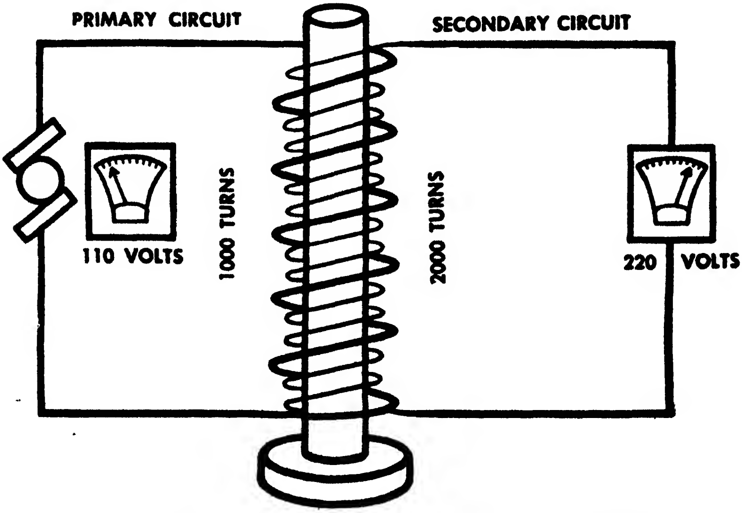


Fig. 40.—Transformers operate on this principle of mutual induction.

It will be recalled that alternating current is constantly changing its direction, so that a magnetic field produced by a coil through which alternating current is flowing will be in a constant state of change and, therefore, capable of *inducing* an E.M.F. in another coil. This law of magnetism is usually referred to as the principle of *mutual induction* and is the basis of transformer operation.

A simple transformer consists of a ring or open square of iron called a *core*, with two coils of wire wound around it on opposite sides and not connected together. One coil would have a current flow pushed through it by a source of alternating E.M.F. (A.C. generator), so that the magnetic field produced in the core would be constantly changing. This coil is called the *primary*. The second coil on the opposite side would have an E.M.F. induced in it by the fluctuating lines of force in the magnetic field of the first coil, and if the circuit of the second coil is completed or closed, an induced current will flow in it. The second coil is called the *secondary*.

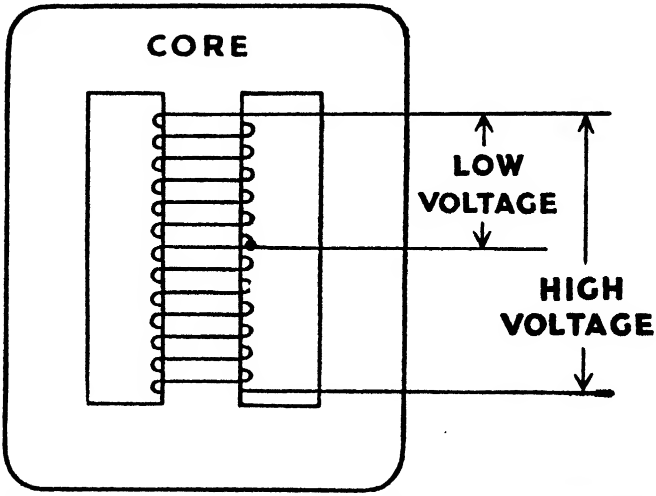


FIG. 41.—Diagram of auto transformer core windings. (See page 48.)

Thus in a transformer we have a means of inducing alternating current from one circuit to another by magnetism, the two circuits not being directly connected in any way. Since a reversal of the magnetic field in the primary coil takes place at every alternation of the generator supplying the E.M.F., and since these lines of force generally follow the iron core and pass through the secondary coil, it is obvious that the induced E.M.F. in the secondary coil will have exactly the same alternating characteristics or frequency. There is, however, a definite ratio between the strength of voltage in one and in the other, and in this ratio lies the practical use of the transformer.

The function of a transformer is to increase or decrease the voltage of an alternating current. The voltage in the secondary circuit depends upon the ratio of turns in its coil to the turns in the primary circuit coil. If the primary coil has, for example, 20 turns and the secondary coil, 40 turns, the ratio is, of course, 1 to 2, so that with the primary connected to a 120-volt A.C. circuit, 240 volts A.C. will be produced in the secondary circuit. Conversely, if the 120-volt line is connected to the 40-turn coil, thus making it the primary, only 60 volts will result in the 20-turn or secondary coil.

This relationship holds true in all simple transformers regardless of the number of turns used in either the primary or secondary, and it can be expressed as follows (except for relatively small losses):

$$\frac{\text{Primary voltage}}{\text{Secondary voltage}} = \frac{\text{primary turns}}{\text{secondary turns}}$$

Transformers may be wound in different ways. One common method which saves space and weight is to place one winding over the other on the same core. In some applications such as radio, the power transformer may have two or more secondary windings, each with a different ratio to the primary so that different voltages may be supplied to the different elements of the radio tubes as required.

The transmission of power from the generating plants to thousands of homes, stores and factories would not be feasible without transformers, since they make transmission of high voltages possible over long distances with consequent lower line losses.

Another type of winding is called an *autotransformer*. This type differs in that only one winding is used, which is divided into two parts. In this case the coils are not separated, but the required voltage change is accomplished.

There is one other factor in transformer construction that should be considered briefly before we leave the subject, and that is the *core construction*. When an induced E.M.F. is set up in a solid bar of metal, the resulting flow of electrons will eddy around in the metal and develop

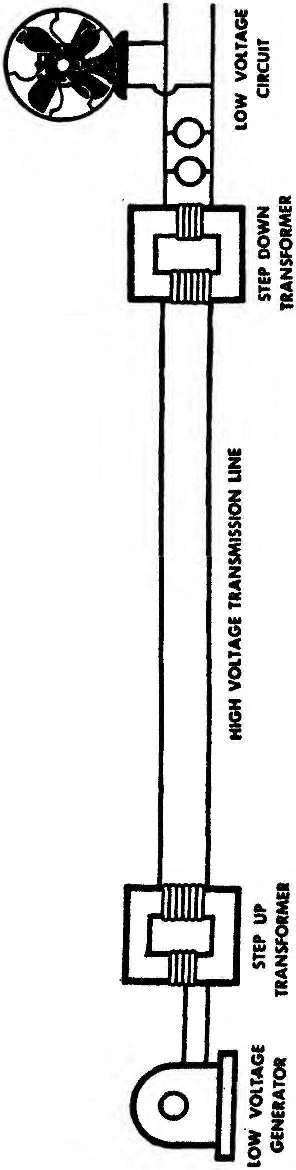


Fig. 42.—Transformers are important in electric-power distribution.

a magnetic field of their own. These *eddy currents* will cause a "dragging" or "damping" effect on the main magnetic field. In order to eliminate this, transformer cores (as well as the cores of other electromagnetic devices such as motors) are built up of thin sheets of metal insulated from each other, instead of from a solid bar of metal. This construction, which is called a *laminated core*, prevents the eddy currents from flowing around but permits the main magnetic field to be useful.

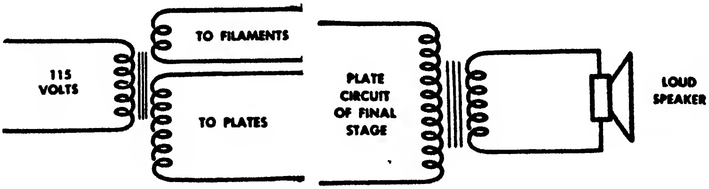


FIG. 43.—A radio power transformer, left, is one example of many methods of winding transformers. So is the circuit of the output on the loud-speaker system shown on the right.

When there is an increase in voltage in a transformer, there is a *decrease* in current in the same proportion. In other words, the voltage increase is gained at the expense of current. This can be expressed as follows:

$$\frac{\text{Primary current}}{\text{Secondary current}} = \frac{\text{secondary turns}}{\text{primary turns}}$$

But, since wattage or power is the product of voltage and amperage (current), it can be seen that there is no appreciable loss of power in a transformer.

Inductance.

It has been explained that when a bar magnet is plunged into a coil of wire and removed from it several times in quick succession, an alternating current is generated in the circuit of the coil as long as the magnet is kept in motion. It has also been pointed out that if an alternating current is forced through a coil around a stationary bar magnet from an external source, it amounts to the same thing as moving the magnet, so that we have in the latter case two distinct E.M.F.'s—one from the external source and one from the magnetic field—pushing current in opposite directions within the coil. The pressure generated by the magnetic field, it will be recalled, is the counter E.M.F., which opposes the start of current flow from the impressed E.M.F. and likewise opposes the stopping of it after it is once flowing, much like the inertia of stationary and moving objects.

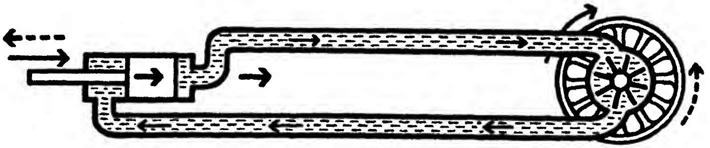


Fig. 44.—Inductance in an electric circuit is similar to inertia. It is the property in the circuit which opposes any change in the current passing through it. The flywheel in the water circuit above presents the same opposition to the flow of water through the pipes.

The property of an electric circuit, by which it opposes any change in the current flow through it, is called *inductance*. In other words, the current has a tendency to be sluggish in responding to the rapid alternations of the voltage or E.M.F. and may lag behind it. Thus the voltage may reach its pressure peak before the current reaches its flow peak.

A water-pipe analogy may be used to illustrate inductance. In Fig. 44, the piston can be compared to the source of alternating E.M.F., the water in the pipe circuit to the current flow and the heavy water wheel to the inductance. As the water in the pipe changes its direction, it must start the heavy wheel in motion—first in one direction and then in the other. The sluggishness of the water in changing its direction of flow in the arrangement can be easily visualized. The alternating motion of the wheel will obviously lag behind the motion of the piston.

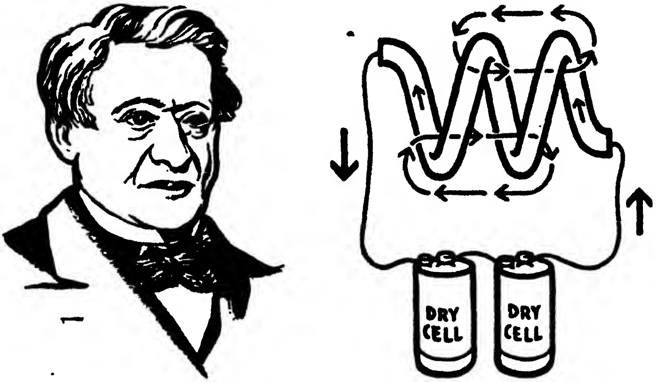


FIG. 45.—The principle of self-inductance is shown in the diagram at the right. The unit of inductance, called a *henry*, was named for Joseph Henry, left, who made many important magnetic discoveries.

The unit for measuring self-induction is called the *henry*, named after Joseph Henry, an American scientist. One henry is the inductance which produces an induced E.M.F. of one volt when the current is changing at the rate of one ampere per second.

Capacitance—Condensers.

The term *capacitance* is always used in conjunction with a device called a *condenser*. As a matter of fact, the word *capacitor* is frequently used instead of *con-*

denser. Since *capacity* usually means *all a thing will hold,* a condenser or capacitor can be thought of as a sort of reservoir in which an abundance of electrons can be temporarily stored. When there is a superfluous number of electrons forced into such a reservoir, the pressure becomes so great that it discharges, and they all rush out like water through a broken dam.

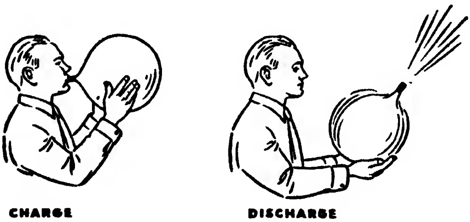


Fig. 46.—Capacitor discharge is like instant deflation of a balloon.

A condenser might also be compared to a toy balloon. As air is blown into it, the balloon swells until finally it will hold no more and the air and pressure can be instantly released. The filling of the balloon is similar to the charging of a condenser, and the instant deflation similar to a condenser discharge.

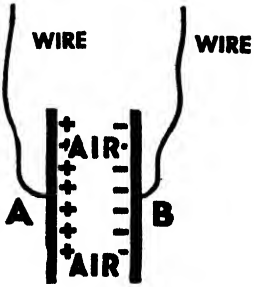


Fig. 47.—Diagram of a simple air condenser.

A simple condenser consists of two plates of conducting material separated by air or by some insulating material such as mica or glass. The capacitance (electron capacity) of a condenser is determined primarily by three factors: first, the total area of plate surfaces subjected to a potential difference (voltage); second, the space between these surfaces; and third, the dielectric (insulating) material or substance which separates the surfaces.

It should be remembered that current does not flow *through* a condenser, but rather *into* it and then *out* of it.

Capacitance in an A.C. circuit has the opposite effect of inductance in that it causes the current to *lead* the voltage. This means that the current will reach the peak of its flow before the voltage reaches its peak pressure. Later on, a practical and common use of capacitance to offset the lag of inductance in a two-lamp fluorescent circuit will be described.

The unit of capacitance measurement is called the *farad* (named for Faraday), but because it is so large, the microfarad (one-millionth of a farad) is more commonly used. One farad is the capacitance of a condenser in which a charge of one coulomb produces a one-volt potential.

Power Factor.

Prior to 1939, power factor was a subject which concerned only power-plant engineers or the manufacturers of rotating electrical machinery and induction devices. During that year, however, the use of fluorescent lamps, which have inductance in their circuits, became quite widespread, and people who used them began to hear about power factor and ask for enlightenment.

There have been many explanations of power factor presented to the general public, but most of them have failed to be completely understood by the layman, partly because he lacks the necessary background of magnetic inductance. It is hoped that the reader, having read this far, will have acquired that background of understanding, because with it the explanation of power factor is somewhat easier.

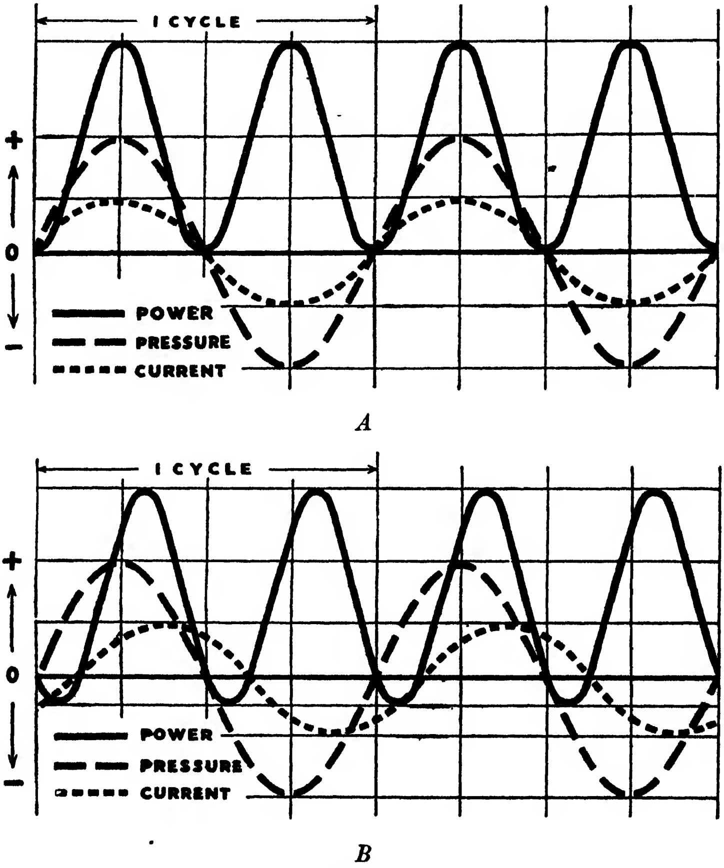


FIG. 48.—Curve *A*, unity power factor; curve *B*, lagging power factor.

It has been explained with a diagram (Fig. 34) how the voltage or pressure of an A.C. system builds up from zero to a maximum value in one direction and diminishes to zero again, and then does the same thing in the opposite direction to form what is called a *sine wave.* It also has been indicated that the current flow follows the same schedule of rise and fall. However, it was pointed out under the subject of Inductance that certain characteristics of the system or circuit may cause the current peak to occur *after* the voltage peak, or to *lag* behind it. Furthermore, it has been explained how capacitance in the circuit will cause the current peak to occur *ahead* of the voltage peak or to *lead* it.

The power factor of a circuit is said to be 1.0 or unity, when the two peaks occur simultaneously. But when inductance is introduced into the circuit as with transformers, induction motors and similar apparatus, and the current peak occurs after the voltage peak, a *lagging* power factor exists since the power drawn by the apparatus actually is less than the product of the voltage and current (amperage). The ratio of what it actually is to what it should be is called the *power factor.*

Perhaps a clearer understanding can be obtained by studying the two curves *A* and *B* (Fig. 48). Curve *A* represents a condition of unity power factor; that is, the voltage and current peaks occur at the same time so that the power peak, being the product of the two, must also occur along with them and always be positive.

But in curve *B*, we find the current lagging after the voltage, which means that not only do their peaks occur at different times, but likewise their zero values. Now since a figure multiplied by zero gives a product of zero, it can be seen that whenever *either* the voltage or current is at zero, the power value *must* be there also. Furthermore, whenever the voltage shows a positive value at the same time that the current shows a negative value (or vice versa), the power value must be negative. In effect, this means that the device which is making the circuit inductive should be using more power than it actually is since a portion of it is negative.

In order to complete an understanding of power factor, it might be well to consider a circuit in which current, voltage and power readings could be taken for either resistance or inductance devices. Figure 49 shows a circuit, supplied by an A.C. generator, in which an ammeter, a voltmeter and a wattmeter have been connected. The load can be either a small motor or an incandescent lamp, depending upon which way the switch is thrown. Let us assume that the switch is thrown downward to make the lamp light and the meter readings are taken. First, we see from the ammeter that the current flow is 0.5 ampere. Next we find from the voltmeter that the A.C. generator is producing a pressure of 120 volts. Then, to find the power or load

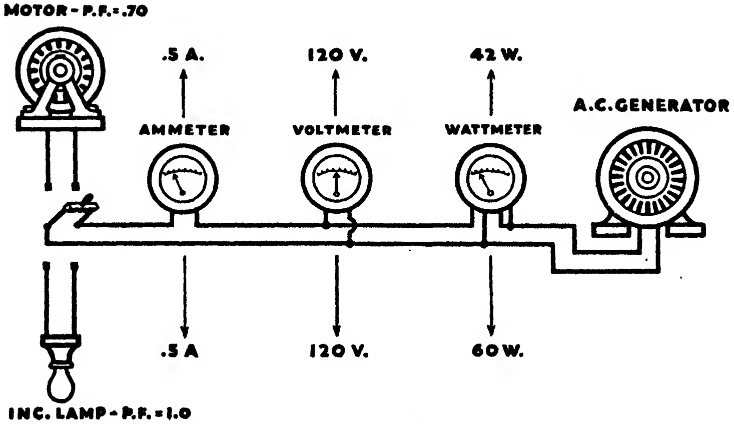


FIG. 49.—Circuit for power-factor calculation.

(wattage), the two readings multiplied together will give 60 watts, which we find is also indicated by the wattmeter. There is, therefore, a 60-watt lamp burning in the socket.

Now let us throw the switch the other way, shutting off the lamp and starting a small motor. Again we find from the ammeter that the current flow is 0.5 ampere, and that the voltage from the generator is the same 120 volts, but that the wattmeter actually shows only 42 watts instead of the product of amperes and volts as before. This difference of 18 watts of power cannot be *lost* because enough current is flowing and enough pressure is there to produce it. Where, then, does it go?

The answer is found in curve *B* of Fig. 48. While the motor draws power from the line as indicated by the power wave or curve, it will be seen that part of the wave is below the zero line or down in the negative region. Perhaps the best way to comprehend power of negative value is to think of it as being returned into the circuit by the motor after being used.

The 42 watts, as indicated on the wattmeter, is, therefore, the actual power, whereas the power used ought to be the product of the volts and amperes. For that reason the power drawn by a circuit containing inductance, such as a motor, is measured, as it should be, in volt-amperes or kilovolt-amperes (KVA) for larger loads, instead of watts or kilowatts.

Since what the power actually is is indicated by the wattmeter, and what it ought to be is the volt-amperes, power factor can be expressed as

$$\frac{\text{Watts}}{\text{Volt-amperes}} \quad \text{or, for larger loads,} \quad \frac{KW}{KVA}$$

Therefore, the power factor of the motor in the diagram, as indicated by the readings found on the meters, would be

$$42/60 \quad \text{or} \quad 0.70 \text{ (70 per cent)}$$

The *leading* power factor of a circuit containing capacitance is determined and calculated in the same manner. For commercial purposes, a meter is used to obtain either lagging or leading power-factor data directly.

CHAPTER 5

Reactance—Inductive, Capacitive and Total.

The counter E.M.F. (explained on page 43) resulting from the self-inductance of a device in an A.C. circuit, opposes the flow of current in that circuit just as a resistance does. When the circuit contains *only* such opposition, that is, no resistance or capacitance, the opposition is called *inductive reactance* and is measured in ohms.

Capacitive reactance is also an opposition to the flow of current in an A.C. circuit, but it is that which is established by a capacitor or condenser when there is no resistance or inductance. It also is measured in ohms.

Total reactance is just what the name implies, that is, it is the combined inductive and capacitive reactance when the two are in series in an A.C. circuit opposing the flow of current.

Impedance.

When in an A.C. circuit there is also a resistance in series with total reactance, the total opposition to current flow is called the *impedance* of the circuit.

The methods of computing reactances and impedance are a little beyond the intended scope of this book, but they are available in modern engineering handbooks.

Resonance.

The term *resonance* is commonly associated with sound. Nearly everyone has had the experience of striking a note on a piano and hearing a piece of paper on the music rack or on top of the piano vibrate and produce the same tone. Instead of the paper that vibrates, it may be a vase or dish on the piano or even elsewhere in the room. The reason these remote objects vibrate is that their resonating characteristics are the same as those of the piano string which is struck; that is, they are in tune with each other, and the remote object is said to resonate or be in *resonance* with the sound wave produced by the piano string.

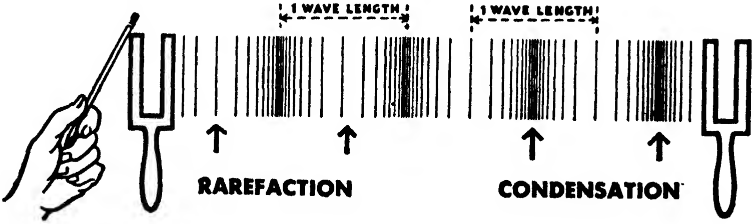
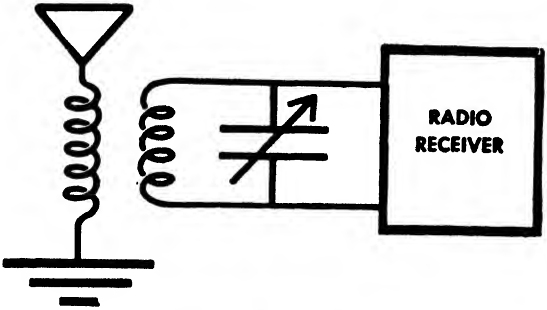


Fig. 50.—Resonance in sound waves, illustrated by use of two tuning forks which have the same frequency (pitch).

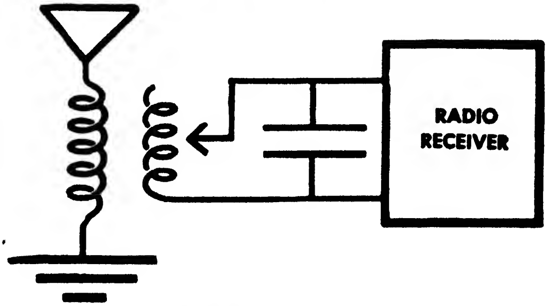
Another example might be two violin strings on the same instrument tuned exactly the same. When the bow is drawn across one of them, the other vibrates and produces the same tone because it is in resonance with the first.

Figure 50 illustrates the same thing with two identical tuning forks set up some distance apart. One of them, when struck, produces sound waves which travel to the second and cause it to vibrate since its natural frequency is the same wavelength as the first. The two are therefore in resonance with each other because they vibrate at exactly the same frequency.

Under average conditions (in air at 32° Fahrenheit) sound waves travel at the rate of about 1,088 feet per second.



A FIXED INDUCTANCE AND VARIABLE CAPACITANCE



B FIXED CAPACITANCE AND VARIABLE INDUCTANCE

Fig. 51.—Practically the same principle as the tuning fork is used in radio broadcasting and reception. The eceiver is *tuned* or made to resonate to the frequency of the transmitter.

Now when a charged condenser is discharged by bringing the two plates in contact, the electrons rush over from one side to the other. With an induction coil also in the circuit, too many of them will get over with the first rush because of the inertia characteristics of inductance, thus leaving one side with too few. Consequently, the condenser discharges again, reversed, so that some electrons rush back again. This seesaw action continues a few times and gradually dies out. Such oscillations are very rapid, the frequency being sometimes as high as two million a second or more.

An electrical circuit which is made to oscillate in this manner sends out or radiates into space electromagnetic waves that are somewhat similar in characteristics to the sound waves just discussed. They travel at a much higher speed, approximately 186,000 miles per second, however, which is also the speed of light and other types of radiant energy. Furthermore, they do not depend upon air, or on solids or liquids, as a medium of transmission, as sound waves do. There is a definite relationship between the velocity, wavelength and frequency of these waves in that the velocity in meters per second equals the product of the frequency (oscillations per second) and the wavelength in meters. This is expressed as

$$V = NL = FX$$

where F = frequency, cycles per second
X = wavelength, meters
V = velocity

It will be recalled that radio broadcast wavelengths are expressed in meters.

Two electrical circuits can be tuned or made to resonate if they can be adjusted to the same frequency. This is the basic principle of all radio transmission and reception. The adjustment is made in the receiver, and we speak of it as *tuning.* The change in tuning or resonance can be accomplished in the receiver by varying either the capacitance (condenser) or inductance.

To vary the capacitance it is necessary (as explained previously) only to change the effective area of the condenser plates; the inductance can be changed by varying the effective number of turns in the coil, fewer turns resulting in a decrease in self-inductance and more turns in an increase. Such variable condensers and coils are found in all radios.

Resonance plays an important part in electrical circuits containing gaseous discharge lamps, fluorescent lamps and other electronic devices. It will be further discussed later.

Harmonics.

Since the electromagnetic waves generated by an oscillating electrical circuit can be compared in a general way to sound waves from the standpoint of resonance, it is reasonable to expect that other characteristics of sound waves will be present in electromagnetic radiation.

Any vibrating string produces, in addition to its primary or fundamental tone, several *overtones,* which may be higher pitched and of less volume. Assuming that such a string vibrates at the rate of 220 oscillations a second, there are also several overtones present at 440, 660, 880 and so on, becoming more faint as their pitch becomes higher. This fundamental tone along with its overtones is called a *harmonic series.*

The fundamental frequency of an oscillating electrical circuit also is found to have its electromagnetic overtones, which likewise are called *harmonics.*

Harmonics in an electrical system manifest themselves in a very decided manner, and frequently present difficult and involved problems. Further technical discussion of them would be out of place here, but the reader should at least be aware of their existence and general character.

Part III

ELECTROMAGNETIC RADIATION

Author's Note: The author recognizes that many of the explanations and statements set forth here are controversial and subject to modification when further researches eliminate the questionable points.

CHAPTER 6

Simple Waves.

In order to obtain a clear concept of the characteristics of electromagnetic waves, it may be well to consider for a moment the simplest and most familiar of all waves—those produced on the surface of water.

Everyone knows how a stone tossed out upon a calm pond sets up a disturbance on the surface of the water which radiates in ever-widening circles away from the point where the stone fell. This disturbance we call *waves*. Further study of such waves reveals that they travel at a fairly constant rate of speed and that they are reflected away from a wall or other rigid surface at the edge of the pond and will start back out toward the center again.

It should be remembered that the water itself does not move toward the shore with the waves, but that it merely rises and falls as the disturbance passes through it. The movement of the water might be indicated by a floating object such as a stick. As the wave approaches, the stick moves upward to the crest and slightly forward, and then as the crest passes, it descends again and moves back to its approximate original position.

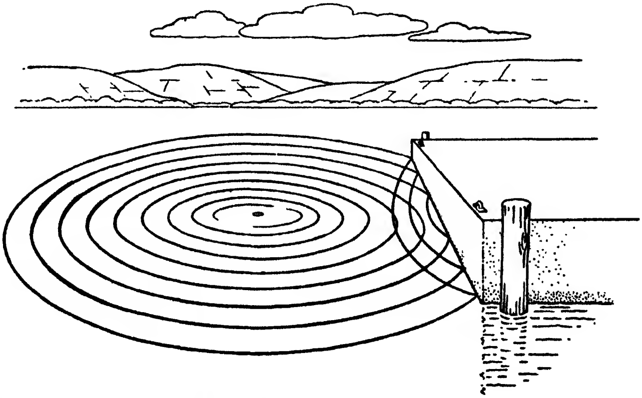


FIG. 52.—Waves on the surface of calm water radiate away from the source of disturbance and are reflected from the surfaces they strike.

The distance between the crests of two successive waves is called the *wavelength*, and the vertical distance between the crest and the level surface of the water (or one-half the vertical distance between the crest and the trough) is called the *amplitude*. Those two terms are applied in a similar manner to electromagnetic waves.

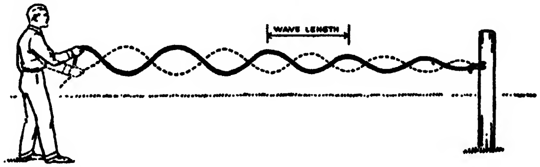


FIG. 53.—Waves travel along a slack rope and are reflected back from the fastened end.

Similar waves travel through solids as well as liquids. A slack wire or rope will transmit a disturbance from one end to the other and back and forth several times before it finally dies out. If a long beam of wood or metal is tapped at one end with a hammer, the disturbance can be felt as it travels from one end to the other. The rates of speed of waves vary with the material through which they pass.

Sound Waves.

Sound waves are transmitted through air, liquids and solids in much the same manner. They are, however, somewhat different in character in that they are *compressional* in form. This form may be illustrated fairly well with a long coiled spring. If the spring is stretched out to moderate tension between two rigid points and three or four of the coils are squeezed together at one end and then suddenly released, this compression will traverse the length of the spring, be reflected back from the opposite end and so on for a few times.

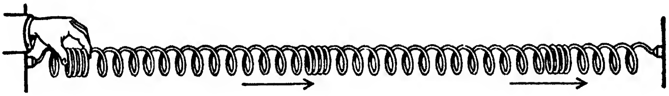


FIG. 54.—Like the waves in a coiled spring, sound waves are compressional; however they do not follow one direction as in the spring.

While sound waves are compressional, they do not follow one direction like those of the spring, or move in a plane as do the waves on the surface of water, but rather radiate in all directions like a rapidly expanding balloon. Sound waves are created by some disturbance just as the stone on the quiet pond creates the water waves. If a rifle is fired in the woods a half mile away, the disturbance caused travels outward in spherical waves so that about

2 seconds later when it reaches our ears we *hear* the waves and interpret the disturbance as a sound.

It has been mentioned previously that sound waves travel 1,088 feet per second in air at 32° Fahrenheit. In water they travel more than four times as fast and in steel, about fifteen times as fast, but they are not transmitted at all through a vacuum. They also are reflected from surfaces as water waves are reflected from the wall. This reflected sound we call an *echo*. The study of how sound waves behave in their reflection from flat and curved surfaces, and how they can be amplified and diminished, is called *acoustics*.

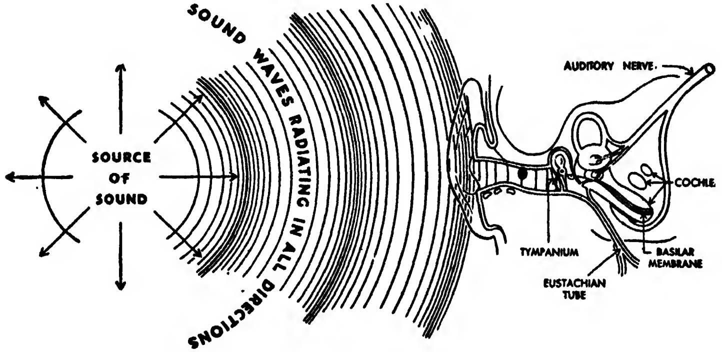


FIG. 55.—Sound waves radiate spherically from a disturbance and, when striking the ear drum, cause it to vibrate, producing the sensation of sound.

During the First World War the presence and location of a submerged submarine was determined by means of sound detectors called *hydrophones*. These instruments were placed on shipboard and connected to delicate sound receivers on the underside of the ship's hull. A much more accurate and extensive method of detecting enemy undersea craft in the Second World War involves electron tubes and supersonic waves instead of audible sound waves. Surface craft and airplanes are located many miles away through fog, haze and in total darkness by means of electromagnetic waves produced and received with radio ranging equipment. Both types of radiation will be discussed more fully later.

Electromagnetic Waves.

About the only similarity between sound waves and electromagnetic waves is that they both radiate spherically from the source of disturbance. Otherwise, they are in a different category. The disturbance which starts electromagnetic radiation has to do with the movement of charges, and while it is known that electromagnetic waves are moving electric and magnetic fields, it is not as yet clear just what such fields actually are.

A study of the frontispiece, giving the range of electromagnetic radiation, shows that while these waves all radiate from the source of disturbance at the terrific speed of about 186,000 miles per second (in air), there is a tremendous difference in their frequency and wavelength characteristics even though the speed is constant. At the extreme right end, for instance, we find waves which are 10 million meters (over 6,000 miles) from crest to crest, and which vibrate only 30 times per second (30 cycles). At the opposite end the wavelengths are so short and the frequencies so high that it is difficult to conceive of them at all. The distances between the crests of these waves are in the order of one ten-thousandth of an Angstrom, an Angstrom being a unit of length approximately equal to one 250 millionth of an inch (100 million Angstroms equal 1 centimeter), and they vibrate at a frequency of over thirty quintillion thousand times per second (30,000,000,000,000,000,000,000 cycles—usually expressed as 3×10^{22} cycles or 3×10^{16} megacycles). Another unit of wavelength measurement is called the millimicron (mu) and is equal to 10 Angstroms, a micron being one-millionth of a meter.

Although, as has been stated, the true nature of electromagnetic waves and their exact cause are not completely understood, we do know how to start them and how to detect them. In some regions of the scale it is much simpler than in others. Nature has endowed all men and animals with two senses which detect or respond to certain bands of wavelengths and frequencies which fall about midway between the two extremes. These senses are *sight* and *touch*. Electromagnetic radiation between 4,000 and 7,800 Angstrom units in wavelength we *see* as visible light in colors ranging from deep violet to deep red. Beyond the red for some distance we *feel* the waves as *radiant heat*, and beyond the violet the radiation is known as the *ultra violet*, which acts upon our skin to cause sunburn.

Other than this, as far as is known, we recognize no sense which interprets naturally the vast range of other wavelengths and frequencies. But science has developed several types of electron tubes which can generate, detect and control the electromagnetic waves in many of those regions which nature has closed to us, and thus place them at our disposal by changing the radiant energy of the waves into a form that we can either see, feel or hear.

The diagram of the range of electromagnetic radiation shows the major divisions or regions which can best be discussed as individual units. Some of these are vital to our everyday life, while others are undergoing development and scientific investigation. There are also a few regions of frequencies and wavelength about which very little is known except that they must exist to fill in the gaps between the more developed and understood regions. Therefore, rather than start at the low or right-hand end of the scale, and consider each bracket in order all the way up, it will be better, perhaps, to discuss them in accordance with their apparent importance to human life, comfort and happiness.

CHAPTER 7

Light.

Solar radiation sustains practically all life on earth. As shown in the electromagnetic range diagram, the sun radiates its energy in a band which includes ultra violet, light, and infra-red or heat. Some of the energy emanating from the sun never reaches the surface of the earth, however, because the envelope of air surrounding the earth filters it out, but the most important radiations get through and permit us to live.

Within the band of solar radiation there is a relatively narrow section of electromagnetic waves having wavelengths ranging between about 4,000 and 7,800 Angstrom units and frequencies of around 500 or 600 billion kilocycles. Nature has provided us with two receiving sets for electromagnetic waves of these characteristics. The receiving sets consist primarily of a group of nerve fibers ending in rods and cones which are sensitive to the wavelengths and frequencies and in front of which are lenses to focus the radiation upon them. We call these receivers our *eyes*. When the electromagnetic waves pass through the lens and strike the nerve ends, the pulsation set up proceeds along the optic nerve to the brain and we experience the sensation of seeing light; that is, we see an object from which light is being reflected, or an object which is emitting light.

Just how the eye and brain work together in transmitting radiant energy of these wavelengths and frequencies into the sensation of sight, no one knows. It doubtless involves some electrochemical process in which a flow of electrons to and from the brain takes place. Beyond that, the working of the mind is known only to its Maker.

Radiation having wavelengths of from 4,000 to 5,000 Angstrom units we see as violet to blue light, whereas in wavelengths of from 6,500 to 7,800 units the sensation is red. Between these limits we see all the other colors as in a rainbow. The wavelength of green colors is around 5,300 Angstroms, and yellow is between 5,500 and 6,000. Orange, obviously, falls between yellow and red, that is, between 6,000 and 6,500 Angstrom units. Above the violet limit in one direction and below the red limit in the other we see nothing, but we know radiations exist because we can feel them naturally as well as produce, control, detect and measure them with devices and instruments designed for the purpose.

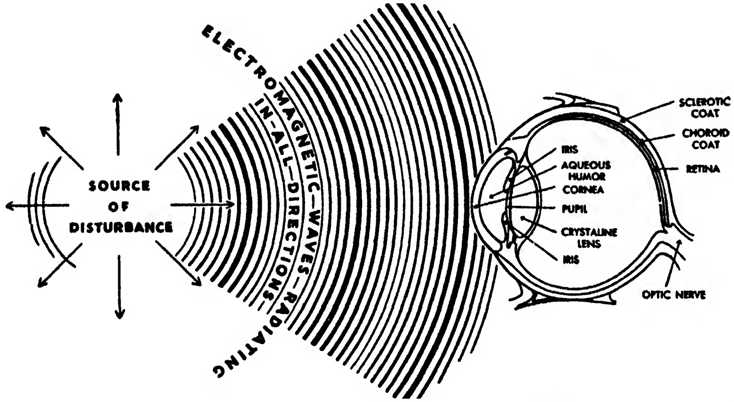


FIG. 56.—Electromagnetic waves radiate spherically from a source of the disturbance and pass through the lens of the eye, which focuses them on the retina, producing the sensation of sight.

Like water waves, electromagnetic waves are energy being radiated from a source of disturbance. The source of electromagnetic radiation, it has been stated, involves the movement of electrons which was described at the beginning of this book as negative elements in the little knots of balanced energy called atoms. Light, therefore, being electromagnetic waves of definite wavelengths and frequencies, is radiant energy and as such must result basically from a disturbance of electrons in which this energy is released and radiated.

It will be recalled that in an electrically neutral atom, electrons revolve about the nucleus, each in its own orbit. But when something disturbs an electron and knocks it out of its orbit, it releases energy while jumping back. If a length of wire or a solid block of metal is heated sufficiently, thus agitating countless billions of atoms, their electrons become abnormally active, and the released energy emanates in electromagnetic waves which we know as *light*. The color of the light depends upon the predominant wavelengths of the radiation. As more heat is applied, increased electron energy results in a consequent shift of wavelength or color from red hot to yellow and white hot. Since the atomic structure of each metallic element is different, different metals burn with characteristic colors of their own. Any metallic element may be identified by this color.

There are other ways of producing light without the application of heat. In chemistry, for instance, phosphorescent light can be produced by mixing together solutions which result in a disturbance of their molecules to the extent that electromagnetic waves will radiate as visible light without heat. This is found in nature when fireflies and many types of sea creatures do the mixing within themselves.

Another method involves the deliberate knocking about of atoms with free electrons to release the energy from the atoms (their electrons) and thus obtain electromagnetic radiation of wavelengths which the eye can collect and send to the brain to interpret as light. This method is the basic principle of today's most efficient gaseous discharge and fluorescent light sources. In nature we see the same phenomenon many miles up in the rare atmosphere of the earth and call it *aurora borealis* or *northern lights*. For the present we are concerned only with a discussion of light as radiant energy. A more complete description of the characteristics of light from ionized gases will be presented later.

Control of Light.

Any discussion of light, no matter how brief, would be incomplete without mention of its control by *reflection* and *refraction*, or an explanation of its measurement. Light waves may be compared to water waves again when considering their reflection, but it should be remembered that while water waves may be anywhere from an eighth of an inch or so to several feet in wavelength, light waves are in the order of one fifty- or sixty-thousandth of an inch in wavelength, and furthermore that light waves are vibrating at the rate of about 500 or 600 trillion times a second, whereas water waves may reach the shore anywhere from three or four per second to one every few seconds. Therefore, in making a mental comparison, we must appreciate that our eyes do not distinguish minute waves of such extremely rapid vibration,

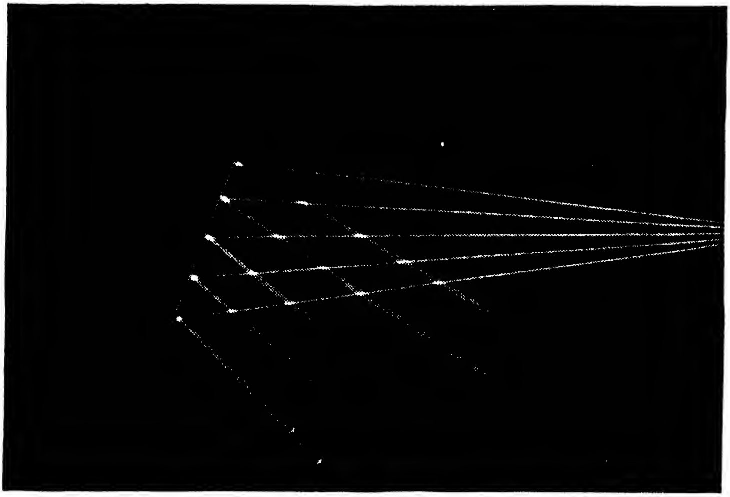


FIG. 57.—Angular reflection of diverging light beams from a specular plane surface. (*Courtesy of the Museum Committee, Massachusetts Institute of Technology.*)

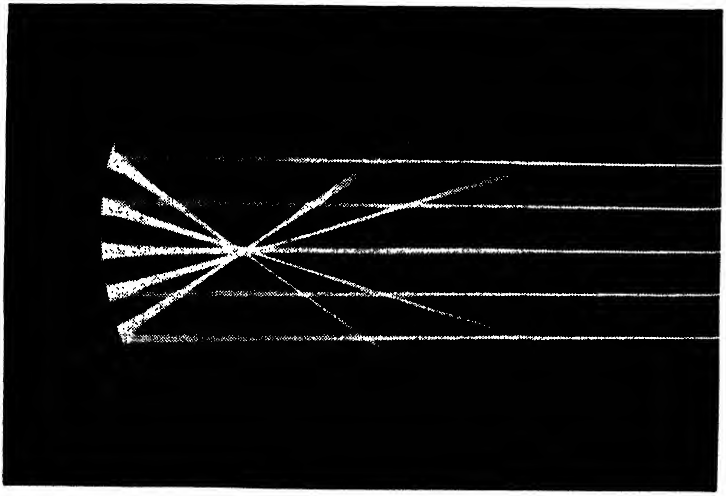


FIG. 58.—Reflection of parallel light beams from a concave specular surface. (*Courtesy of the Museum Committee, Massachusetts Institute of Technology.*)

but rather give us a concept of light as a steady or "solid" flow in all directions, spherically.

A beam or ray of light can be compared to a segment of a water wave or rather to a whole series of segments, one after the other. Both travel in a straight line from their source. Both are reflected away from a smooth surface at the same angle that they strike it. If the surface is rough or uneven, the reflected beam or succession of waves is diffused in both cases. If the surface is circular or parabolic in shape, the pattern of reflection is essentially the same for both.

In either instance, reflection means that the energy of the waves "bounces" back from the surface after some is absorbed by the surface. The ratio of what energy bounces back to what strikes the reflector is called the *efficiency* of the reflector.

The water-wave analogy cannot be used in discussing light refraction because water waves are not transmitted through a solid such as glass. A comparison with the transmission of sound waves might be used, but it is not particularly satisfactory since sound waves cannot be seen except with laboratory apparatus.

Light waves travel at a different rate of speed through transparent solids and liquids than they do through air or a vacuum. As a matter of fact, they travel slightly slower in air than in space beyond the earth's atmosphere (vacuum). In water the speed of light is about three-fourths that in air or approximately 140,000 miles per second.

In passing from one medium to another, light is bent or refracted. Nearly everyone has noticed the broken or bent appearance of a rigid stick thrust into

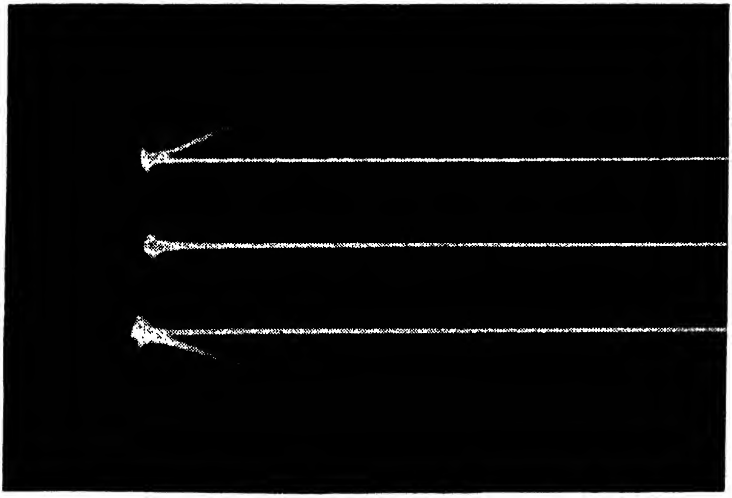


FIG. 59.—Reflection of parallel light beams from a convex specular surface. (*Courtesy of the Museum Committee, Massachusetts Institute of Technology.*)

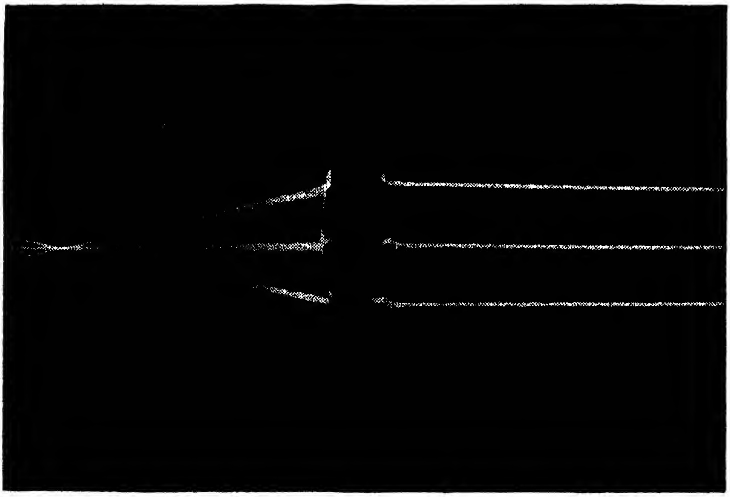


FIG. 60.—Refraction of parallel light beams through a condensing or converging lens. (*Courtesy of the Museum Committee, Massachusetts Institute of Technology.*)

shallow water at an angle. At the surface where the stick enters the water, it seems abruptly to change its direction to the bottom. A shallow pool always looks shallower from above than it actually is, and the depth appears to decrease as the distance away from the bottom area, directly below, increases.

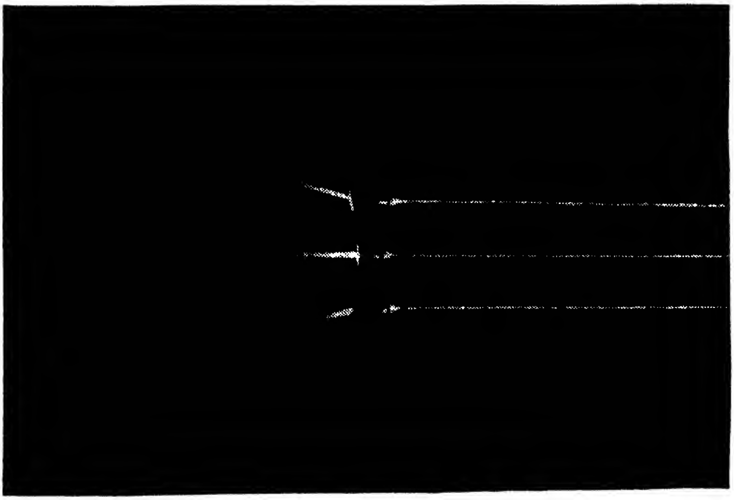


FIG. 61.—Refraction of parallel light beams through a concave or diverging lens. (*Courtesy of the Museum Committee, Massachusetts Institute of Technology.*)

At sunrise and sunset the sun seems larger than at noonday because its radiation comes to us in rays tangent to the earth's surface and, therefore, must pass through more and denser air than when directly above. The air in this case refracts or bends the rays, causing the same visual effect as the water in the shallow pool when it makes the bottom look nearer.

The refraction of light through glass is the basic principle of all optical instruments. The varying thick-

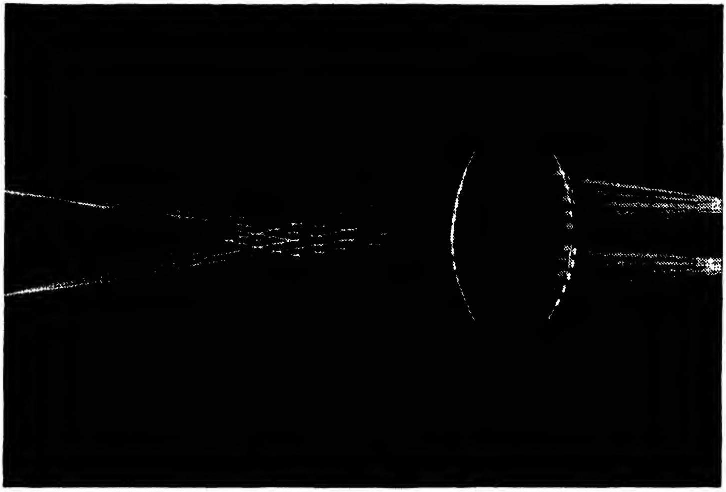


FIG. 62.—Refraction of two sets of diverging light beams through a converging lens. The sources are at the right. (*Courtesy of the Museum Committee, Massachusetts Institute of Technology.*)

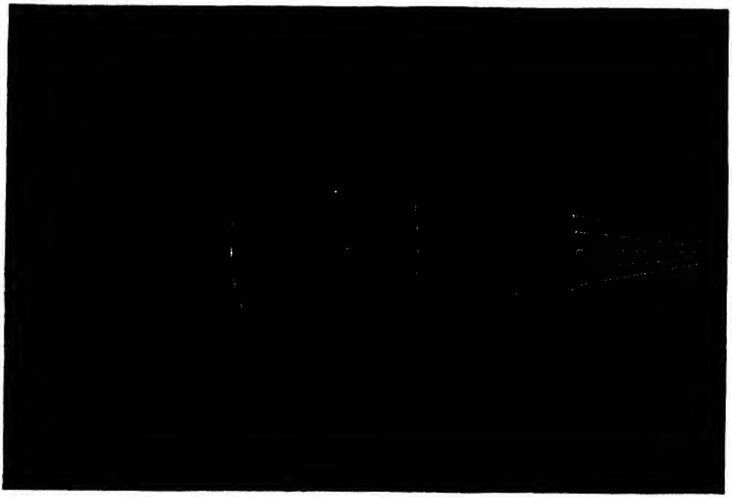


FIG. 63.—An optical system illustrating accurate control of light beams with three lenses. (*Courtesy of the Museum Committee, Massachusetts Institute of Technology.*)

nesses of lenses result in the high-power magnification which brings within the range of our vision the sun, moon, planets and other heavenly bodies, as well as the realm of bacteriology and the physical structure of material.

The study of light reflection and refraction is called *optics*, and to cover it completely would require many volumes. We must not leave it here, however, without some consideration of the prism.

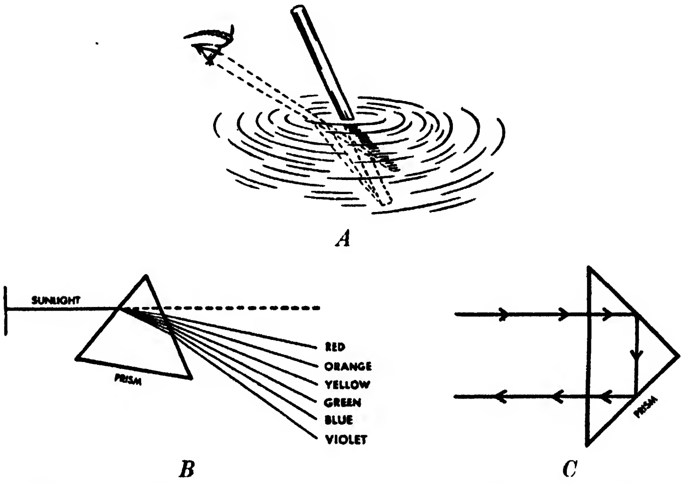


FIG. 64.—*A*, because of refraction, a stick thrust into shallow water appears to the eye to be broken where it enters the water. *B*, example of dispersion of white light into its component wavelengths or colors by means of refraction through a prism. *C*, total refraction of light with an isosceles-right-triangle prism.

As was previously pointed out, electromagnetic waves producing the visual sensation of deep-red light have a wavelength nearly twice as long as those producing deep-violet light. In passing through a liquid medium such as water or a solid medium such as glass, the shorter wavelengths (higher frequencies) are retarded more than the longer ones (lower frequencies), so that they are bent or refracted to a greater degree. Thus when a beam of light of all wavelengths, which appears to us as white light, enters these media at an angle and passes through and out again, the colors separate in the order of their respective wavelengths and we have a pattern of colors with red at one end and violet at the other. This occurs in nature when sunlight passes through rain drops or mist and we see a rainbow.

A prism is simply a short length of glass which is triangular in cross section. White light passing through two of its plane surfaces is *dispersed* or broken up into the component colors. Prisms may be cut to produce different results when light enters at different angles. If the cross section is an isosceles right triangle and a light beam is made to enter normal to (perpendicular to) one of the short sides, the beam will be refracted back out through the other short side without dispersion by being totally reflected from the hypotenuse or long side. Since in this case the light enters and leaves the glass perpendicularly, there is no bending of rays and therefore no breaking up into colors. The same prism will refract a light beam back in the direction from which it came if the beam enters the hypotenuse perpendicularly, so that no dispersion occurs.

Fresnel lenses, which are used extensively in airport beacons, lighthouses and a great many other similar mechanisms, utilize the refraction of multiple prisms (as well as spherical or cylindrical sections) to control the light in well-defined patterns. Certain types of commercial and industrial lighting fixtures and lenses depend entirely upon the refraction of many small prisms for their diffusion and light distribution.

Prisms cut cross sectionally as equilateral triangles (all sides and angles equal) do not refract light beams without dispersion because the beam cannot both enter and leave the glass perpendicular to the surfaces through which it passes, owing to the light-bending-angle characteristics of the glass. Prisms of this type are used in the *spectroscope*, an instrument specifically designed to break up light into its component colors for analysis.

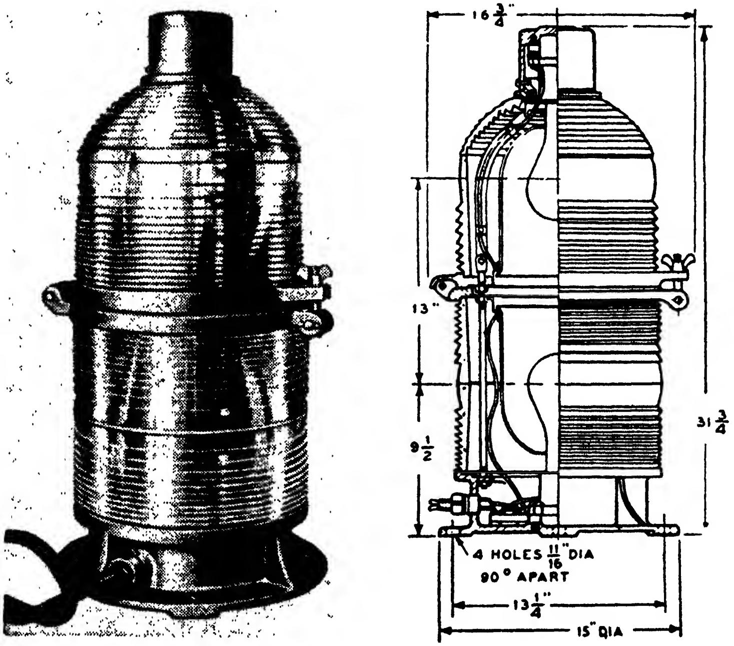


Fig. 65.—An airport code beacon utilizes two circular Fresnel lenses which produce a thin, horizontal *disc* of light 360° around the unit. (*Photograph courtesy of Crouse-Hinds Company.*)

Spectra and their infinite value to science deserve much more space than can be devoted to them here. Briefly, spectrum analysis is a means whereby the presence of any of the elements can be detected, even in the most minute quantities. The spectra (color dispersment) of incandescent or burning solids or liquids, or of ionized gases and metallic vapor discharges, contain lines (light or dark, depending upon the method of analysis used) which always appear at the same place for the same element. They are different and characteristic for each element. These lines may occur singly or in groups and appear deep in the regions beyond the range of visible light as well as within it. For each element there are always the same characteristic lines identified with the element, appearing at precise wavelength positions in its spectrum.

This being the case it is obvious that light emanating from sources of unknown make-up can be analyzed in a spectroscope, and by the characteristic lines appearing at certain wavelengths it can be determined of just what elements the emitting source is composed. This has been done with the sun, planets and other celestial bodies many times as well as with countless compounds in the laboratory. New elements have been discovered through the appearance of unfamiliar lines at new wavelength positions.

Since light is electromagnetic radiation resulting from a disturbance in the normal electron orbits around the nucleus of an atom, and since the number of electrons is different for each element, it follows that there is a relationship between the released electron energy causing light radiation and the lines appearing in the spectrum. This correlation of atomic structure in terms of the spectrum lines of a substance has been a fruitful field of science during the last two decades. From it has come most of our basic understanding which has developed into the science of modern physics.

It has been explained that light is made up of rapid pulsations of energy or electromagnetic waves radiating spherically from a source of electronic disturbance. If we can imagine these waves passing through a fine grating such as a comb, the teeth of which are no farther apart than the waves are to each other (approximately one fifty-thousandth of an inch), it can be seen that after passing through, the waves will be sliced into thin "sheets," each of which will be only the thickness of the space between the teeth of the "comb." Thus, the waves can continue to radiate up and down only if the teeth are vertical, from side to side only if they are horizontal, or in any other direction the teeth will permit. Light having undergone this fine "slicing" process is said to be *polarized.*

If a second comb is placed in front of the first, it is obvious that the radiating light will pass through it also only if the teeth point the same way. If they point at right angles and in a parallel plane to those of the first comb, the slices are sliced again or "diced," as it were, into dimensions smaller than their actual wavelengths so that the radiation is completely absorbed. This should not be confused with louvering of light, which merely effects a cutoff by reflecting or absorbing the radiation.

Light will be polarized by reflection if it falls upon a surface at a certain angle and may result in what is commonly called *reflected glare* if viewed at the same angle from the opposite side. Other angles will only partly polarize the light, and different materials have different angles of polarization. If an observer sees this reflected polarized light through glasses made of material which serves the function of a second "comb" at right angles, it is obvious that a large amount of the annoying and harmful reflected glare can be eliminated.

Polarization of light has been known for many years and was accomplished in laboratories with certain types of crystals which have, naturally, the necessary minute grating characteristics. Relatively recently, however, a method of manufacturing a material having polarizing properties was developed by Edwin H. Land in Massachusetts, and is commercially available today in sun glasses and other forms.

Polarized light also plays a vital part in many industries in the examining of various materials for stresses and strains. Under polarized light the strains appear as symmetrical color formations which change their shape to conform with the shifting of the load under which the material is placed.

The word *light* is frequently used in conjunction with the word *flux*, so that the combination, *light flux*, more properly describes perhaps the flow of light in electromagnetic waves from its source. Physicists measure light flux, that is, the flow of radiant energy, in ergs per second, just as the layman might refer to water flow in gallons per minute.

Since the flow of light is so rapid, however (186,000 miles per second), the general concept of it is as a static quantity like gallons, with no reference to time involved.

Illuminating engineers speak of the total light flux of a source or of the flux in a certain direction, but the common units of light measurement disregard the elements of time because there obviously can be no visual sensation of light-wave movement.

Measurement of Light.

The first basic unit of light measurement applies to the power of the source and is called *candlepower.* This

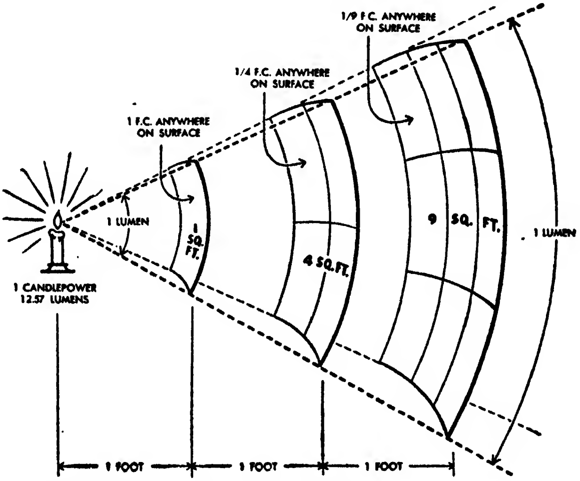


FIG. 66.—A diagram which illustrates the inverse-square law of light and the units of light measurement.

unit was established in 1909, when an agreement was reached between the standardizing laboratories of the governments of the United States, Great Britain and France that a standard light-source power unit should be the luminous intensity of a candle flame—the candle itself to have certain dimensions as well as definite specifications as far as the tallow and wick were concerned. Since then these laboratories maintain the original standard candlepower with incandescent lamps of precise operating characteristics.

Some light sources are rated in accordance with their luminous power. We purchase automobile headlight lamps, for example, by their candlepower size, whereas ordinary incandescent lamps for use in home, store or industrial illumination are rated according to their electric-power requirements—in watts.

Large searchlights have a unit called *beam candlepower* applied to them, which, as the term indicates, is the luminous intensity of a beam of light in any specified direction within the confines of the beam.

The second fundamental unit of light measurement is the *lumen.* It is a unit of light flux quantity, that is, the amount of light falling upon an area of surface. When a one-foot square of any flexible material, such as paper, is placed one foot away from a one-candlepower source, and curved so that all points of the square are one foot away or equidistant from the source, the square has one lumen of light upon it. It intercepts this amount radiating from the source. Obviously such a square would be part of the area of a sphere, 1 foot in radius. Since a sphere with a one-foot radius will have 12.57 square feet of surface ($4\pi r^2$), a source of 1 candlepower must always emit 12.57 lumens. A 2-candlepower source will emit twice as many or 25.14; 3-candlepower, three times as many, and so on.

It should be remembered that the size of the sphere or the area upon which the light falls has nothing to do with the lumen rating of the source. Areas intercept some of the lumens (or a portion of one) emitted by the source. Certain types of street-lighting lamps are size designated in lumens rather than in watts, so that a true measure of their light output will be indicated. All light sources have a published lumen rating in order that their actual light output will be known to the purchaser. The efficiency of an electric-light source is the ratio of its light output in lumens to its power input. This efficiency is expressed in *lumens per watt.* In other words, if a standard 100-watt incandescent lamp emits 1,620 lumens, its efficiency will be 16.2 lumens per watt.

The third basic unit of light measurement, called the *footcandle,* is quite well known. The footcandle is no direct indication of the power of the source or the amount of light it emits (except through calculation) but rather is a measure of the intensity of light at a point on any illuminated surface. It can be defined as the illumination at a point one foot distant from a one-candlepower light source. Since a lumen is the amount of light on a one-foot square one foot distant from a one-candlepower source, it can be seen that every point on that square will be illuminated to an intensity of one footcandle.

A study of the diagram should clarify the relationship between these three units of light measurement, as well as illustrate the principle of the *inverse square law,* which states that the illumination on any surface perpendicular to the direction from which the light flux is traveling varies inversely as the square of distance of the surface from the source.

Color Temperature.

While *color temperature* would not be considered one of the basic units of light measurement, it has become quite well known to the general public as a result of the widespread application of fluorescent light sources.

In scientific illumination work, use is made of a theoretical object or substance which, when heated sufficiently, will radiate energy in colored light just as a hot stove lid will first become deep red, then orange, and so on until it reaches white heat and eventually its melting point. This theoretical object is called a *black body* and is assumed to have perfect characteristics for emitting all the colors of the visible spectrum from red to violet as it becomes hotter. A light source is said to have a certain color temperature when its radiation has the identical color characteristics as the theoretical black body at this given temperature.

Color temperature is indicated in degree Kelvin, which is a temperature scale (sometimes called *absolute* temperature) having its zero at −273° Centigrade (or −459.4° Fahrenheit, a temperature at which no heat exists and all molecular motion ceases). Thus, when an incandescent lamp is said to have a color temperature of 2700° Kelvin, it means that the filament is the same color as the black body would be at 2700° Kelvin, or yellow-white hot.

Color temperature should be applied only to light which is generated by heat, but it has become more or less customary to apply it to the colors of fluorescent lamps for the sake of simplicity in distinguishing one color from another. Standard "white" fluorescent lamps, for instance, may be designated as 3500° white, but actually a black body at this temperature would be slightly different in color. The fluorescent white lamp, however, will be nearer to the color of the black body at 3500° than at any other temperature.

Noon sunlight will average between 5000° and 6500° Kelvin, but if the total light from the sun and the clear blue sky is considered, the average will be somewhat higher.

The science of illumination involves many terms relating to brightness, brightness contrasts, relative visibility and a number of other factors having to do with optics and vision. It is a science which vitally affects the health and comfort of all mankind. For that reason considerable space has been devoted here to those electromagnetic waves in the spectral region that we sense as visible light.

CHAPTER 8

Infra-red.

Referring again to the diagram of the range of electromagnetic radiation (frontispiece), we find a rather wide band of wavelengths between the limits of about 7,800 and 1,500,000 Angstrom units called *infra-red* radiation. The frequencies of these electromagnetic waves range from about 400 billion to somewhere around 700 or 800 million kilocycles.

As previously mentioned, wavelengths longer than deep red (at 7,800 Angstroms) we cannot see, but we do feel them as radiant heat. It is not quite correct to refer to infra-red radiation only as heat radiation, however, because all wavelengths of radiant energy generate some heat when they are absorbed. But since infra-red energy does little else but produce the sensation of heat, as far as we know at present, it is always closely associated with it.

Heat is a relative term. A red-hot stove is cool when compared to molten steel. An ice cube is warm as compared to carbon dioxide snow (dry ice), and carbon dioxide snow (at −78° Centigrade) is warm as compared to other liquefied gases. All matter, therefore, radiates heat or infra-red radiation at some wavelengths whenever the surrounding medium is cooler. When the medium is warmer, matter absorbs heat from the medium. Thus we see that nature is again trying to seek a balance, just as with the discharge of electrons from a charged object to one which is more nearly in an electrically neutral state.

It is interesting to recall and associate two facts that have been pointed out: that the movement of electrons in a solid is stimulated by heat, and that absolute zero (−273° Centigrade) is a condition wherein *no* heat exists and all molecular motion ceases. This condition and temperature (or rather lack of it) are believed to exist in outer space where there is no matter in any form to absorb any of the electromagnetic waves.

The infra-red band is usually split into two regions for the sake of analysis. The region adjacent to visible light extends from the 7,800-Angstrom wavelength to about the 38,000-Angstrom wavelength and is called *near* infra-red. Almost all the practical applications of infra-red radiation utilize wavelengths in the near region; so most of what will be discussed here will deal with those shorter wavelengths. The other portion of the infra-red band is called *far* infra-red. The shorter wavelengths of this far portion, that is, those above 28,000 but below about 50,000 Angstroms are produced by ordinary ovens at around 300° Fahrenheit. Uses for the longer ones ranging between 50,000 and about 1,500,000 Angstroms are being developed and as yet have no widespread application.

Near infra-red energy for commercial and industrial use usually is produced by incandescent lamps so designed that some of their visible light output is sacrificed in order that the infra-red radiations will be produced with greater efficiency. Another efficient method utilizes gas-fired infra-red units called *gas radiants.* Like other wavelengths of electromagnetic radiation, infra-red waves travel through space at the 186,000-mile-per-second speed until they strike a surface where they are absorbed and heat is generated in the material they strike. Most non-reflective substances will absorb and convert into heat a large percentage of the radiant infra-red energy striking them, whereas reflecting surfaces redirect and control it just as visible light waves are reflected and controlled.

The heat energy thus absorbed by a substance such as iron will be transferred from one iron atom to another until within a short time the whole body of the object is warm even though the infra-red radiation is falling upon only a part of it. This transfer of heat within the object itself is called *conduction*. The most familiar example of conduction is found in a steel rod or poker. The handle can become unbearably hot, even though only the opposite end is thrust in the fire. Some materials conduct heat much less rapidly than others, which explains why wooden handles are placed on the metal pots and pans used on the kitchen stove and why aluminum, being an excellent conductor of heat, makes highly satisfactory cooking utensils.

When an object is hot, or even warm, it radiates its heat into the cooler air until it eventually reaches the temperature of the air. The surrounding air thus absorbs the heat energy and, if air circulation exists, this warmer air around the hot object rises and circulates away. This type of heat transfer is called *convection*.

All three types are present in heating the average home. Combustion of the coal, oil or gas fuel produces radiant heat (infra-red energy) which is absorbed by the boiler pipes and transferred to the water in them by conduction. This hot water is circulated through the radiators so that they become warm and heat the air surrounding them. Normal air circulation within the rooms carries this warm air about so that the heat is transferred by convection and the house is warm and comfortable. A fireplace is a good example of infra-red radiation at home. While some air is heated and circulated through the house, we must sit before the fire really to feel its heat. The same is true with electric sun bowls, which are quite widely used for "spot" heating.

Aside from providing heat to make us comfortable, infra-red is put to work in many industrial processes. These include paint and enamel drying, baking, preheating and dehydrating.

Basically these processes are the same. Banks of incandescent lamps are used, each lamp being equipped with its own reflector. The reflector can be applied as an "aluminized" surface to the glass bulb itself, or as a separate element in back of a lamp. Gold-plated steel reflectors, while they are not so efficient as other surfaces for visible light, do reflect the greatest amounts of useful infra-red and are used extensively in industry. Such reflectors control the infra-red flux just as do those used for visible light. An opaque object placed in the "beam" of radiant heat will cast an invisible "shadow" by absorbing the radiations that strike it.

The one pronounced advantage of using radiant infra-red energy for drying paints, lacquers and similar finishes, or for dehydrating and baking materials, is the reduction in time involved to accomplish the task.

Near infra-red radiation is penetrating, that is, the heat is absorbed *within* the object being treated so that a film of paint tends to dry from the inside out, rather than from the surface inward as with oven drying or baking. Processes that formerly required as much as 15 or 20 hours normal drying time are frequently completed with infra-red in a matter of 15 or 20 minutes. Others may require no more than 1 or 2 minutes as compared to over an hour with oven drying.

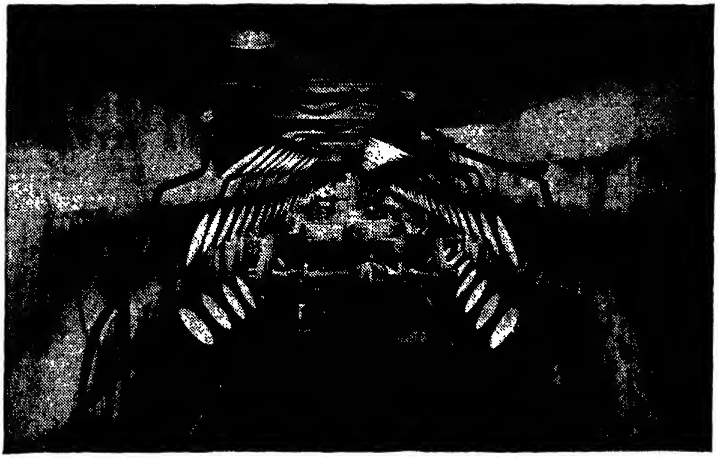


Fig. 67.—This infra-red oven bakes the prime and finish coats of paint on Army jeeps. It takes 9 minutes for this method compared with the 45 minutes which it took previously in a convection oven. (*Photograph courtesy of C. M. Hall Lamp Company.*)

Obviously there can be no established drying-time rule to cover all applications. Different materials, such as iron and wood, have different heat-conducting characteristics, as was pointed out earlier by the mention of wooden handles on kitchenware. In addition, the types of finishes to be dried or baked vary widely in their composition, so that more time will be required for some than for others. The color of a finish also affects its drying time. Light finishes usually take longer to dry thoroughly because some of the infra-red will be reflected, whereas darker paints or lacquers dry more rapidly by virtue of more rapid infra-red absorption. The same time differences occur in dehydrating operations. A hard wet surface of metal can be dried more quickly, for example, than a wet rug or a water-soaked piece of wood, but in either case the drying time would be less than with heated air as the only drying medium.

Radiant heat requires no air for its transmission, and the air present between an infra-red source and the object is heated only to a comparatively negligible extent. Thus, with infra-red radiant drying it is not necessary to exclude air circulation or to provide insulation to keep the heat in.

These factors result in speed and economy in a great many processes. It is apparent that the technique of utilizing these wavelengths of electromagnetic radiation is just crossing the threshold of a much wider range of industrial application than is generally appreciated.

Infra-red radiation also serves in the field of medicine. The sun, producing more than an abundance of infra-red, has been considered and recognized as a great healing agency since the dawn of civilization. The same radiations as those of the sun, produced artificially in therapeutic lamps, have the characteristic penetrating powers, so that heat is generated deep in the body tissues beneath the skin. Bruised and strained muscles and ligaments can be relaxed and soothed with a consequent decrease in pain with infra-red therapeutic application. Lamps and reflectors for this purpose are found in all gymnasiums and doctors' offices where athletic injuries are treated. Such treatment is sometimes referred to as *deep therapy* to distinguish it from heat treatment of surface abrasions.

There is evidence which indicates that visible light of different colors possesses a healing or tonic effect upon the human system; that blue or green light, for instance, has definite curative powers for some ailments while red light will produce healing results for others. It is quite likely, however, that such effects, where evident, are largely psychological rather than physiological, since the nervous reaction to color is very pronounced in most individuals.

The use of infra-red radiation in photography has made it possible to extend that art beyond the limits of vision. Objects can be photographed in absolute darkness or through a haze which makes them visually obscure.

It has been explained that we see an object by virtue of the visible light it reflects, and that most objects reflect infra-red as well as light, but that infra-red is beyond the limit of eye sensitivity. A camera, however, equipped with film sensitized to infra-red radiations by means of special emulsions, will capture objects or landscapes which the eye cannot see. Thus an object in the kitchen can be photographed at night and without light, merely by heat from a stove which is not even red-hot.

Since infra-red possesses far greater penetrating powers than visible light and since all objects reflect infra-red, it is possible to photograph landscapes through a haze so thick that they cannot be seen. After considerable research work, film has been developed which is sensitive to infra-red radiation as long as 12,000 Angstroms in wavelength. If used in the daytime, special lens filters, which are opaque to visible light but not to infra-red, must be placed over the lens.

Black and white photographic prints from an infra-red film have a somewhat unusual reversed appearance due to reflection factors of objects which are different for infra-red than for visible light. A blue sky or lake, for instance, will appear quite dark, whereas, red, green or yellow objects will show up much lighter than in a regular photograph.

The infra-red region in the range of electromagnetic waves, particularly the longer wavelengths of the far portion, is just beginning to be investigated, and developments during the next few years should be of great interest and benefit to everyone.

CHAPTER 9

Ultra Violet.

Beyond the violet limit of the visible light band in the diagram of the range of electromagnetic waves, and in the opposite direction from infra-red, the radiations are called *ultra violet.* The lower or long wavelength limit of the ultra violet band is established at about 4,000 Angstroms, or where visual color sensation ceases, but the upper or short wavelength extreme is somewhat indefinite. It is generally considered as around 100 Angstroms, which is a decided overlap with another band known as *X-rays.* (These will be discussed later.) The frequencies of ultra violet radiations are, of course, higher than those of either infra-red or visible light since the wavelengths are much shorter. These vibrations range from 800 or 900 thousand billion per second to somewhere in the order of 200 or 300 thousand trillion per second—an almost inconceivable frequency, but still not as high as others to be considered.

Like infra-red, the ultra violet region is split into *near* and *far* portions for the sake of analysis, the near being adjacent to the violet end of the light spectrum, and the far encompassing the shorter wavelengths. Sometimes a *middle* portion extending between 2,000 and 3,000 Angstroms is referred to in textbooks, but since the limits are more or less arbitrary, we can, for the sake of simplicity here, avoid the middle designation and consider the border between near and far ultra violet as being at the 2,000-Angstrom wavelength. With this borderline established, most of our discussion will involve the near portion, or wavelengths between visible violet light (4,000 Angstroms) and ultra violet (at 2,000 Angstroms).

As with visible light and infra-red, nature's most abundant source of ultra violet is the sun. Although the sun radiates a great amount of ultra violet energy into space, only a relatively small amount of it (the longer wavelengths) reaches the earth. The atmosphere filters out or absorbs nearly all the radiation of a wavelength shorter than 3,000 Angstroms. This is indeed fortunate because these shorter wavelengths, even in amounts much less than the longer wavelength energy which we do receive, would cause burns and injuries so severe that life could not exist, at least in the open.

Careful study and analysis of the sun's spectrum indicates that its temperature is around 10,000 or 12,000° Fahrenheit and that its maximum energy is radiated in the visible region at a wavelength of about 4,700 Angstroms. At the earth's surface from 1 to 5 per cent of the energy is ultra violet between 3,000 and 4,000 Angstroms, from 41 to 45 per cent is visible light, and from 52 to 60 per cent is infra-red. This is with the sun at average height in the sky under average seasonal conditions. As the afternoon passes and the sun sinks lower, the energy is absorbed to greater extents by the increases in the thickness of air through which it must pass. Obviously, the reverse takes place during the forenoon hours as the sun approaches the zenith.

It has also been found that while the noonday summer sun is only 10 per cent more potent in infra-red radiation than in winter, it is about 1,000 per cent richer in ultra violet in summer. In view of this, it can be seen that between these two extremes the additional visible light energy in the summertime will become increasingly greater for each successive color from red to violet.

Everyone has experienced a severe sunburn after being exposed to the mid-summer sun. The physiology of sunburn (erythema) is somewhat complicated for a complete discussion here, since it involves a study of several layers of skin, various parts of the body and subjects having different complexions. In general, blonds will sunburn more rapidly than brunettes, and, as a rule, the nature of the latter's skin is such that they "tan" more readily than blondes. Wavelengths between 3,000 and 3,200 Angstroms will penetrate the skin deep enough to reach the pigment-producing cells and cause a tan, but those between 2,800 and 3,000 Angstroms merely burn with but very little tanning effect.

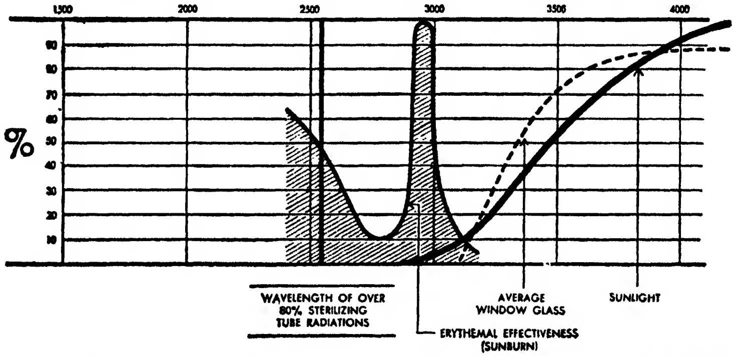


Fig. 68.—The curve indicated by the shaded area shows the region of sunburning radiation in the ultra violet spectrum. The maximum effect is found at 2,900-Angstrom units.

While sunburn (tanning and burning) is produced by ultra violet radiation between the wavelengths of 2,800 and 3,200 Angstroms, the maximum effect is at about 2,970 Angstroms (in nature). It will be recalled that very little ultra violet energy shorter than 3,000 Angstroms reaches the surface of the earth owing to atmospheric absorption, but it should be remembered also that the sun is an abundant producer of all wavelengths, so that those longer than 3,000 Angstroms which penetrate the atmosphere are amply potent to cause severe and painful burns with sufficient exposure time. In other words, if the air were thinner, as at very high altitudes, so that the maximum sunburning wavelengths around 2,970 Angstroms could pass through, we would suffer terrific burns in a matter of a very few minutes.

Unlike infra-red, ultra violet is not penetrating as compared to other wavelengths of electromagnetic radiation. We do not become sunburned while sitting by a closed window because the rays will not pass through ordinary window glass. There are certain types of glasses, however, which are specially made to permit the transmission of ultra violet. One such glass, called *Corex*, is used in certain types of ultra violet sun-lamp bulbs and transmits wavelengths as short as 2,900 Angstroms. Certain other materials, such as cellophane and sodium silicate (water glass), also transmit ultra violet in amounts depending upon their thickness. Special glasses, to allow much shorter wavelengths (2,000 Angstroms) to pass through, will be discussed shortly.

Ultra violet radiant energy behaves to a large extent like visible light and infra-red. It has just been indicated how it is transmitted by some glasses and other materials. These materials also refract ultra violet as they do light, and since quartz has a high transmission factor for ultra violet, quartz prisms are frequently used for the purpose of wavelength study. Ultra violet is also reflected by various surfaces, the most efficient ones being metallic.

There are a great many more phenomena connected with ultra violet radiation than can be covered here, but we can discuss the most important ones. These phenomena occur at different wavelengths. In nature, where ultra violet is practically all above the 3,000-Angstrom wavelength, the sunburning effect is the most prominent and has already been briefly covered. Below 3,000 Angstroms we must deal with radiations produced artificially, since they are not present in solar energy reaching the earth.

Ultra violet radiation is produced by some materials when they are heated to brilliant incandescence. Today, such heating is accomplished electrically, but a hundred years or so ago it was done chemically with an oxyhydrogen flame and a piece of rare-earth oxide or lime. Such a device was called a *limelight*, or sometimes a *calcium light*, and was used to illuminate theatrical stages since it produced visible light of high brilliancy as well as relatively long wavelength ultra violet radiations.

Although such sources have the advantage of burning without an enclosure in the open air, they are cumbersome for commercial application and are not rich enough in ultra violet to be of practical use.

A high-voltage electric spark or an arc between metallic electrodes, such as iron or carbon, is also a producer of ultra violet in the open air, but mercury-vapor arcs created in an inert gas such as argon are widely used at present for the commercial generation of ultra violet. Of course, such mercury-vapor discharges must be confined within a sealed glass or quartz envelope.

It has been explained how ordinary window glass will not transmit any except the very long wavelengths of ultra violet adjacent to the visible light region, so that although the discharge itself may be extremely rich in ultra violet, the potency of the source is wholly dependent upon the transmission characteristics of the glass envelope.

Quartz is perhaps the least opaque to ultra violet of all commercially available substances, and will transmit radiations having wavelengths as short as 1,850 Angstroms, depending upon its thickness. As that approximate limit is approached, the oxygen in the air itself undergoes certain chemical changes, and the production of ozone, which results from the absorption of far ultra violet radiations by the air, creates an envelope of ozone around the source through which short radiations cannot pass. The sun, radiating ultra violet of all wavelengths, creates a protective layer of ozone high above the surface of the earth in the outer limits of the atmosphere, thereby absorbing the short, harmful rays.

In the laboratories, equipment is used which permits the study of extremely short-wave ultra violet. This equipment utilizes fluorite and other substances which allow far greater transmission of short-wave ultra violet than quartz. For several years there remained an unexplored gap between the shortest ultra violet radiation and the longest X-rays, but comparatively recently this region has been penetrated to the extent that ultra violet and X-rays are found to overlap at their respective extremes. This is indicated in the diagram of the range of electromagnetic waves (frontispiece).

Below the quartz-transmission limit of about 1,850 Angstroms, we have no interest in this discussion of ultra violet since the far or extreme region has little commercial application at present. Future development, in the technique of generation and control, will, no doubt, bring many benefits to mankind in the fields of surgery, bacteriology and medicine.

In the near region of ultra violet radiation, however, particularly that portion sometimes referred to as *middle* ultra violet, between 2,000 and 3,000 Angstroms in wavelength, great progress has been made during the past few years. Much of this progress is due to Corning Glass Works' development of glasses which pass ultra violet at different wavelengths. Many of these glasses can be looked upon as protective glasses since they transmit those wavelengths desired and shut out the shorter ones, which are damaging to the eyes. Some of them, however, must be used with extreme care since they are deliberately designed to transmit short wavelengths for bactericidal and other purposes.

Quartz lamps, lamps made of glass transmitting wavelengths shorter than 3,000 Angstroms, and open arcs such as are used in welding will cause serious damage to the eyes and skin unless they are properly shielded. The skin injury is an inflammation similar to sunburn, and the eye injury is an inflammation of the conjunctiva, a mucous membrane covering part of the eyeball as well as the inside of the lids. *Conjunctivitis*, as the inflammation is called, is usually indicated by the feeling that the eyes are full of sand and the lids stuck together. It is frequently quite painful and may be of several hours' duration. Prompt treatment by a physician may avoid permanent damage, and in extreme cases even blindness.

There are a great many physiological effects of ultra violet energy, besides those on the skin, which are evidenced by sunburn and tanning, although *sun-bath* treatments (heliotherapy) are looked upon as the major function of ultra violet. Of recent years, however, the general public seems to have acquired some respect for ultra violet and has avoided excessive exposure to the hot summer sun.

Ultra violet penetrating the thin outer layers of skin is absorbed by the blood stream and enables it to accumulate more phosphorus and calcium. These two elements are essential for the building and maintenance of sound bones and teeth, and consequently result in the avoidance or cure of a bone disease called *rickets*. Vitamin D, which is abundantly present in fish-liver oil and milk, aids in the same purpose and is frequently referred to as the *sunshine vitamin*.

The healing of some types of skin diseases has been found to be hastened by ultra violet radiation. If the disease is of such a nature that deep wounds exist, it is probable that infra-red, which is of course more penetrating than ultra violet, may be more effective if used in conjunction with the ultra violet. In natural sunlight exposure the increased blood circulation and toning effect of the infra-red is present along with the bactericidal and cauterizing action of the ultra violet.

Extensive analysis of the action of certain wavelengths of ultra violet has been carried on by several investigators. The published works of Dr. Henry Laurens and of Ellis and Wells are particularly complete and cover a great many effects on the blood, skin, circulatory system, metabolism, respiration, heart beat and human diseases. In general, it can be said that ultra violet radiation of wavelengths no shorter than found in nature can be beneficial and curative in moderate amounts, and that a lack of sufficient radiation can be at least partly made up with a diet properly regulated to include the necessary additional vitamin D and A components.

The effective wavelength for the production of calcium and phosphorus in the system is in the region of 3,020 Angstroms. Since the effect is on the blood stream, it is obvious that irradiation of only one part will affect the whole body as the blood circulates through it.

A comparable result can be accomplished through the irradiation of several types of foods instead of the body itself. Irradiated milk is readily available and is perhaps the best known of irradiated foods, although the vitamin D content of certain cereals, starch foods and vegetable oils can be appreciably increased through ultra violet irradiation.

Experiments with other vitamins and with diseases other than rickets have met with little success. It seems at present that the primary function of ultra violet radiation upon the human system is to assure sound healthy bones and teeth.

Considerable successful work has been done in conjunction with the raising of poultry and the production of eggs. Calcium and phosphorus are vitally important in this industry since they have as much effect upon the egg-laying capacity of hens as upon the development of their bones. Incandescent tungsten-filament lamps having special ultra violet transmitting glass bulbs have been developed specifically for application to poultry. These lamps are called *CX* lamps and although the amount of ultra violet produced is relatively small, their consistent use has been a successful means of increasing egg production and improving the health and sturdiness of chickens.

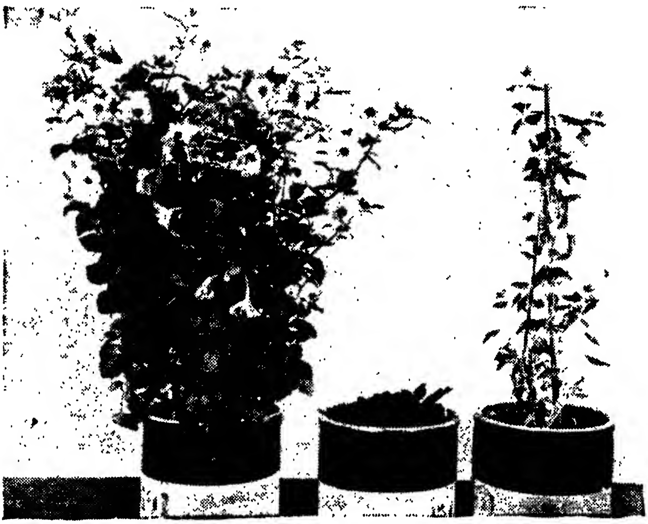


Fig. 69*A*.—Three petunia plants. The one on the left was exposed to the natural complete spectrum of sunlight; the center one received only the violet and blue light (the longer wavelengths were filtered out); the plant at the right received only infra-red, red, orange and yellow light from the sun. (*Photograph and data from the Boyce Thompson Institute for Plant Research, Yonkers, New York.*)

As far as the effect of radiant energy on plants is concerned, considerable investigation reveals that, as a rule, plants grow best under light of all wavelengths as found in nature. Excessive amounts of ultra violet (or

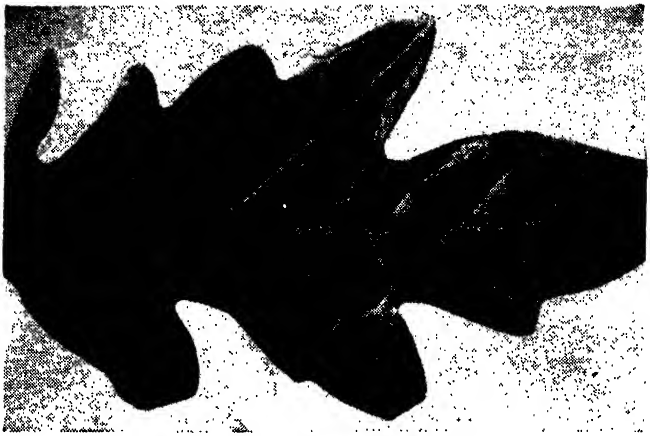


FIG. 69*B*.—A normal healthy leaf, diagonally across which a band of 2,650-Angstrom wavelength ultra violet from a mercury arc was cast for a few hours. This wavelength of ultra violet was separated out of the spectrum with quartz prisms. The dark band across the leaf shows the killing or injuring of the epidermal layer of cells on the leaf where they were exposed to the short wavelength of ultra violet. (*Photograph and data from the Boyce Thompson Institute for Plant Research, Yonkers, New York.*)

FIG. 69*C*.—Tomato plants. The one at the left is the normal control plant. The center one was taken from a greenhouse and exposed to a mercury-vapor arc in quartz for 3 minutes. The plant at the right was deprived of all light for 4 days, then similarly exposed to a mercury arc. (*Photograph and data from the Boyce Thompson Institute for Plant Research, Yonkers, New York.*)

infra-red) will cause serious damage, although the elimination of solar ultra violet does not result in an appreciable improvement in growth. Plants can be "forced" with light up to certain point, after which a leaf injury may appear and increase until the leaves completely wither and drop off. Complete studies on the correlation between radiant energy and plant growth have been carried out at the Boyce Thompson Institute for Plant Research at Yonkers, New York. An accurate generalization covering all plants is difficult because different plants may vary in their response to different wavelengths of visible light, ultra violet and infra-red.

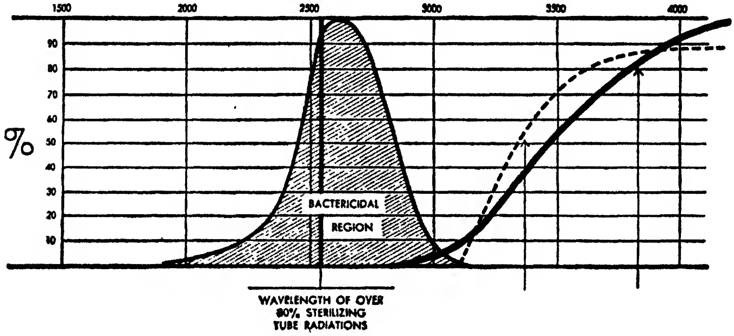


FIG. 70.—The curve enclosing the shaded area indicates the bactericidal region of the ultra violet spectrum. The 2,537-Angstrom mercury line falls at the approximate peak of this region.

The bactericidal effect of ultra violet has been known for many years but was not commercially applied until a glass with adequate transmission characteristics at this wavelength was developed a few years ago. The sun has long been recognized as a germ-killing medium, and practically all types of bacteria can be killed, or at least weakened by it, if sufficient exposure time is allowed.

Since practically no ultra violet radiation of a wavelength shorter than 3,000 Angstroms reaches the surface of the earth, it is evident that at least some of this radiation must be bactericidal.

Extensive research shows that while there is a slight bactericidal effect in the extreme lower limits of solar radiation, there is a tremendous bactericidal potency in radiations in the region of 2,537 Angstroms, a wavelength not present in solar energy. Obviously, therefore, the sun's germicidal value lies in the fact that it is a tremendously powerful source of the less potent wavelengths. Of course this is fortunate because, as has been explained, wavelengths shorter than 3,000 will seriously damage the skin and eyes.

In order successfully to apply bactericidal ultra violet, it is natural that the most potent wavelengths should be employed. Therefore a lamp which is rich in 2,537-Angstrom wavelength ultra violet is necessary. There were a number of difficult problems involved in the development of a lamp which could be applied commercially. While the carbon arc produced an abundance of 2,537-wavelength ultra violet, it also produced brilliant light and considerable heat (infra-red), so that it was extremely awkward to handle. Likewise a high-voltage disruptive spark presented problems, so that the most likely remaining source was a mercury-vapor arc discharge within a glass envelope which would permit the transmission of the 2,537 energy through it.

Such a glass was produced a few years ago, and today there are several types of sterilizing or germicidal lamps available for use in hospitals and other locations where sterilization of the air and exposed surfaces is essential.

A description of these lamps and their operating characteristics will be presented in Part IV.

In addition to bacteria killing, the 2,537-wavelength ultra violet will arrest the development of many types of molds and fungi by killing the spores of these organisms which float about in the air. The author has conducted several tests with common bread mold and has concluded that if properly irradiated bread is enclosed in an airtight wrapper (which also must be irradiated), it will not become moldy over an extended period. It may become dehydrated and unpalatable, however, the moisture condensing on the inside of the wrapper. These tests were conducted in a large bakery where special ultra violet equipment was applied to irradiate the automatic slicing knives and all surfaces touching the bread as well as the bread itself and its wrapper. Control loaves (not irradiated) showed mold colonies in from 3 to 4 days, whereas irradiated loaves did not show indications of mold for over twice that period even though the wrappers were not airtight. Since cellophane transmits some amount of ultra violet, several loaves were irradiated after being wrapped in it, but the results of this test could not be considered conclusive. It must be added that mold spores are much more resistant to the lethal effect of ultra violet than are bacteria, and at least one type of mold appears to thrive under it.

There are a great many possible applications for ultra violet irradiation to kill microorganisms, many of which are in successful operation today. There are also many installations of ultra violet sources wherein the actual value is rather dubious. Their use in refrigerators, particularly in the large walk-in type used for meat storage, appears to have considerable merit from the standpoint of reducing trimming losses by arresting the growth of slime on the surface of meats. In order to avoid an excessive accumulation of such slime, a low humidity is maintained in the refrigerator with a consequent amount of dehydration or drying of the meat surface. This dry and hardened meat must be trimmed off before sale. With ultra violet lamps in operation, however, a higher humidity may be maintained without an excessive formation of slime which results in less dehydrated-meat-trimming losses.

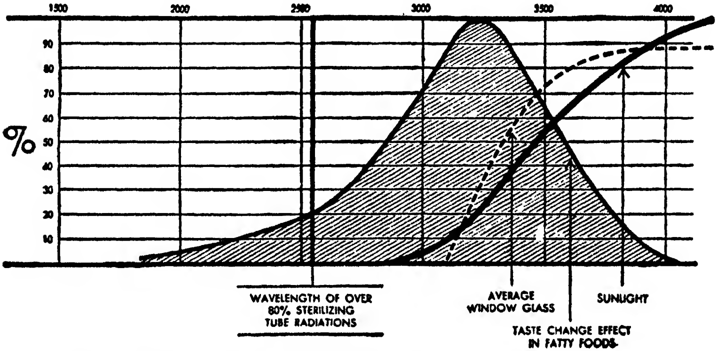


Fig. 71.—The curve indicated by the shaded area shows the ultra violet wavelengths that cause a taste change in certain foods.

Whenever such foods as milk, butter and fatty acids are exposed to ultra violet, care must be used to avoid over-exposure, since a taste change occurs which may render these foods extremely unpalatable. This change in taste results from oxidation of proteins as well as the de-emulsification of fats and is not to be confused with the souring of milk or the rancidity of butter. The effect occurs at long wavelengths of ultra violet as well as at shorter ones, since it can be detected in a sealed bottle of milk left standing for some time in the sunlight. The thickness and type of glass used in the bottle would be such that only very near ultra violet in the order of 3,700 or 3,800 Angstroms in wavelength could be transmitted to the milk itself.

Before leaving the subject of ultra violet radiation it might be well to discuss ozone again, briefly, since as the use of sources producing shorter wavelengths of ultra violet become more common in industry and commerce, the problem of ozone control may reach critical proportions.

Ozone is a rather unstable and active form of oxygen which results when the oxygen atoms which make up an oxygen molecule are torn apart and reformed under unusual conditions. This reforming occurs most often when air, of which oxygen is a large part, is circulated through a high-voltage spark gap. Such a spark produces, in addition to visible light, considerable ultra violet, some of which may be shorter than 2,000 Angstroms in wavelength. Ultra violet energy, radiating at such short wavelengths, also is produced by a mercury-vapor arc enclosed in a tube of quartz or special glass designed to transmit it. When these radiations pass through (or attempt to pass through) the oxygen in the air, the tearing apart of the normal oxygen molecules takes place and the ozone is formed. But being active in this form, the ozone molecules quickly join together again and revert to oxygen, particularly if water vapor is present in the air.

Ozone has a characteristically clean odor and is frequently noticed in nature after a near-by stroke of lightning occurs. It may be temporarily stimulating when inhaled but may also cause serious damage to the respiratory system if inhaled for a period of time. The odor of ozone can be detected if it is present in only a few parts per million of air and even in this quantity may be harmful; and therefore in laboratories where work with apparatus producing ozone is in operation, precautions are always (or should be) taken to exhaust or absorb it so that workers will not be required to inhale it constantly.

Strangely enough, when methods of generating ozone were first developed a few years ago, its initial stimulating effect was considered beneficial to health, and "ozonators" were placed on the market to produce it deliberately. Now, however, much more is known about its characteristics. It is sometimes used in laundries with special apparatus to impart a clean, fresh and absolutely harmless odor to laundered articles before they are sent back to the owner.

As far as its application to destroy odors is concerned, there is some question as to whether it actually destroys such odors or merely covers them up with its own. Possibly it is a combination of both.

There are many other effects of a chemical and biological nature which occur throughout the entire range of ultra violet waves and frequencies, and the study of volumes devoted entirely to the subject is suggested to those who wish to pursue them further.

CHAPTER 10

X-rays.

Overlapped by short-wavelength ultra violet radiation at one end and long-wavelength gamma radiation at the other, we find a region called *X-rays* or *Roentgen rays* (frontispiece).

The term *X-ray* is familiar to the civilized world, and there are few of us, in this country at least, who have not been subjected to these radiations by the dentist when he wants to study the roots of our teeth or by the surgeon, who finds it essential to know more about broken bones or organic disorders within our bodies.

The discovery and recognition of X-rays as electromagnetic waves shorter in length than ultra violet make a rather interesting story. In 1895, a scientist named W. K. Roentgen, while working on a high-voltage vacuum tube noticed that some photographic plates enclosed in a box near by frequently became cloudy and unfit for use even though they were never exposed to light. In searching for a reason, he soon discovered that this clouding occurred whenever a discharge took place in the tube. The correct conclusion was that some sort of extremely penetrating radiation emanated from the tube during its discharge. This radiation, being unknown at the time, he called *X-radiation* or *X-rays.*

Since that time science has discovered that when electrons are released from a hot metallic solid such as an incandescent filament, to streak through a vacuum at terrific speeds and strike the atoms of another metallic solid, the splash of energy released by the collision radiates away in electromagnetic waves. These waves may be as long as 600 or 800 Angstroms, so that they may be considered as either X-rays or ultra violet at such wavelengths, or they may be as short as one- or two-hundredths of an Angstrom. They vibrate at frequencies ranging from 2,000 or 3,000 trillion times a second to over 100,000 quadrillion times per second. In general, the higher the voltage or pressure forcing the electrons out of one solid (the cathode) and on their journey to strike the other solid (the anode), the faster they will travel, the faster will be the vibrations of released energy resulting from the collision, the shorter will be its wavelengths and the deeper the radiation will penetrate a solid. Extremely long wavelength X-rays will not pass through even thin glass (as was pointed out in the discussion of short-wave ultra violet), whereas the shortest ones which are produced by a pressure of well over a million volts will penetrate several inches of metal.

Since X-rays, like visible light, infra-red and ultra violet, are electromagnetic radiations but of much shorter wavelengths, it might be expected that they will have the reflection and refraction characteristics of those radiations in the longer wavelength regions. However, since their wavelengths are of the order of size of atoms, it is difficult to obtain anything other than a scattering and dispersion of rays, as well as absorption. Certain crystals having a precise spacing of atoms in their lattice structure will break X-rays into their component wavelengths similar to the way a prism breaks up light into colors. Only at extremely glancing angles, however, does regular reflection occur. One crystal which may be used in studying X-ray frequencies is ordinary rock salt (sodium chloride) since it has the necessary atom-arrangement characteristics.

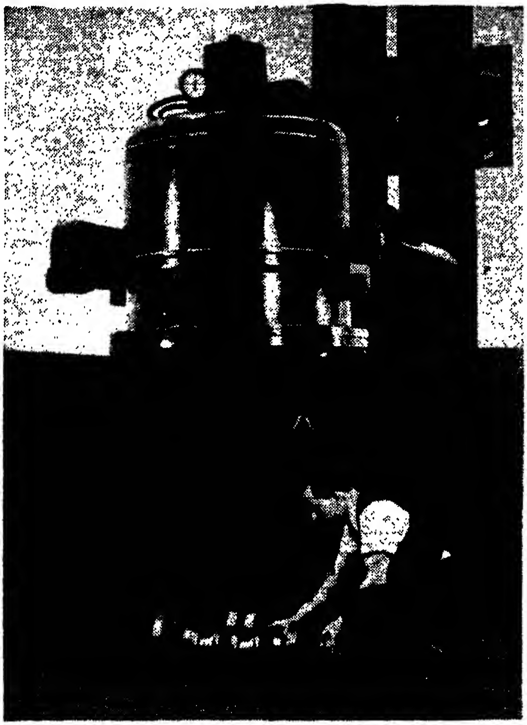


FIG. 72.—This giant million-volt X-ray tube is used in industry to detect flaws in a metal casting.

Because of the atomic dimensions of X-rays, they are used commercially to explore crystal structures. Million-volt X-rays are applied quite extensively in industry where metal hardening is accomplished with high heat and a consequent change in the crystalline structure of the metal. X-ray analyses of this sort are responsible for much more efficient production of much higher quality metals.

While the infra-red and ultra violet regions are split up into portions referred to as *near* and *far*, depending upon their distance from the visible light band, X-rays are designated as *hard* and *soft*. Hard X-rays are those resulting from voltages upwards of 100,000 volts, whereas the soft ones originate with much lower voltages with, of course, much longer wavelengths and less penetrating power.

In ordinary medical work, X-rays are made to pass through the body and strike a photographic plate where the amount of radiation penetrating is recorded similar to the way a camera will record the visible light passing through a translucent solid. Bones or foreign objects which may have become lodged within the body do not permit as much transmission as skin or flesh, so that they show up on the photographic plate as *shadows*. Thus, broken bones, bullets, swallowed buttons, pins and, similar objects can be readily located. Changes in tissue structure, such as might result from infection or malignant or tumorous growths, are also easily detectable on X-ray plates, so that the physician and surgeon find it possible to work much more accurately with an X-ray "blueprint" of their tasks.

Such shadow pictures are also used extensively in many industries to locate defects in products made of wood, rubber, plastics, leather and even metal.

Gamma Rays.

It will be seen in the frontispiece that there is a wide overlap of X-rays with a region of radiations called *gamma rays.* This indicates that the radiations within this overlap can be called either X-rays or Gamma rays, and that they are identical in character, regardless of their name or of how they are produced.

Gamma rays are those which radiate from radio-active elements or substances such as radium or uranium. While the names of Pierre Curie and his wife, Marie Curie, are associated with the discovery of radium, the radio-activity of uranium was noted shortly after Roentgen's discovery of X-rays by a French scientist named Antoine Henri Becquerel. Like Roentgen, Becquerel used photographic plates and found that uranium emitted radiations which fogged them. The Curies, in an effort to find more potent radiations than those resulting from uranium, experimented with the substance from which uranium is obtained, pitchblende, and did obtain radiations several times as strong. Further analytical work with pitchblende resulted in the discovery of a new element which they called *radium*, in which the radio-activity was several million times stronger than in uranium.

Radium is extremely rare, a great many tons of rich pitchblende ore being required to obtain one ounce of radium worth somewhere around $20,000 or $25,000. Its radio-active property is the result of the instability of its atoms. All atoms, it will be recalled, are made up of a nucleus around which electrons swarm in definite established orbits, but in radium atoms, as in those of other radio-active elements, there is a tendency for them to change their own structure with explosive force. There is a tremendous amount of energy (potential) within radium atoms, so that when the explosion takes place with an atom, the energy is released as electromagnetic radiation of extremely short wavelengths and high frequencies. The amount of energy thus released in the complete change of one gram of radium is approximately equal to the energy supplied in the burning of a ton of coal.

This energy is not released, of course, by all the atoms at once. They explode at random, but there are so many billions of them in a visible amount of radium that released energy is radiated at a rate which can be considered constant. Three types of rays are emitted when a radium atom explodes. One type is called *alpha rays,* which consist of positive particles released from the nucleus and which have comparatively little penetrating power. *Beta rays,* the second type, consist of negative electrons and are much more penetrating. The third type, *gamma rays,* are not particles at all but electromagnetic waves. Radium atoms do not become inactive with one so-called *explosion,* but rather undergo a series of them over a period of many years. When completely deactivated, radium becomes lead, and the period of time required for such a complete transition to a stable element is calculated at many millions of years. Thus, while the potency of radium diminishes gradually, it remains practically a constant source of energy over the span of many lifetimes.

For medical purposes radium is usually used in the compound radium bromide of which about half is radium. Minute quantities of this compound are placed in tiny metal tubes no larger than a small sewing needle and inserted into tumor and cancer tissues where the radiations destroy the tissues. Other methods may be used, but basically the treatment is so to apply the radiations that the diseased tissue will be killed without destroying too much of the surrounding healthy tissue. Obviously the problems are usually extremely difficult and the success of such treatments requires the skill and technique of a specialist. As has been explained, radium emanations are very penetrating and their precise control deep within the body is not always possible. When stored, the minute radium pellets are placed in jackets of steel or lead and kept in boxes of lead of considerable thickness, so that no damage will be done to persons circulating in the vicinity of the storage vaults.

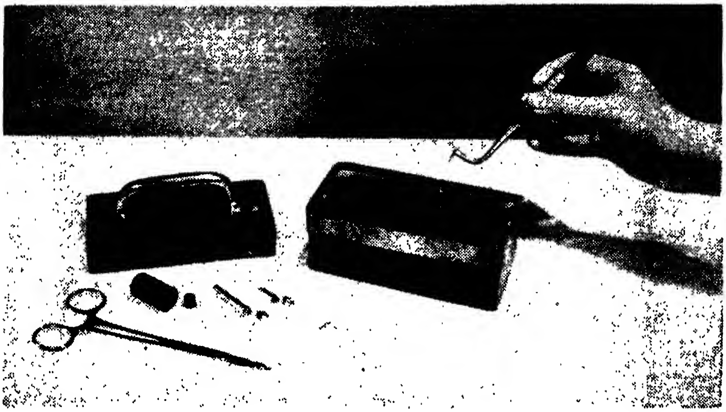


FIG. 73.—Equipment used in radium therapy. The tiny metal needles, held in the instrument and on the table in front, each contain 5/1,000 gram of radium bromide. These and others containing 10/1,000 gram are stored, when not in use, in the solid 4-inch-thick block of lead. (*Courtesy of Dr. Paul E. Tivnan, Salem, Mass.*)

Since X-rays of short wavelengths and gamma radiations from radium are one and the same, X-rays are replacing radium in certain types of medical treatment. Such X-rays, if they are to be of the same wavelength as gamma rays, must be produced by a million volts or more. Three, four or five million volts will produce even more penetrating and effective X-rays.

High-voltage X-ray technique has developed rapidly during the past few years. Since the equipment required is less difficult to handle (though larger), and the treatments less delicate, the costs involved may be appreciably less than with radium. For that reason, X-ray equipment is found in many of the finest hospitals. The fact that such extremely high voltages are used does not indicate that there is danger of the patient's being electrocuted. Where treatments of high-voltage X-ray are given, the electrical apparatus and giant X-ray tube may be quite remote from the patient, such as in a room on the floor above with the radiations passing through special devices in the floor to the patient, who reclines comfortably in pleasant surroundings in the room below.

As scientific research develops the means and methods of generating many millions of volts in electron tubes, the shattering of atoms by streams of electrons traveling at inconceivable speeds will doubtless produce electromagnetic radiations much shorter in wavelength and much more penetrating than the ultra-short X-rays of today. As a matter of fact, such radiations are detected in nature and are known as *cosmic rays*, but there is as yet a gap between man-made X-rays and the region of cosmic rays.

Cosmic Rays.

Over 40 years ago, physicists concluded that some sort of radiation must exist in the atmosphere because under all circumstances air is found to be slightly ionized (a few of its atoms are found to be minus an electron and therefore positively charged). Furthermore, a comparatively simple device, called an *electroscope*, indicated the penetration of the unknown radiations at a depth of 30 or more feet in lake water as well as underground in mines and caves. The fact that these radiations were consistently much stronger at high altitudes than at the earth's surface led to the further conclusion that such radiations did not originate on this earth but rather somewhere out in the interstellar space.

In recent years investigations of the character of cosmic rays and their origin have been carried on extensively by a large number of scientists, both cooperatively and individually. Foremost among these men are R. A. Millikan, A. H. Compton and their coworkers, as well as a number of others. A few years ago the newspapers all over the world carried accounts of a Belgian scientist named Auguste Piccard who rose thousands of feet into the stratosphere in a specially designed balloon. At the time, the novelty of the ascents appealed to the general public, but actually Piccard was accumulating valuable data on cosmic radiation strength at high altitudes.

From the information at hand, it appears that cosmic rays are very complex, some being more penetrating than others. There is evidence that these rays may be of a particle nature such as a shower of electrons at terrific speeds. There is also other evidence which indicates that they are electromagnetic waves of much shorter wavelengths and higher frequencies than the shortest X-rays or gamma rays as shown at the extreme left end of the diagram of electromagnetic radiation (frontispiece).

The origin of cosmic rays has not been definitely established. The fact that they do not reach the earth with greater strength during daylight hours eliminates the sun as a major source. Also, since their intensity does not diminish during the day or increase at night, they cannot be associated wholly with any particular group of stars such as the Milky Way.

Gamma rays result when the atoms of a radio-active element disintegrate, or when electrons traveling at high speeds strike atoms and split them apart, thus releasing energy which radiates away in electromagnetic waves. Some theories suggest that cosmic rays are born when the reverse process takes place, that is, when atoms are put together. According to such theories, somewhere out in space, matter is being created and some of the energy which results with mass radiates away as cosmic rays—some of them reaching this earth.

Any further consideration of cosmic radiation would be not only controversial but much too involved for discussion here. Part IV will cover more in detail the movement of electrons (cathode rays) and the movement of positrons (positive rays).

CHAPTER 11

Subsonic and Slow Oscillations.

At the extreme right end of the electromagnetic-wave-range diagram (frontispiece), we find radiations having the opposite characteristics of cosmic rays; that is, they are extremely long waves of very low vibration frequency. Although the slowest frequency indicated is 10 per second or 10 cycles, it is possible to produce slower ones since such oscillations are generated by a coil of wire rotating in a magnetic field, and the rotation can, of course, be made slow enough barely to move the coil. Such very low-frequency and long-wavelength electromagnetic radiations, however, are very difficult to obtain, requiring a long antenna and special equipment. They have little if any practical commercial value at present, but they do serve in certain experimental work.

Slow oscillations called *subsonic* are not electromagnetic radiations at all, but are sound waves too low in pitch to be audible. Although they may have the same frequency as slow electromagnetic oscillations, they should not be confused with them as there is a vast difference in the character of each. They will be discussed further, shortly.

It was indicated in Chapter 6, in the general discussion of electromagnetic waves, that such waves are moving electric and magnetic fields and originate with the movement of electrons. Since electric current involves the flow of electrons from negative to positive, and since a magnetic field is produced around a wire through which electrons are flowing, it follows that pulses or waves can be made to radiate away from a wire with every alternation of the generator. Alternating current is most frequently generated at 60 cycles, although 50, 40 and 25 cycles are occasionally found in this country and more often in foreign countries. Frequencies higher than 60 cycles are usually generated for special purposes. Thus, we may have electromagnetic waves of 25-, 40- or 60-cycle frequency, whichever the case may be, or of some intermediate or higher frequency, depending upon the generator design and speed.

These waves can be detected mechanically, electrically, magnetically or through certain thermal effects of alternating currents. The upper or higher frequency limit of the slow oscillation region is established, more or less, by the ability mechanically to rotate a coil in a magnetic field. This ability is restricted by friction and other natural laws so that the upper limit of 10,000 alternations per second (10 kilocycles), as indicated in the diagram of the range of electromagnetic radiation (frontispiece), is an arbitrary one. The top speeds of practical centrifuges used in medical work are in the order of only about 2,000 revolutions per second, although experimental devices have been developed which will whirl in air at nearly a million revolutions per minute. It is obvious therefore that to obtain higher frequency oscillations a method other than the mechanical rotation of a coil of wire in a magnetic field must be employed.

During the discussion of resonance in Chapter 5, it was pointed out that a condenser or capacitor can be made to charge and discharge back and forth from one side to the other and that such seesaw oscillations are very rapid as compared to those produced mechanically. This method provides the higher frequencies and will be discussed more in detail later.

Supersonics.

Strictly speaking, the subject of supersonics (or subsonics) does not belong in a discussion of electromagnetic waves. Supersonic waves are sound waves of a vibrating frequency (pitch) too high to be heard and, as such, require a medium such as air or water through which to travel, whereas electromagnetic radiations require no medium. But since supersonic frequencies fall between the region of slow oscillations and radio waves, and since electron tubes are involved in their production and control, we can consider them briefly here.

The average human ear is capable of hearing the deep sound produced by vibrations as low as about 20 to 25 per second or 20 to 25 cycles. Below that, the motion of a vibrating object or string may be seen and felt, but no audible sound is produced, and the frequencies are termed *subsonic.*

The upper limit of audible sound is somewhere in the order of 20,000 vibrations per second or 20 kilocycles. At about 15 kilocycles the sound is so shrill as to be most annoying; at 18 kilocycles it begins to fade from audibility; and at 20 kilocycles there is no sound at all that the human ear can detect although the hearing organs of animals, birds and insects may be able to do so. This region of sound waves too high in pitch to be heard is called the *supersonic* region.

These waves can be produced electrically with a coil and a metal disc which vibrates at the required frequencies or with certain types of crystals. They can be focused or sent out in a beam similar to the way audible sound waves can be directed with a megaphone. Supersonic waves, however, being of shorter wavelengths than sound waves, can be controlled much more sharply, particularly if traveling through water, since they are not dispersed or spread out as readily by the medium through which they are passing.

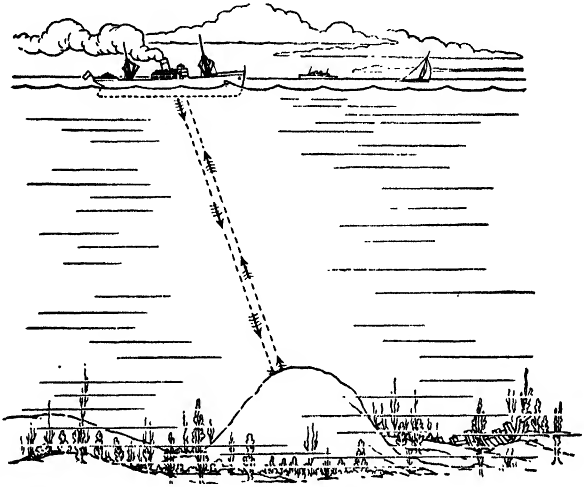


Fig. 74.—Supersonic impulses sent to the ocean floor travel down and echo back at a constant speed so that the depth may be calculated accurately.

Thus it is possible to send out a "beam" of supersonic waves. Underwater detection involves such a method of locating submarines, reefs and other submerged objects, and depth finding with supersonic waves is quite well established. The method involves the calculation of distance in accordance with the speed of the supersonic impulse to the floor of the sea or to the submerged object, and its echo back. As was stated in the section on Sound Waves, in Chapter 6, such waves travel at the rate of 1,088 feet per second in air at 32° Fahrenheit and a little over 4,000 feet per second in water. This is much slower of course than electromagnetic wave speed at 186,000 miles per second. Supersonic waves travel at the same rate as sound waves in various mediums of transmission, since they are identical except for frequency and wavelength.

The technique of determining marine depths requires that extremely short packets of supersonic waves be sent to the ocean floor. Otherwise, if the duration of the impulse were long, a blurring reception would result with consequent inaccurate calculations of the depth. These instantaneous impulses are sent down at regular intervals and echo back to the receiving device so that the time interval required is in direct proportion to the distance they travel.

The electron tube which controls the duration of the supersonic impulse and the frequency of them is called a *strobotron.* These act as trigger tubes for the supersonic-wave-beam generator and will be described more in detail in Part IV.

Radio Waves.

The electromagnetic waves used in radio extend from the slow oscillation region to an indefinite limit which approaches infra-red radiation. The frequencies range from about 10 kilocycles to the region around 10,000 megacycles (thus far), and the wavelengths from 30,000 to 40,000 meters to a small fraction of a centimeter. Different bands in this radio-wave portion of the electromagnetic spectrum are used for different types of radio communication depending upon how their characteristics can best be utilized.

When commercial radio communication first became practical, it was believed that the longer wavelengths and lower frequencies could be transmitted farther and more reliably than the shorter ones, and transoceanic wireless utilized a band embracing wavelengths of from 3,000 to 30,000 meters and frequencies from about 10 to 100 kilocycles. Amateur radio operators, at that time considered of secondary importance by some, were assigned a band of shorter wavelengths and higher frequencies so as not to interfere with commercial communication. The amateurs, however, proved their worth by determined and persistent work, and it was soon found that their communications of short-wavelength high-frequency energy were extending farther around the globe than the commercial stations using the longer wavelengths.

Investigations as to the reason for this resulted in the discovery that high above the earth there exists a multiple layer of ionized (electrically charged) gas which acts as a refractor for radio waves, bending them back to the earth. If the frequencies are too high, however (above about 45 megacycles), and the wavelengths too short (less than about 8 or 9 meters), the radiations are not readily bent back, but pass on out into space. Such layers were referred to in Chapter 9, where it was explained that short-wavelength ultra violet from the sun produced its own protective envelope of gas around the earth so that damage to animal and vegetable life would not result from exposure to it.

These layers of electrically charged gas may be found sometimes as low as 30 miles above the earth during the daytime or as high as 200 miles or more at night. They are called the *Kennelly-Heaviside layers* after those two scientists showed independently of each other that their existence was highly probable. They are also known as the *ionosphere.* There have been many interesting phenomena observed in conjunction with the ionosphere, but we cannot dwell too long upon them here. The effectiveness of the ionosphere as a refractor of electromagnetic waves varies quite widely from time to time. Since it is produced by radiations from the sun, it is obvious that changes in the sun's surface (sunspots) will affect its ability to send radio waves back to the earth. While long-distance, long-wavelength transmission is usually not as good during the day as at night, the reverse is often true with short-wavelength transmission. Since the layers are not always consistent as far as thickness or density is concerned, their effectiveness as a refractor of radio waves continually fluctuates, which accounts to some extent for the fading of short-wave transoceanic

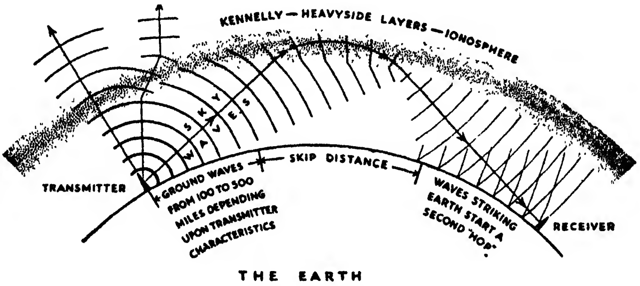


Fig. 75.—The behavior of radio waves in passing over the earth's surface depends upon their refraction from the layers of ionized gas high above the surface.

signals. It is interesting to note also that short-wave transmission is often less effective at relatively short distances than at greater distances of several hundred miles. This circular band of poor or no reception around a short-wave transmitter has been referred to as *skip distance* and results from the fact that radiations traveling nearly straight upward from the transmitting antenna are not refracted back to the earth as readily as those striking the layers at an angle farther away; this phenomenon is similar to the behavior of light waves when they are passing through a refracting medium. Since lower frequency long-wavelength radiations are refracted to an extent that they can almost be considered as reflected, skip distances are much less pronounced with such transmission.

Commercial broadcasting is carried on within a band of wavelengths from about 700 to 200 meters and from 600 to 2,000 kilocycles. In order to avoid confusion and interference with others, each broadcasting station is assigned a specific wavelength and frequency at which it may operate, and by tuning our radio to the same frequency and wavelength at which a station is broadcasting we can transform the electromagnetic waves it is sending out into sound without interference from other stations broadcasting at different frequencies at the same time.

Many radios have a short-wave band which is established at wavelengths between about 50 and 15 or 18 meters, and frequencies ranging from around 5 to 16 megacycles (5,000 to 16,000 kilocycles) so as not to interfere with commercial broadcasting. Within this short-wave band thousands of amateur radio operators talk with each other across oceans, police officers cruising about a bustling city in their cars talk with and receive orders from the station, air-line pilots learn about weather conditions at a distant airport where they are scheduled to land and music from foreign lands reaches our ears at home in a fraction of a second—all without interference because each uses a different wavelength and frequency to which we can tune our radio, excluding the others.

Before passing along to the uses of still shorter wavelengths and higher frequencies of electromagnetic radiations, which are used for television, radio ranging and other purposes, it may be well to consider for a moment the basic operating principles of radio transmission and reception.

Production of Radio Waves.

A circuit containing only a battery and resistance, as shown in Fig. 76*A*, cannot be tuned because, while there will be a magnetic field around the wire, it does not oscillate with any frequency or radiate away in waves, but rather might be considered as a stationary field of force around the wire coil. In such a circuit the electrons flow continuously in one direction until the circuit is broken or the battery exhausted. But if a condenser is substituted for the resistance as in *B*, the electrons will flow out of condenser plate 2, through the battery and into plate 1 in a number depending upon the pressure or voltage provided by the battery and the capacity of the condenser. If the battery is suddenly replaced by a short length of wire, the electrons which had left plate 2 for plate 1 will rush back to plate 2, so that there will again be a balanced equal number in each plate as before. Now, if the battery is replaced by an inductance coil instead of by the length of wire, as indicated in *C*, the electrons, although they will get started more slowly, will keep moving back to plate 2 until it has more than the normal balanced amount and becomes negative (electrons being negative charges) instead of positive as originally, and plate 1, having too few electrons, becomes positive. This inertia or tendency of current to stay in an inductance coil is explained in the discussion of Inductance in Chapter 4.

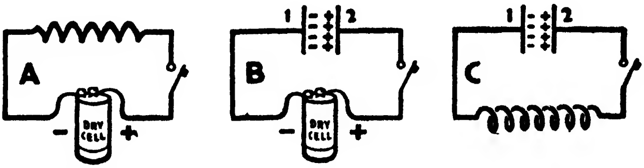


FIG. 76.—Three electrical circuits discussed above.

With the two condenser plates again electronically unbalanced, the electrons rush back again to plate 1, with a few too many getting over this time also. Thus a few pulses of current will alternate back and forth through the circuit until they fade into a condition of balance again. When this fading occurs, the pulses are said to be *damped* out. Such damping takes place very rapidly as a result of resistance losses in the circuit unless new energy is supplied.

Energy may be supplied to such a circuit and thus provide *undamped* high-frequency oscillations by coupling the circuit to an oscillator, as shown in Fig. 77, so that a pulse through the oscillator circuit will induce a pulse through the other one (see Chapter 4). An oscillator may be a high-frequency A.C. generator or it may be a vacuum tube having its elements so designed that controlled pulses of energy will be sent out. Such tubes will be described more in detail in Chapter 12.

A certain amount of time is consumed in getting a pulse under way through either a condenser or an inductance—the larger the capacitance or inductance, the longer the time required. Any combination of a condenser and inductance is therefore responsive to only some one frequency and is, therefore, *resonant* to that frequency (see Chapter 5).

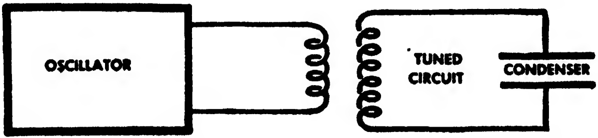


FIG. 77.—An oscillating circuit, providing undamped high-frequency oscillations, is basic in the production of radio waves.

Thus we have in the circuit a continuous alternating current which oscillates at high frequency and radiates or broadcasts electromagnetic energy (via an antenna) in wavelengths and frequencies as determined by the tuning characteristics of its condenser and inductance.

The transmission of code messages by radio quite naturally preceded the broadcasting of the sounds of voice and music. In order to transmit code signals it is necessary simply to break up the electromagnetic wave train produced by the oscillating current into dots and dashes of the Morse code by means of a contactor or key.

The transmission of sounds as in radio broadcasting, however, employs a different principle. In this case the train of electromagnetic radiations is not broken as with code signals, but rather is continuous but *modulated* by the much lower frequency oscillations produced by the microphone. In other words, although the higher frequency waves are continuous, they are made to increase or diminish in amplitude (see Chapter 6, Simple Waves) in accordance with the current from the microphone, which, in turn, is determined by the sound waves of voice or music that enter it.

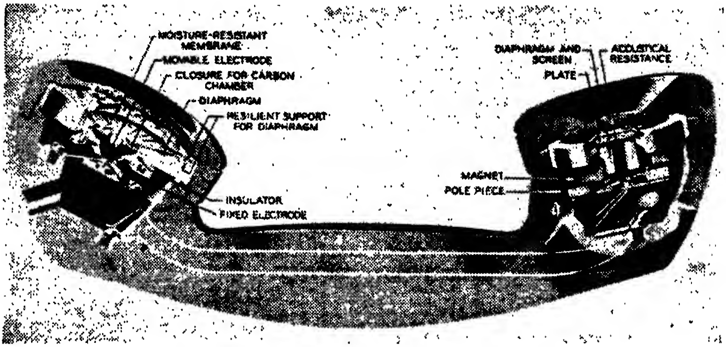


FIG. 78.—A modern telephone handset showing the internal construction of the carbon transmitter (left) and the receiver (right). (*Courtesy of Bell Telephone Laboratories.*)

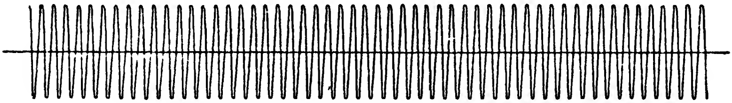
Ordinary telephone transmitters contain a thin disc or diaphragm behind which is packed a quantity of small carbon granules. Sound striking the diaphragm causes it to vibrate in accordance with fluctuations of the sound waves. Such vibration results in varying degrees of compression of the carbon particles, so that when electric current is passed through them, the resistance encountered changes in accordance with the degree of compression of the particles. Thus a telephone transmitter is, in effect, a device to make the electric current passing through it fluctuate almost exactly in accord with the flucutations of the sound waves which strike it.

The microphones used for radio broadcasting require a more accurate transposition of sound waves into electric-current variations, and different methods have been developed—some for extreme fidelity, some for sensitivity and others for ruggedness. One type, called the *induction microphone,* utilizes induction coils and a metallic ribbon, another makes use of carefully cut and adjusted crystals and a third method utilizes the principle of a condenser and is called a *condenser microphone.* In the last device two parallel diaphragms are used, separated by an air gap in the order of a thousandth of an inch. One of them vibrates in accordance with the sound waves striking it, just as does the telephone transmitter, but in this case, instead of carbon granules being compressed, the distance between the diaphragms fluctuates. With the two diaphragms acting as the two plates of a condenser, it can be seen that the capacitance will vary in accord with the vibrations of the sound waves (see Chapter 4, Capacitance), so that a changing current is caused in the circuit connected to the two plates.

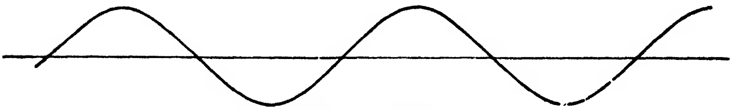
It is this changing current from a microphone which *modulates* the continuous train of higher frequency electromagnetic waves produced by the oscillating current of the radio-transmitting equipment. The high-frequency (radio-frequency current) oscillations are called the *carrier waves,* and when they are modulated or made to vary in amplitude in unison with the variations of audio-frequency current from the microphone, they are called *amplitude-modulated waves.*

The Reception of Radio Waves.

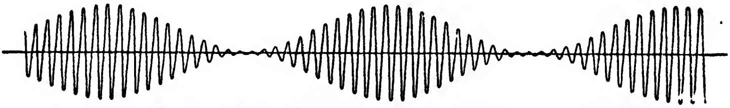
The modulated or broken, whichever the case may be, electromagnetic waves radiate out into space from the antenna and travel at the same speed as light, infra-red, ultra violet, X-rays and all the others of the electromagnetic spectrum—186,000 miles per second.



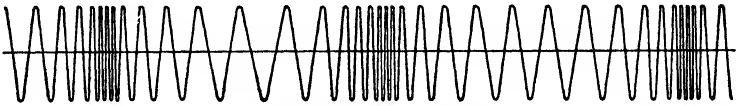
UNMODULATED RADIO-FREQUENCY CARRIER WAVES



AUDIO FREQUENCY WAVES



RADIO-FREQUENCY CARRIER WAVES, AMPLITUDE MODULATED BY AUDIO-FREQUENCY



FREQUENCY MODULATED WAVES

Fig. 79.

At the receiving point the incoming train of waves sets up an oscillatory current in the receiving antenna. Since the wavelength of the waves has been established at the transmitting station by adjusting or tuning its inductance and capacitance to a certain frequency of vibration, the reverse must be done at the receiver; that is, the inductance or capacitance of the receiving circuit must be made to match or be put in resonance with the frequency of the transmitter (see Chapter 5, Resonance). This matching is called *tuning* a radio. When we turn the dial, we change the capacitance of a variable condenser (or change the inductance of coils) in our radio set so that it will respond to or pass the same frequency of oscillations radiating from the station to which we wish to listen.

The method of changing the modulated electromagnetic waves back into sound waves via a loud-speaker or headphones involves electron tubes (radio tubes) or a crystal detector and will be covered in detail in Part IV. The pickup circuit must not only be tuned to the frequency of the transmitter but must also provide means of separating the modulating wave from the carrier before the headphones or speaker vibrate so as to produce sound waves like those entering the microphone in the broadcasting studio.

The basic operating principle of a telephone receiver, radio headphones or a radio loud-speaker is essentially the same for each. The function, of course, is to change the fluctuating current back into sound waves. This is done in a manner similar to the reverse of a transmitter; that is, a diaphragm is made to vibrate in accordance with the current variations coming to it from the receiver. A magnet is used, around which coils are wound and the fluctuating current passed through them. The strength of the magnet changes with each fluctuation of the current, and the diaphragm, which is placed in front of the poles of the magnet, is pulled back and forth, thus vibrating rapidly in accord with the current variations and producing sound waves.

Radio, therefore, is a means of changing sound waves into modulated electromagnetic waves, broadcasting them and then changing them back into sound waves again.

Short-wave Radio.

It has already been indicated that as the wavelengths of electromagnetic waves used in radio become shorter and as the frequencies become higher, their characteristics and behavior change somewhat. Short-wave radio is successful in long-distance transmission as long as refraction from the layers of ionized gas high above the earth takes place. But when the wavelengths become much shorter than 10 meters, we find that they have different characteristics.

One reason why newer developments in radio, such as frequency modulation and television transmission, are in the short-wave and ultra-short-wave regions is that they will be out of the crowded longer wavelength bands where commercial broadcasting is carried on. Since static disturbances are electromagnetic impulses in a hodgepodge of wavelengths and frequencies, it is difficult to sort them out of any broadcast band. Static occurs whenever a bolt of lightning or some other similar disturbance sets up a short train of powerful waves radiating in all directions.

Frequency Modulation.

Frequency modulation is a subject to which several excellent textbooks have been entirely devoted. Basically, it is a method of transmitting and receiving radio waves which are modulated in frequency (and wavelength) rather than in amplitude, as previously explained. Amplitude modulation can be compared to sound waves producing one tone of a certain pitch which is modulated or varied in its degree of loudness. Such a tone would waver in intensity but not in pitch, like a *tremolo* in organ music. A frequency-modulated tone, however, would not vary in amplitude or loudness but would wave up and down regularly in pitch like a *trill* in music.

Frequency-modulated radio broadcasts have been placed in a rather narrow band at about 8 or 9 meters wavelength and 40 to 45 megacycles frequency. Receiving sets designed for the reception of these waves are becoming widely used in homes, and the freedom from static interference and the high fidelity of tone resulting with frequency-modulation transmission and reception will no doubt make them very much in demand within a short time.

Television Transmission.

The principal difference between the transmission of pictures by radio and the transmission of sound by radio lies in the method of picking up the energy which is to be converted into electromagnetic waves. The waves themselves are the same in each case except that in television, shorter wavelengths and high frequencies are used to avoid conflict and interference from static as well as from other signals.

It has been explained how, in converting sound waves into amplitude-modulated electromagnetic waves, a microphone causes fluctuations of the current in its circuit in accordance with the sound waves producing vibrations of its diaphragm. In television the fluctuations are caused by the variations in light intensity over the surface of a picture within the range of vision of a lens focused upon the scene to be televised.

One type of electron tube which converts the gradations of light into fluctuations of electric current is called an *iconoscope*. Its operation and construction will be covered more fully in Part IV, but at this point we can think of it as a device which breaks the scene into thin horizontal lines of light and dark, one after the other from top to bottom, until eventually the whole scene is scanned. It is similar to reading this page. Instead of grasping the page as a whole, the eye travels along each line, carrying each word to the brain until eventually the whole page is read and its meaning impressed upon the brain. The individual words or lines mean but little until enough of them have been read to start the formation of a mental picture. So in television, a thin beam of electrons sweeps rapidly back and forth more than 500 times across an image on the screen of an iconoscope as the reader's eyes sweep each successive line of a printed page. In order to avoid a disturbing flicker at the receiving end, the whole scene must be swept in this manner about thirty times in each second. Current from the iconoscope, which pulsates in accordance with the gradations of the scene lines, is converted into electromagnetic waves and broadcast in the same manner as the sound which accompanies and is synchronized with the scene.

Present television broadcasting is carried on in a wavelength band ranging from about 8 to 3 meters, with frequencies from 50 to 100 megacycles or more. To distinguish it from the transmission of sound (*audio*), television is called *video* transmission. Developments now in progress in this field of radio will, in all probability, lead to colored moving television pictures in stereo (three-dimensional depth) projected upon a screen of good size within the average home.

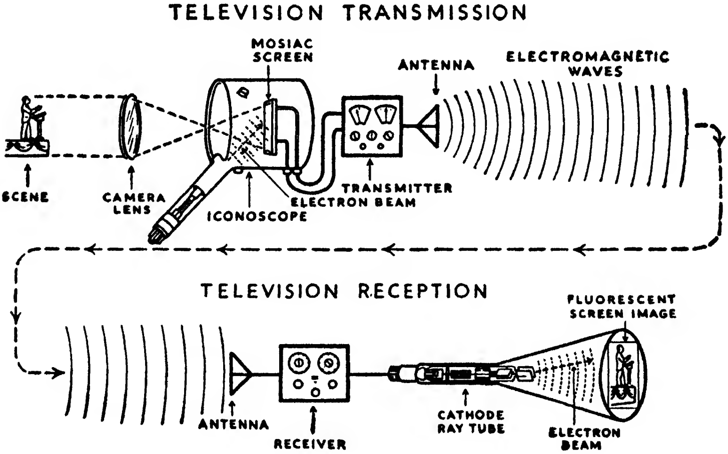


FIG. 80.

Television Reception.

Television reception is basically the reverse process of transmission, that is, the transformation of electromagnetic waves of the broadcasting wavelength back into those of light wavelength which can be seen. The receiver is similar in many respects to our ordinary radio except that the video oscillations, instead of being sent to headphones or to a speaker for transformation into sound waves, are sent to a cathode-ray tube for transformation into light. The details of cathode ray tubes will be presented in Part IV, but we can discuss their function in a general way here.

A cathode-ray tube consists primarily of an electron gun which emits a thin needle-like stream of electrons, a system of electromagnetic plates which deflect this stream of electrons up and down or sideways, depending upon how the control is operated, and a screen of fluorescent powder coated over the flat end of the tube. When and wherever the electron stream strikes the fluorescent screen, a bright spot, pinhead in size, is created upon it. The brightness of this spot depends upon the strength of the stream, that is, on the number of electrons in it.

If the stream is swept almost instantly across the screen, the eye sees its path not as a series of light dots but as a bright line. If, during its progress across the screen the number of electrons in the stream decreases, the line will be brighter at its starting end than at its finish. If its strength fluctuates during the sweep, the line will have gradations of light and dark in accordance with the electron stream-strength fluctuations.

The stream from the electron gun in a cathode-ray tube does just this, and it sweeps over 500 lines across the fluorescent screen from top to bottom, completely covering the screen with light and dark areas. Furthermore, it makes the complete coverage thirty times each second, traveling somewhere in the order of 180,000 inches per second. It is these light and dark areas which make up the television picture on the end of a cathode-ray tube.

In the previous section on television transmission it was explained quite briefly how the iconoscope does the same thing to the subject or scene being televised and how the current from the iconoscope fluctuates in accordance with the light and dark areas of the scene as its own electron stream sweeps or scans the scene line by line. It was also pointed out that this fluctuating current is converted into modulated electromagnetic waves and broadcast in the same manner as ordinary radio waves.

Television therefore is, in a sense, a means of converting the electromagnetic radiations of light into much longer wavelengths which can be broadcast, and then of changing them back into light again so that they can be seen. Of course sound-transmission waves are synchronized with the video transmission to complete the intelligence of the broadcast.

Ultra-high Frequencies and Microwaves.

On page 142 of the section on Short-wave Radio, it was stated that, as the wavelengths of electromagnetic radiations become shorter and their frequencies higher, the characteristics and behavior of such waves change somewhat. As we proceed beyond the short-wave region into wavelengths still shorter (less than a meter), we find the waves abandoning many characteristics of the longer ones. As a matter of fact, a moment's reflection and a glance at the frontispiece will reveal that we are approaching the infra-red or radiant-heat region and that such waves might be expected to behave something like radiant heat and even visible light. This is just about what they do in the upper limits of the microwave region thus far explored; that is, radio waves of these ultra-high frequencies and short wavelengths can be focused more readily into a beam much like a searchlight.

In the consideration of microwaves, we must also shift the ideas of electric-current flow which were described in Part I. At low frequencies and long wavelengths electric current flows *through* a conductor, but at the high frequencies of microwaves the current flow is more nearly in the surface of the conductor, actually penetrating it only very little. Thus we see that instead of thinking of electric current as flowing, like water, through a pipe, we must think of it as flowing along the outside of a pipe when the very high frequencies of microwaves are involved.

Paradoxical as it may seem, pipes are actually used instead of solid conductors to conduct these extremely high frequency currents. Such pipes are called *wave guides* and may be round, square or rectangular in cross-sectional shape. Wave guides carry microwave currents just as a speaking tube carries sound waves, keeping them within its boundaries and allowing them to come out at the listening end diminished somewhat by losses which radiate away from the tube along its length. A few readers may have observed the way in which light flux passes through a fused quartz or Lucite tube—traveling around bends and out the end with but little loss through the sides. This analogy of wave-guide behavior is perhaps more physically accurate than the speaking-tube description.

Since the microwave region involves wavelengths of only a few centimeters, the physical dimensions of the wave guides become the essential factor in their function. The manner in which the radiations travel within their boundary limits is determined largely by their cross-sectional size and shape.

Wave guides should not be considered as conductors in the sense that they are connected to a source of energy such as an A.C. generator. They are just what their name indicates. They guide electromagnetic radiations of microwave proportions from one point to another, the waves radiating perhaps from a small rod-like antenna placed at one opening of the guide, so that they can propagate along its length to the other end, where further control and use may await them.

It is dangerous to attempt a further discussion of the characteristics of microwaves in a book of this sort without recourse to the more technical aspects, which have deliberately been avoided. It is hoped, however, that the reader will have gained at least a general concept of the behavior of the electromagnetic radiations in this region.

At present it seems to be questionable whether wavelengths still shorter than those we have just discussed will be of much use in distant communication. The structure of air is such that shorter waves have a tendency to attenuate or be absorbed when radiating through it. Future developments, however, may open new uses for wavelengths and frequencies in the region between microwaves and infra-red radiation.

Ranging and Detecting by Radio.

As this is written, ranging and detecting by radio are among the most potent offensive and defensive weapons of both the enemy and ourselves. As such, we cannot discuss the subject too openly. It involves ultra-high frequencies in the microwave region and utilizes those characteristics which are similar to the behavior of infra-red and visible light. Specifically, these radiations can be sent out and controlled in direction like a searchlight beam, and, when striking an object, they are reflected back in a way similar to that in which light would be reflected back. The important difference, however, is that the microwaves making up the ranging beam penetrate fog and haze, whereas light is absorbed by the atmosphere.

The range of power used for this work is tremendous. The electron tubes which produce these ultra-high frequency waves are capable of generating extremely powerful outputs. This energy is sent out in a beam, and upon its striking an object a minute quantity is reflected back. The equipment which detects the reflected energy is extremely sensitive to the minute quantities which return to it. Some concept of the range of radiant-energy power involved in ranging and directing may be obtained from the following analogy:

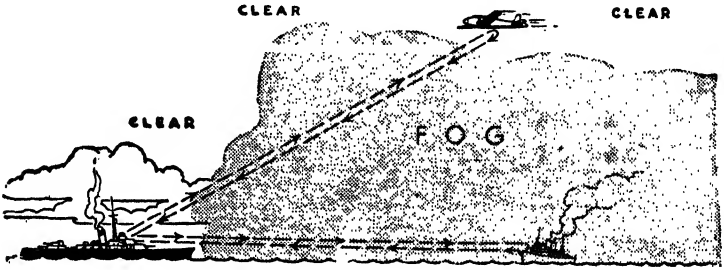


FIG. 81.—Radio ranging and detecting operation

If it were possible to scoop up all the sand on a typical seashore and throw it at a plane somewhere out of sight behind the clouds and to have one grain bounce back to tell exactly where the plane was located, we should have a picture of the relative energies involved.

Since the speed of electromagnetic radiation of all wavelengths and frequencies is the same (186,000 miles per second—see Chapter 6, Electromagnetic Waves), the location of the object can be accurately computed from the time involved for a pulse or packet of microwaves to travel to the object and return. Of course, such a time interval is extremely short and is measured in millionths of a second (microseconds).

Although this development has been responsible for a great deal of damage to the enemy, it will be applied to peacetime living and travel to make safer and more reliable transportation. It will be the "eyes" of a ship at sea in the thickest of fogs. It will guide air lines around treacherous mountain peaks on the blackest nights through blinding rainstorms and assure their safe arrival at airports.

Part IV

BASIC ELECTRONICS

AUTHOR'S NOTE

Thus far, the author has endeavored to take the reader through the fundamental principles necessary for a basic understanding of how electron tubes do their work. Part I covered only the simplest facts relating to the flow of electric current. Part II treated in some detail the effects of magnetism and how they are produced and used electrically. Part III explained electromagnetic radiation throughout its entire range of wavelengths and frequencies and how each region is used for the benefit of mankind.

The science of electronics is, in a sense, a correlation of all these factors through the use of electron tubes which utilize electric current to move electrons and magnetism to control their movement. Such controlled electron movement results in either the generation of electromagnetic radiation or a means of regulating it after it has been produced by other methods.

CHAPTER 12

Electron Emission.

At the very beginning of Part I it was pointed out that all materials contain electrons, some of which are not securely bound in atoms but can more or less move or vibrate rapidly from one atom to another within the substance. These are called *free* electrons. In solids they do not usually possess sufficient speed to overcome molecular or atomic forces and are confined to the limits of the material. In liquids, free electrons are not restrained quite so much as in solids. In gases there is no surface barrier at all.

Heat is a convenient form of energy which can be used to speed up the activity of electrons, atoms or molecules to such an extent that they will actually leave the substance of which they have been a part. When a kettle of water is heated sufficiently, for example, the molecules of water will leave the surface in the form of steam. We call this *evaporation*. If a solid, such as a metallic filament in an incandescent lamp, is heated sufficiently, the electrons become very active and acquire enough speed to overcome the surface barrier and escape from the solid wire entirely. This is called *thermionic emission*. It differs from water evaporation in that electrons escape instead of molecules (see Chapter 1), and the electrons are negatively charged, whereas the water molecules are uncharged.

At the time of his death in 1931, Thomas A. Edison had been granted more than 1,200 patents on inventions. In 1883, when he was 36 years old, he made the first experimental verification of electron emission, but it was several years later that his observations were satisfactorily explained. He sealed a short length of wire through the glass bulb of one of his incandescent lamps and connected a battery and meter to it. He noted that when this wire was connected to the positive terminal of the battery, an electric current flowed through it, even though it was not in contact with the filament of the lamp. The wire, being positive, attracted the negatively charged electrons. This is known as the *Edison effect*, and is the basic principle of all electron tubes today. The elements in electron tubes which correspond to Edison's filament may be filaments also, or they may be

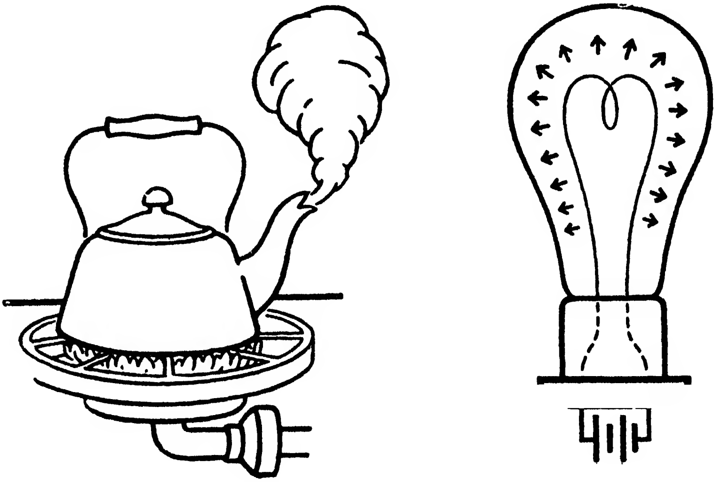
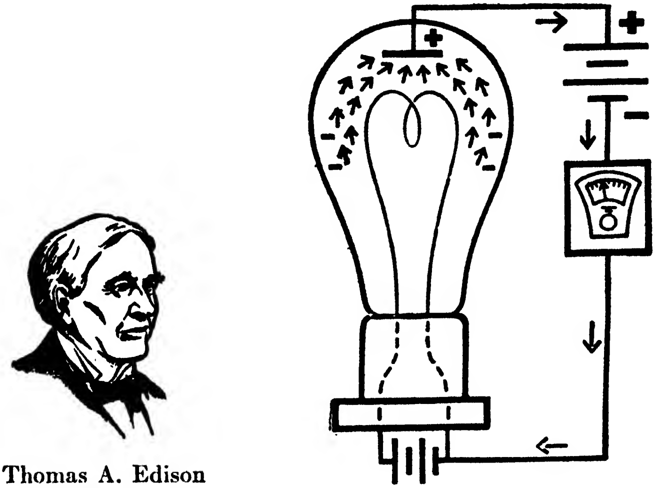


FIG. 82.—Water evaporation (left) is similar to electron emission. The evaporation of electrons from a solid body (such as the filament in the lamp above) is thermionic emission.

in the form of a ribbon, bar or block of metal. They are called *cathodes* and emit electrons when heated. The elements corresponding to the short length of wire in Edison's device may be wires, plates, cylinders or other metallic forms and are called *anodes*.

Studies in thermionic emission show that the amount of electron flow depends upon the temperature and nature of the cathode and upon the amount of positive voltage applied to the anode.



Thomas A. Edison

FIG. 83.—The basic principle of all electron tubes today is the so-called "Edison effect" illustrated above. Edison experimented with this in 1883.

As indicated above, there are a great many ways of designing cathodes and anodes. One type of cathode which is quite satisfactory in certain tubes utilizes a small metallic cylinder to which heat is applied indirectly by means of a heater element or filament inside the cylinder and insulated from it.

The emission of electrons from cathodes can be greatly increased by coating them with certain materials such as the oxides of strontium, barium and calcium. Another material used in some types of vacuum tubes utilizes thorium dissolved with a small amount of carbon in a tungsten filament. This is called *thoriated tungsten* and has excellent electron-emission characteristics until such time as heat has reduced the metallic thorium content at the surface of the wire to such an extent that the electron emission drops to the poorer characteristics of the tungsten. When this occurs, the cathode is said to be *deactivated.*

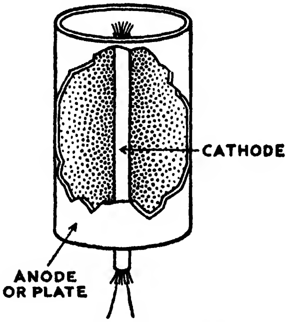


Fig. 84.—Diagram showing the space charge effect.

The distribution of electrons around a hot wire or cathode is called the *space charge* of electrons, and it varies with the temperature to which the cathode is subjected. This variance occurs in the quantity of electrons around the cathode and in the speed at which they travel. When the cathode is cold, the space charged is nil or practically so, but as the temperature is increased, more and more electrons leave it with increasing velocities so that the space charge extends farther and farther away.

If the positive voltage on the anode or plate is kept constant, the flow of electrons to the plate will increase only up to a certain cathode temperature. Beyond that point the electron flow will remain constant even though more electrons are being driven from the cathode. This is due to the fact that in the immediate vicinity of the cathode the density of the negative electrons becomes greater than at the positive plate or anode. The consequent cloud of free electrons formed around the cathode hinders the passage of newly emitted electrons to the anode so that they return to the cathode. Thus this cloud or space charge will limit the flow of electrons or *plate current.*

The Diode Tube.

The experiments of Edison resulted in the electron's being put to work. The simplest vacuum tube contains only a cathode and anode such as just discussed and is called a *Fleming valve* or a *diode.* The electrodes are placed in a glass tube or bulb from which as much of the air as possible is exhausted, and the necessary lead wires are brought out through airtight seals. The high vacuum is desirable so that the electrons may move from the cathode over to the plate or anode without too many collisions with molecules of air. (Electronic research has

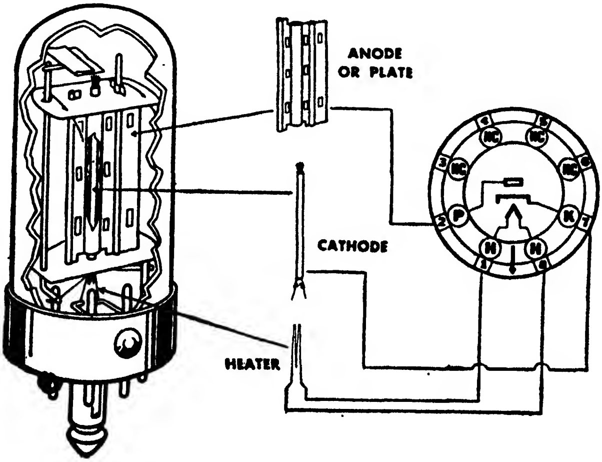


Fig. 85.—Diagram of the construction and wiring of the diode tube.

made gas-filled diodes possible, and they are widely used today.) The principle of the diode is identical with that in Edison's experiment.

One of the most important uses of diode tubes is to change alternating current to a pulsating direct current. Current thus changed is called *rectified* and the tubes which do it, *rectifiers*. Since electrons are negative charges, they fly to the plate only when the plate is positive. When it becomes negative, it repels the electrons back to the cathode from which they were emitted. Therefore, when alternating current is applied to the plate, it becomes alternately positive and negative so that plate current (electron flow) flows only during that half of the time when the plate is positive, and only in one direction.

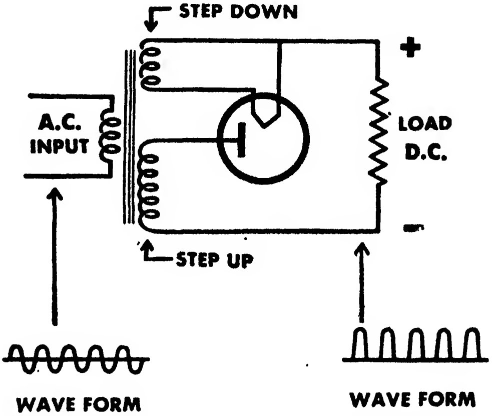


FIG. 86.—The half-wave rectifier circuit.

A diode tube operating in this manner cuts off the negative halves of the A.C. cycles and is called a *half-wave rectifier*. To avoid the loss of half of each cycle, two diodes may be used so connected that the anodes or plate of one will be alternately positive while the other is negative. This arrangement can also be incorporated in

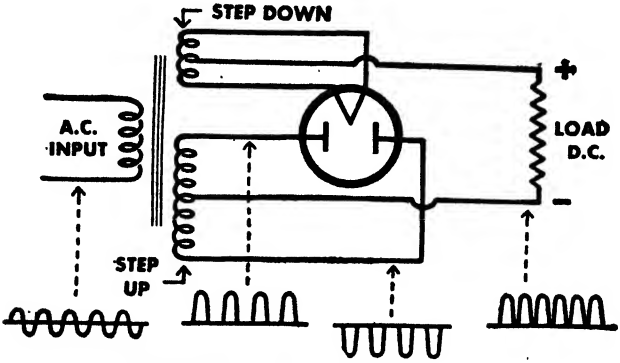


FIG. 87.—The full-wave rectifier circuit.

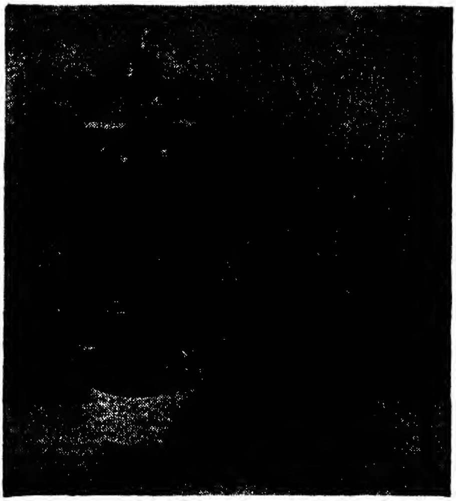
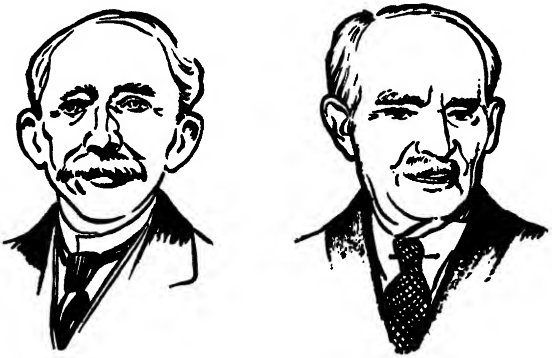


FIG. 88.—The VT129 rectifier as compared with the tiny type 6AN6 multiple diode tube. There are a number of very large tubes manufactured for rectifier purposes, one of which is called the *kenotron*.

one tube, the voltage on one anode being positive while the other is negative, with the conditions reversing every half cycle. In this way both halves of the alternating cycle are utilized and the tube is called a *full-wave rectifier*. Groups of several diodes are used to rectify the current from three or more phase supplies.

Radio Detectors.

It was explained in Chapter 11 how radio waves radiate away from the antenna of a radio transmitter and set up an oscillatory current in the receiving antenna and how the receiver itself must be tuned to the frequency of these waves. It was also indicated that means must be provided for separating the modulating wave from the carrier before the headphones or loud-speaker can be made to produce sound waves.



Fleming De Forest

Fig. 89.

This separating can be accomplished with a crystal detector or a vacuum-tube detector such as a diode. In either case, the detector acts as a rectifier or valve by allowing current to flow in only one direction through it, thereby changing the high-frequency alternating oscillations (radio frequency) to slow-frequency pulsations (audio frequency), which are then made to produce sound waves in the headphones or loud-speaker. Such *demodulation,* or sorting out, of the audio frequencies from the carrier- or radio-frequency waves (see Chapter 11) is necessary because the diaphragms of headphones and speakers will not vibrate at such high frequencies. Even if they did, the sound waves produced would be away above the upper limit of audibility so that no purpose would be served.

Certain crystals such as galena, silicon, carborundum and others have the property of unsymmetrical conductivity and allow current to pass through in one direction much more readily than in the other, thus rectifying the current, but diode-tube detectors have replaced crystal detectors in commercially available radio sets.

The Triode Tube.

In the diode tube there is no way to control the electron flow (plate current) except to change the plate voltage. In 1906 Dr. Lee De Forest introduced a third element into the diode tube, making it into what is called a *triode.* This third element is a *grid* and consists, as a rule, of a spiral mesh of wire inserted between the cathode and the plate in such a way that the cathode is completely surrounded by it. The grid acts as a control of the electron flow from the cathode to the plate, since the electrons must pass through it on their way over.

The amount of electron current flowing in a triode depends upon the voltage applied to the grid. If it is made negative with respect to the cathode, the electrons will be repelled (being negative charges) and if positive,

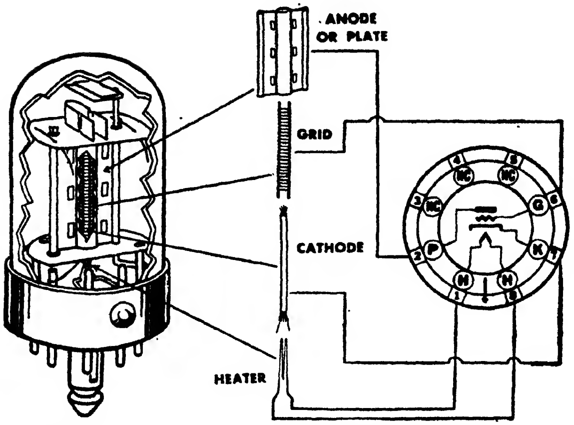


FIG. 90.—Diagram of the construction of a typical triode tube with wiring connections to the base.

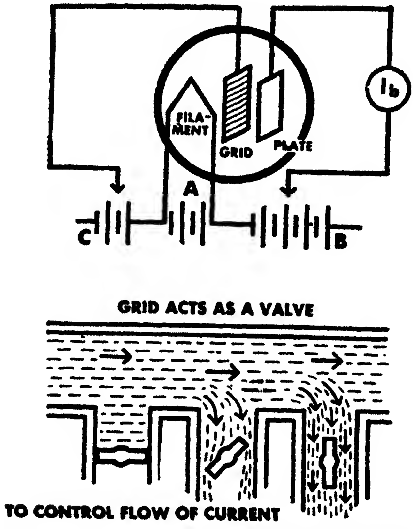


FIG. 91.—Basic hookup of triode tubes.

the electron flow may be even greater than if the grid were absent. Thus, by varying the voltage from a negative to a positive value on the grid, it can be made to act as a valve to regulate the flow of electrons from the cathode to the plate.

Amplification.

As has been explained, the plate current (electron flow) is affected by either a change in the plate voltage or a change in the grid voltage. The latter, however, has a much greater effect than a plate voltage change; that is, a slight change of grid voltage can vary the electron flow as much as a large change in the plate voltage. The ratio between the two values required to maintain a constant plate-current or electron flow is the *amplification factor* of the tube.

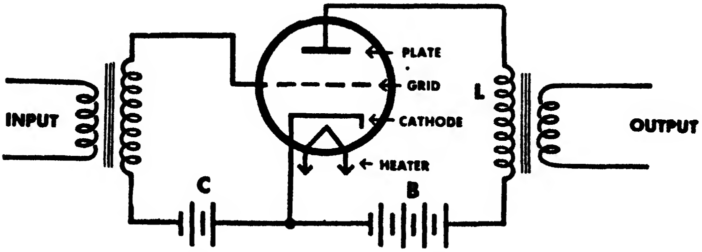


FIG. 92 —Hookup of a triode tube used as an amplifier.

It can be seen by a study of Fig. 92 that large variations in plate current resulting from grid-voltage changes will induce voltage variations in the inductance *L* through which the plate current flows. These induced voltages will be greatly magnified or amplified reproductions of a radio signal voltage when it is applied to the grid.

Oscillators.

In the section covering the production of radio waves in Chapter 11, it was mentioned that oscillating carrier

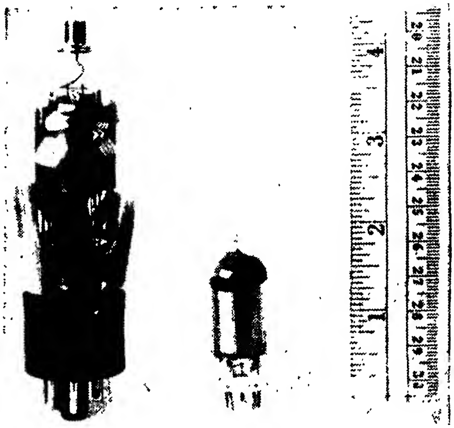


FIG. 93—Two types of amplifier tubes. Left, the 6KG7 and, right, the 1T4. The latter is a small high-frequency amplifier tube used in hearing aids and in miniature radio sets such as used by the Army and Navy for field-communication work.

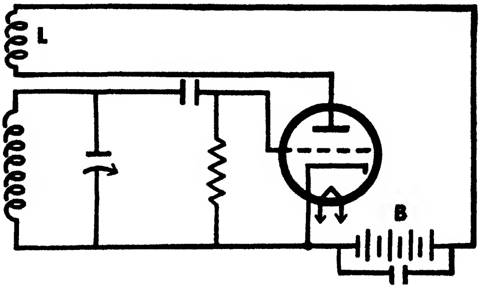


FIG. 94.—Wiring diagram of a triode used as an oscillator.

waves may be produced by a certain type of vacuum tube called an *oscillator*. Triodes are used for this purpose when connected as shown in Fig. 94.

If the inductance L is so connected that part of the energy resulting from the plate current is fed back to the grid circuit, the circuit will produce oscillating currents of constant frequency and amplitude. In such a circuit the tube operates as a rapidly acting valve which transfers energy to the grid circuit at the precise moment to sustain oscillations—much the same as a rubber ball can be kept bouncing by striking it downward at the top of each bounce.

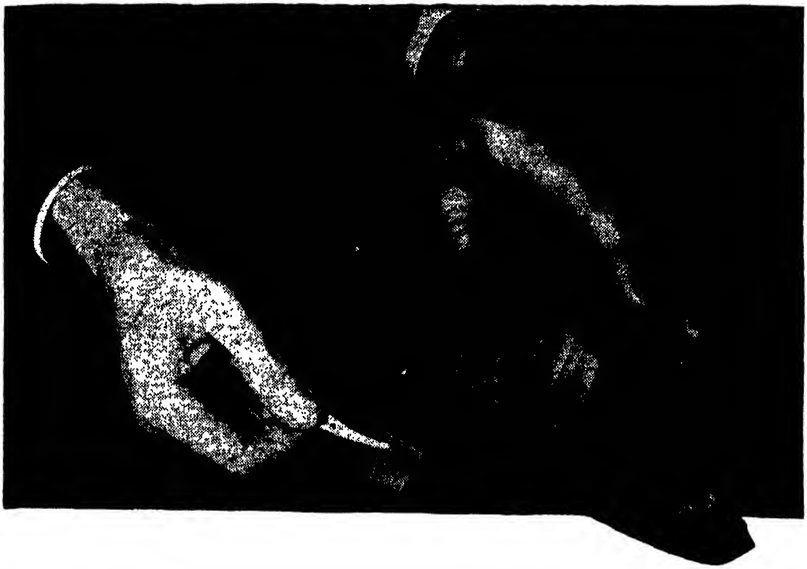


Fig. 95.—A large mother crystal with oscillator plate that has been cut from the mother as illustrated. (*Courtesy of Crystal Products Company.*)

Oscillators of this type are widely used for both radio and wire communication circuits to provide the carrier waves. There are several types of circuits employing various methods of producing oscillations.

In high-frequency and ultra-high-frequency work, quartz crystals are used in conjunction with oscillators

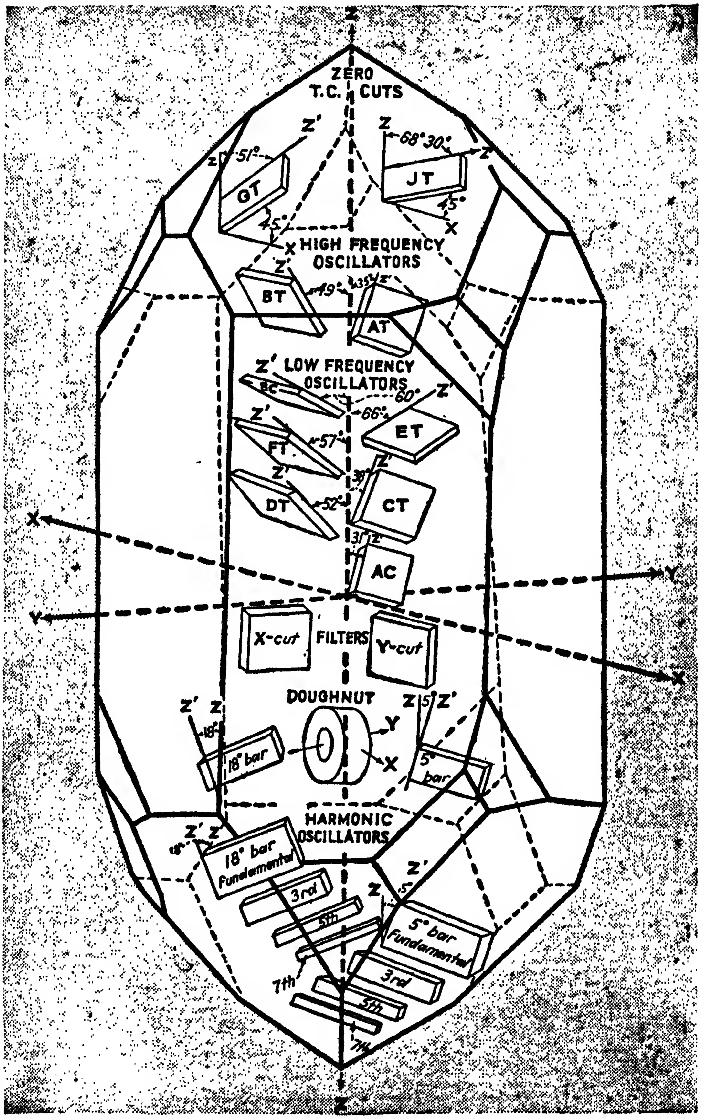


Fig. 96.—Quartz oscillator-plate cuts showing their angular relationship to the axes of a mother crystal. (*Courtesy of Crystal Products Company.*)

to provide extremely precise control of frequency. The crystals are cut from the mother crystal in wafer and other forms with a very high degree of accuracy, and the angle of cut with respect to various axes of the mother crystal determines their *piezo-electric* characteristics.

Piezo-electric effects were first noted by Pierre Curie, who is identified with the discovery of radio-active elements. These effects are the result of the natural arrangement of atoms in the lattice structure of quartz crystals and appear when the wafers or plates are subjected to either mechanical or electrical distortion. If one side of a quartz plate is compressed or deformed mechanically, electric charges will occur on the opposite face, or if one side is subjected to an electric charge, the plate will become physically distorted. Thus, when such crystal plates are influenced by alternating voltages, they will oscillate along certain axes in accordance with the frequencies being applied.

Quartz oscillator plates are placed in vacuum-tube circuits to stabilize or *fix* the frequencies of the oscillations, since a circuit of this sort will oscillate only at the frequency permitted by a quartz plate which has been cut at a carefully predetermined angle from the mother crystal. Their physical dimensions and angular cut determine their resonance or oscillating frequency characteristics, so that extreme care and accuracy must be used in the cutting and grinding technique.

Tetrodes, Pentodes and Beam-power Tubes.

The grid and plate of a triode operate in a manner similar to a condenser having capacitance (see Chapters 4, Capacitance, and 5, Resonance). Energy can be fed back from plate to grid through this capacitance so that triodes used as amplifiers frequently begin to oscillate. In order to avoid this, a second grid, called a *screen grid*, is placed between the first (control grid) and the plate and is usually operated at a lower positive voltage than the plate. Such a four-element tube is called a *tetrode*.

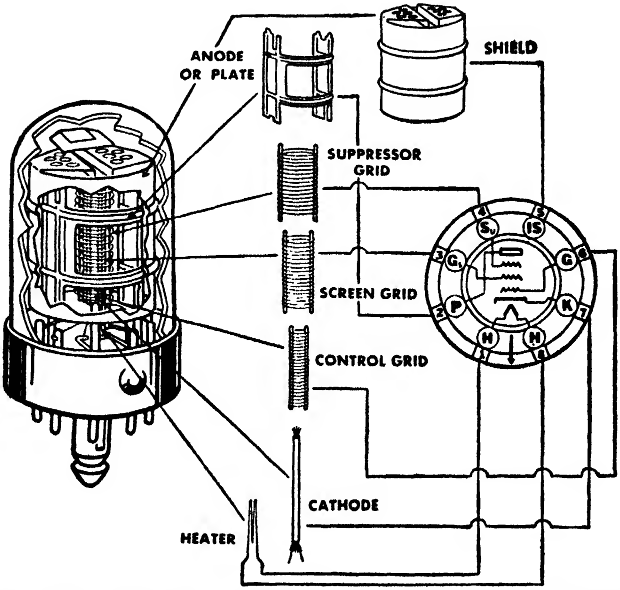


Fig. 97.—The construction and basic wiring of a typical pentode tube.

When electrons strike the plate of a tube, they cause other electrons to be knocked off the plate, much the same as a stone raises dust when thrown against the dry ground. This release of other electrons is called *secondary emission* and in a triode causes no trouble because the newly released electrons fly right back to the positive plate from which they were knocked. In a tetrode, however, many of them may be drawn to the screen grid

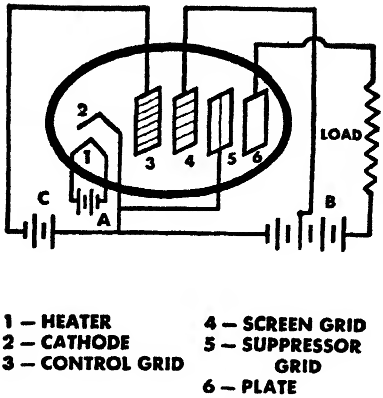


Fig. 98.—The basic hookup of a pentode circuit.

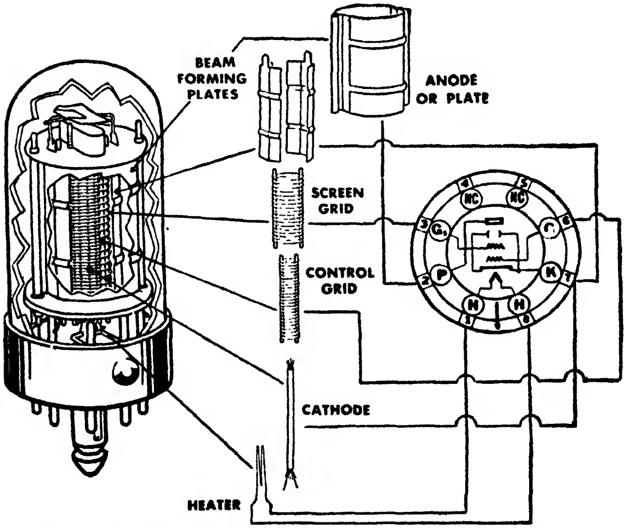


Fig. 99.—The construction and basic wiring of a typical beam-power tube.

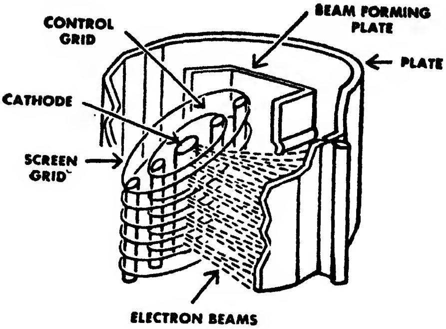


FIG. 100.—Cutaway view of beam-power-tube operation.

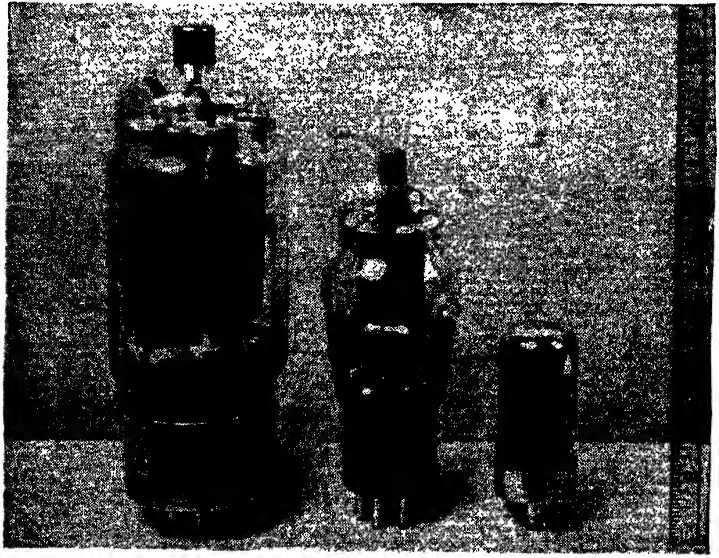


FIG. 101.—Three types of beam-power tubes. Left, the 813, which is a transmitting beam-power amplifier. Center, a 1625 transmitting beam-power amplifier. Right, the small 7C5 beam-amplifier tube. There are in service much larger tubes, some of which are several thousand watt water-cooled tubes.

under certain conditions when the screen-grid voltage is relatively high, instead of returning to the plate. This results in a counter flow of electrons which can be eliminated by adding a third grid called a *suppressor grid.* This third one is placed between the plate and the screen grid and is connected to the cathode and thus, by virtue of its negative potential, forces the secondary electrons back to the plate. A five-element tube such as this contains a cathode, a control grid, a screen grid, a suppressor grid and a plate and is called a *pentode.*

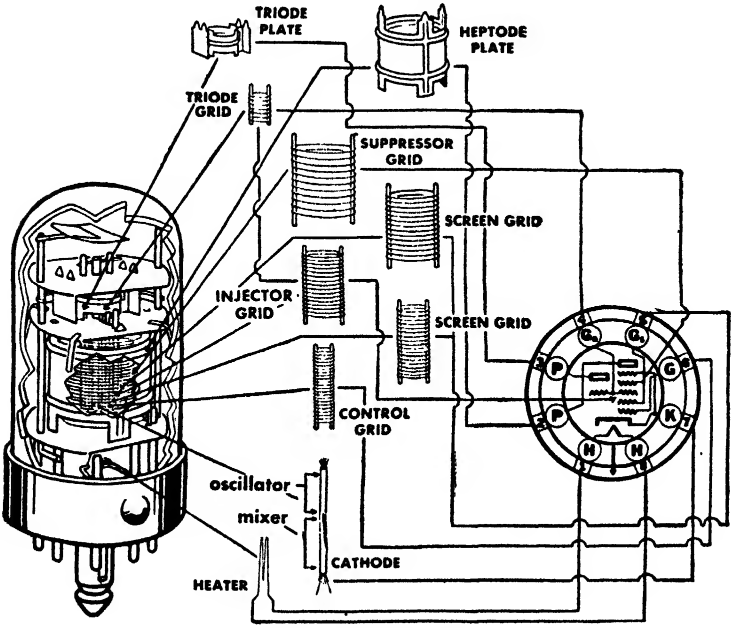


FIG. 102.—The construction of a triode heptode converter and the construction of the base pins.

When pentodes are used for higher power output, unsatisfactory operation results from the fact that the wire suppressor grid introduces distortion and nonuniform suppressor action. This is overcome by the use of beam-forming plates instead of a suppressor grid. These plates concentrate the electrons in a beam during their passage between the screen grid and the plate, and the suppressor action is obtained from the space charge which occurs with the concentration of electrons. Large tubes of this type are used in radio transmitting circuits, whereas smaller ones function as amplifiers (audio and radio frequency) in receivers.

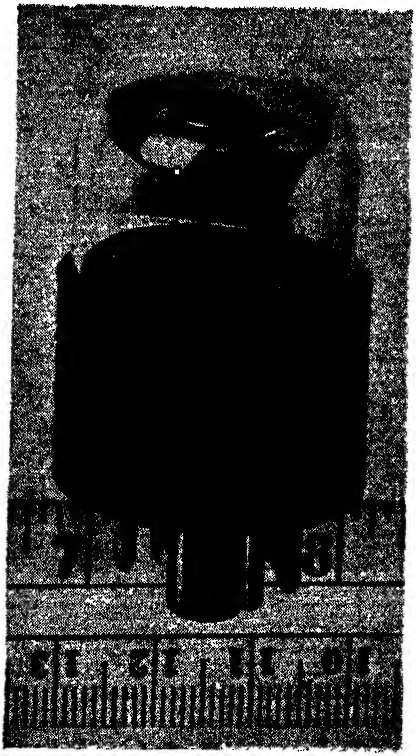


FIG. 103.—An electron ray tube which is used to indicate resonance in some types of radio receivers. This tube has a cathode within a bowl-shaped target which is coated with fluorescent material. A segment of the bowl glows green to indicate the closest degree of tubing in a radio receiver.

There are other methods of radio tube construction employing more devices than those just discussed. The pentagrid converter, for example, utilizes five grids in addition to its cathode and plate. In other types the functions of two separate tubes have been combined in one, such as the previously described full-wave rectifier. Fundamentally these other types are similar to the more common ones covered in this chapter.

CHAPTER 13

Incandescent Lamps.

If we are to adhere to the definition given at the beginning of Chapter 1, an incandescent lamp cannot be considered as an electronic tube. Although electrons are released from the tungsten filament as a result of its becoming white-hot, such thermionic emission is incidental and serves no purpose in the production of light. Even so, incandescent lamps are the most widely used electric-light sources in the world at present, and we cannot afford to ignore them entirely.

Ever since 1876, when Swan demonstrated his first crude incandescent lamp, and 3 years later, when Edison passed an electric current through lengths of carbonized bamboo, horsehair and filaments of metal sealed in evacuated glass bottles and finally produced light for 45 hours, the development of incandescent lamps has been rapid. The filaments have undergone changes in material as well as in shape. The early carbon filaments were replaced by tantalum and other metals for a short time until finally, when a method of drawing tungsten into fine wire was established, that metal was, and still is, used. The effectiveness of tungsten as a filament lies basically in its high melting point. It is capable of becoming extremely hot without melting, thus producing a comparative abundance of light.

The shape of the filament has also changed from the original single loop of carbon wire 8 or 10 inches long to a coiled coil of wire about the same length when straightened out but only little more than a half inch long in its coiled-coil form. The primary reason for concentrating the filament in this manner is to keep its heat from being carried away (by a gas) as rapidly as with a straight wire; thereby greater heat is provided on the filament with consequent more light.

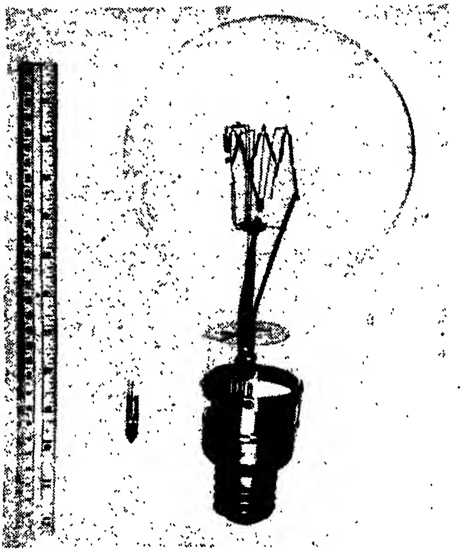


FIG. 104.—Left, the small incandescent lamp used as a circuit signal for telephone switchboards. These lamps range from 4-volt 0.170 ampere to 60-volt 0.045 ampere in size. Right, a standard 2-kilowatt PS52 incandescent lamp such as is used in certain types of floodlighting and high-bay illumination. There are still smaller incandescent lamps such as the "grain-of-wheat" light used in medical work, and larger ones up to 50,000 watts.

Other changes involved the gases used to surround the filament. The first lamps were evacuated as completely as possible at the time, and the use of vacuum lamps became widespread. In fact, many of the smaller types of incandescent lamps today are vacuum lamps. When it was discovered that an inert gas such as nitrogen would retard the evaporation of the filament, resulting in less pronounced lamp blackening and higher efficiency, the gas-filled lamp appeared. Nitrogen was used exclusively for a while until argon proved to be more effective, being heavier and acting somewhat like a blanket around the filament in keeping the evaporation rate at a minimum. There are other advantages to the use of gas in incandescent lamps, and at present argon mixed with a very small percentage of nitrogen is used in all gas-filled lamps.

During these 60 or more years of development, the efficiency of incandescent lamps has in some instances increased in the order of 1,000 per cent. One-hundred watt lamps, which in the early days had efficiencies of 2 or 3 lumens per watt, are now rated at over 16 lumens per watt (see Chapter 7, Measurement of Light).

It appears as though future increases in incandescent-light-source efficiencies will be small and slow to come since each increase in the operating temperature of the filament brings it nearer to its melting point. The lighting industry has developed other methods of producing light, however, which even at the outset showed efficiencies of more than double those of filament lamps. These sources involve the entirely different principles of gaseous discharge and fluorescence and will be discussed shortly.

The incandescent lamp has served and is serving mankind well. It has aided in hundreds of scientific developments and when correctly used has saved countless pairs of eyes from serious damage and even blindness. Those who have been closely identified with lighting during the past two decades will, in a sense, be sorry to see it, like an old friend, go, if go it must (for general use), during the coming decade.

Ionization of Gases.

Normally, gas is a poor electrical conductor. There are, however, several methods by which it can be made conductive. The method with which we are primarily concerned in the production of light involves charged particles in the gas, or *ionization* of the gas.

These electrified particles are called *ions* and may consist of atoms (or molecules) of the gas from which one or more negative electrons have been removed, thus leaving the atoms positively charged and the negative electrons free to take up an orbit around some other neutral atom or to remain unattached. Atoms which have adopted an extra electron are negatively charged and called *negative* ions. Those which have lost an electron are *positive* ions. The electron removal may be the result of one or more influences. Ultra violet radiation, for example, will ionize air, as was pointed out in the discussion of the ionosphere or Kennelly-Heaviside layers, high above the earth's surface. X-rays, gamma rays and cosmic rays also cause the same effect.

Another method which is the basis of gaseous discharge lamps may be called *ionization by collision.* Under all circumstances there are a few ions in a volume of gas, and when a high enough potential or voltage is applied across such a volume, these positive and negative ions will start to move toward the terminals of opposite polarity from themselves. In so doing they collide with neutral molecules of the gas, splitting them up into ions also, so that they in turn enter into the activity. Thus the gas becomes ionized within an instant, and an electric discharge or arc is formed.

A gaseous discharge of this nature enclosed in a glass tube has certain characteristics which occur in accordance with the pressure of the gas and with the voltage applied to the electrodes. The major characteristic is the production of visible light and ultra violet. Part of the electrical energy is absorbed when atoms or molecules are knocked apart to form ions, and part is absorbed in forming *excited atoms.* An excited atom is one in which an electron does not leave the atom but merely shifts its orbit. These excited atoms almost immediately release the energy they have absorbed, so that it radiates away as visible light and ultra violet. The color, brilliancy and distribution of this light along the length of the tube depends to a large extent upon the pressure of the gas being ionized as well as upon the voltage applied. At times there are two dark bands which appear to separate the continuous column of light. These are called the *Crookes* and the *Faraday dark spaces.* The

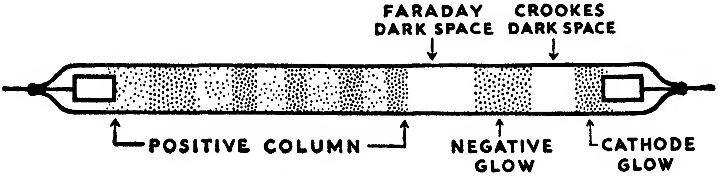


FIG. 105.—Dark spaces and glow columns are found in low-pressure discharge lamps. These columns of luminous gas and dark spaces vary in accordance with the gas pressure.

first occurs quite near the cathode end of the tube and is separated from the second, which appears nearer the center, by a band of light called the *negative glow*. The Faraday dark space occurs between the negative glow and a wide band of light called the *positive column*, which itself may be striated. These dark spaces and bands of light change in size and intensity as the gas pressure, voltage or both are varied, the dark spaces becoming more pronounced as the gas pressure is reduced. Thus we have a method of producing light without the extremely high temperatures required in an incandescent lamp.

Gaseous-discharge-light Sources.

Perhaps the most elementary forms of gaseous-discharge-light sources are those with which many high-school physics students are familiar. They are called *Geissler tubes* and are simply tubes with electrodes sealed in at each end. The glass tubing is bent in various shapes and filled with different gases at whatever low pressure will produce the most light when the proper voltage is applied. Geissler tubes were the forerunner of present-day gaseous-discharge-tube advertising signs, usually referred to as *neon* signs because neon gas is used to produce the attention-compelling orange-red glow within the tubes.

The history of the development of gaseous-discharge tubes for advertising display or for lighting is not the history of a single development by one individual, but rather is the intermingling of numerous developments by several investigators. Among the best known names in early gaseous-discharge-tube work are D. McFarlane Moore and Georges Claude. Both these men made demonstration lighting installations of tubing at about the beginning of the present century.

While neon gas has been widely used in display tubing, its color obviously eliminates it as an acceptable light source for ordinary visual work. Certain other gases such as helium and carbon dioxide produce a much more nearly white light, but it was not until the vapors of such metals as sodium, cadmium or mercury were introduced into the tubes that they became relatively successful sources of useful light.

The sodium-vapor lamp, which has been most successfully used for the illumination of the clover-leaf type of highway intersection and for bridge and bridge-approach lighting and similar applications, is a lamp utilizing neon gas and sodium vapor at very low pressure. When these lamps are first lighted, their color characteristics are the orange-red of ionized neon gas, but as the sodium becomes vaporized by the heat of discharge, the spectral quality of the light shifts to a golden-yellow color identified with sodium.

Light of this nature is monochromatic or nearly so; that is, it contains only one narrow band of yellow light from the visible spectrum with none of the other colors present. There seems to be a mistaken impression abroad that monochromatic light as produced by sodium-vapor lamps has great advantages over other sources in increasing the acuity of vision at night. While it does appear to aid the eyes in determining the character and shape of very small objects at low levels of illumination, the value of a sodium-vapor lamp as a source for highway lighting is not its monochromatic light, but rather its high efficiency (approximately 40 to 50 lumens per watt, depending upon size) as well as its low brightness resulting from the relatively large physical dimensions of the discharge.

Mercury-vapor lamps have found extensive use, primarily in industry. There are several types all basically the same with respect to the method of producing light, but different in gas pressure, physical size, shape and operating characteristics. Their blue and blue-green color is easily recognizable, and they are usually used in conjunction with incandescent lamps to provide color correction in the illumination.

These sources utilize argon or a gas which ionizes readily and, of course, mercury vapor. Those operating at low and medium pressures and temperatures are less efficient than the high-pressure sources. The well-known Cooper-Hewitt lamps are low-pressure tubular lamps and the first linear light sources to become acceptable to industry. They utilized a pool of mercury for a cathode and an iron anode. Such low-pressure mercury-vapor-arc discharges produce considerable ultra violet radiation, but the glass used for the tube was of a type which is opaque to ultra violet wavelengths so that no serious amount of the radiation passed through.

With an increase in the vapor pressures above a certain maximum, much of the radiant energy from the lamp is shifted from the shorter wavelength regions to longer ones, so that high-pressure mercury-vapor lamps produce less ultra violet and more visible light and are, therefore, more efficient as light sources. The efficiencies of high-pressure mercury-vapor lamps are somewhat less than those of sodium-vapor light sources, ranging from about 30 to 40 lumens per watt, depending upon the size and type, but their color characteristics make them much more suitable for industrial-lighting applications. One type of mercury-vapor source operates at very high vapor pressure with a consequent high temperature and efficiency (65 lumens per watt). This source requires a quartz envelope to enclose the discharge as well as an outer bulb of hard glass so that cool water may be circulated around the inner quartz tube. Since the discharge itself is of small dimensions, the lamp is extremely brilliant. These sources are used primarily for special projection purposes.

The blue tubes used in advertising signs a few years ago employed mercury vapor also, and to obtain the green color, yellow-tinted glass tubing was used in conjunction with a mercury-vapor discharge. The combination of the blue discharge and yellow glass produced the green color. During the last few years, however, such advertising-tube colors result from a fluorescent coating on the inside of the tube rather than from the discharge itself.

Luminous-advertising-tube operation is somewhat different from that of the discharge sources directly used for illumination. The vapor pressure is low, the cathodes are operated cool as compared to the temperature of the thermionic types used in radio tubes, fluorescent lamps, and the sodium- or mercury-vapor lamps just discussed, and high voltage is required to operate them.

Hot-cathode Fluorescent Light Sources.

It has been explained how gases and vapors enclosed in an envelope of glass are ionized when their molecules collide with electrons emitted from a cathode and how the ions thus formed move about and cause further collisions with other molecules of the vapor. It has also been explained how energy is released and radiates at various wavelengths in the visible-light and ultra violet regions.

It will be recalled, further, that at certain low pressures mercury-vapor discharges are rich in ultra violet radiation but relatively poor in visible-light radiation. Basically, the fluorescent lamp is a means of converting this invisible ultra violet energy into visible light with a degree of efficiency hitherto not accomplished with any light sources generally applicable to commercial and industrial illumination.

The converting process is accomplished by certain chemical compounds such as zinc silicate, cadmium borate, magnesium tungstate and several others. These compounds are called *phosphors* and have the property of absorbing the radiant energy of ultra violet wavelength and reradiating it at longer wavelengths, which we can see as visible light. In other words, the compounds are *excited* to fluorescence by ultra violet of the proper wavelength.

This exciting process of the phosphors is similar in one respect to the ionizing process of the gas. The ultra violet energy disturbs the normal electron orbits of atoms making up the compound molecules so that the electrons, in returning to their normal orbits, release energy of a visible-light wavelength. In the case of the zinc silicate compound, the predominant wavelength of the released energy is in the order of 5,200 Angstroms, so that we see the radiation as green light. Excited cadmium borate, on the other hand, radiates visible light at wavelengths in the region of 6,000 Angstroms, and so the color we see is predominantly pink. Calcium tungstate, another compound, is excited to blue light of wavelengths around 4,500 Angstroms.

By careful blending of these compounds it is possible to provide almost any desired color with a high degree of efficiency, but certain colors have been established for standard fluorescent lamps. The green fluorescent lamp, while not applicable to general lighting because of its color, has the highest efficiency, of about 70 lumens per watt. The white lamp, which produces light approximating a color temperature of 3500° Kelvin (see Chapter 7, Color Temperature), is rated in efficiency at 52 lumens per watt for 40-watt lamps and 42 lumens per watt for 100-watt lamps. The fluorescent compounds coated on the inside of daylight lamps have been deliberately

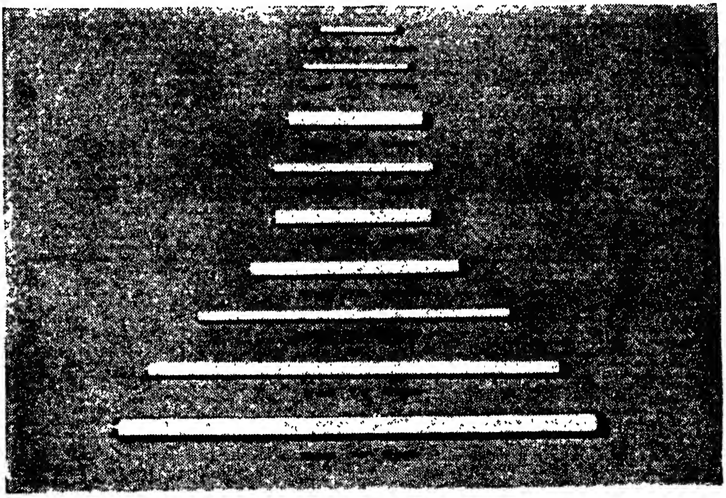


FIG. 106.—The range of available sizes of standard hot-cathode fluorescent lamps.

blended to match *standard* daylight closely, which has been designated as a combination of sky conditions producing natural light of a color temperature of 6500° Kelvin. The efficiency of daylight fluorescent lamps is established at 45 lumens per watt for 40-watt lamps and 37 lumens per watt for 100-watt lamps. Without doubt, progress in fluorescent-lamp manufacture will result in increased efficiencies to match the progress that has taken place over the past half century with incandescent lamps.

While the fluorescent compounds used in fluorescent lamps become excited throughout a fairly wide range of ultra violet wavelengths, different ones show their maximum or peak excitation at different wavelengths. In the spectrum of a mercury-vapor arc at a few microns pressure, there is a very pronounced resonance line at 2,537 Angstroms, at which wavelength 80 per cent or more of the ultra violet energy is radiated. This wavelength is not the most potent exciter for all the phosphors used in fluorescent lamps, but it is the most potent one for the largest number of them, and it is not very far from the peak excitation region of the others.

In fluorescent-lamp manufacture there is a very careful correlation between the excitation properties of the fluorescent chemicals and the pressure characteristics of the vapor discharge, since even a slight increase in pressure will shift some of the radiant energy to longer wavelengths, which do not possess so much ability to excite the chemicals, so that a lower output of visible light results.

In addition to accurate pressure control, extreme purity of the argon gas and mercury is essential along with the highest quality methods of exhausting, in order that swirling or "snaking" arcs may be avoided. Swirling arcs were sometimes found in early fluorescent lamps. They are caused by extremely minute quantities of a foreign gas such as carbon dioxide or of a vapor such as water, which are either not removed in the exhausting process or are present in the argon when it is placed in the lamp. Such impurities may also be driven from the cathode into the discharge under adverse starting conditions. The negative ions of a foreign gas or vapor of this nature seek the outer limits of the column of gas where they form in rings or "doughnuts" around the inside of the tube. Convective currents within the tube cause them to rotate in an eccentric fashion, and the arc, constricted where it passes through the "holes," is forced to follow the motion of the "doughnuts." With two or three of these rotating within a lamp, the discharge takes a spiral or swirling path along the tube.

Our primary interest in this discussion of fluorescent lamps lies in the basic electronic principles involved rather than in their characteristics and applications as light sources, particularly since the latter have been adequately covered in several handbooks, manuals and published bulletins. However, some of the physical elements of fluorescent lamps as well as certain essential features of their operating circuits may be included since they are related to the electronic performance of the lamps.

Standard fluorescent-lamp cathodes are similar to those in a radio tube; that is, they consist of a coiled-coil tungsten wire coated with a material which facilitates thermionic emission (see Chapter 12, Thermionic Emission). There are also, in some lamps, two probes extending along each side of the filament which act as anodes during the starting process and aid in the rapid ionization of gas in the immediate vicinity of the cathode. They also carry part of the current during lamp operation.

FIG. 107.—A type of hot cathode used in standard fluorescent lamps showing the mercury-filled sleeve extending downward from the right-hand support

A very small quantity of extremely high purity mercury is placed in the lamps either during the exhausting process in a free form or sealed in a tiny metallic sleeve welded to one of the filament supports of one cathode. In the latter method, precise measurement is obtained and possible contamination of the mercury from a dispensing device is avoided. The mercury in the filled sleeve (called a *mercury bomb*) expands from the heat of the cathode when current is first passed through it, so that the sleeve bursts or explodes, releasing free mercury and mercury vapor in the lamp.

Fluorescent-lamp Circuits.

Fluorescent lamps have cathodes at each end which, at the start of lamp operation, are in series with each other through either a manual starting switch or an automatic thermal (or magnetic) starter, as well as in series with a choke coil called a *ballast.* When the current is first turned on, it passes through the choke coil, one cathode filament, the closed starting switch and the other cathode filament and thus completes the circuit. With current flowing through the cathode filaments, they become hot, and thermionic emission takes place, the electrons being emitted from the filament and flying to the anodes (or lead wires when anodes are not used), thereby ionizing a volume of gas at each end of the lamp. As long as current is permitted to flow through this series circuit, the filaments will glow and gas will be ionized at each end, but a discharge through the column of mercury vapor along the length of the lamp will not take place.

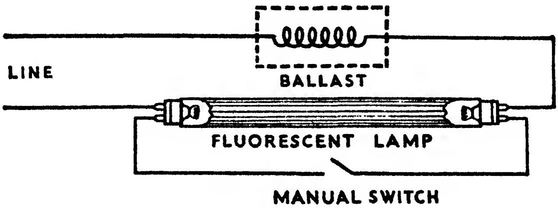


Fig. 108.—A simple single fluorescent lamp circuit with manual starting switch.

At this point, if the switch or starter is opened, either manually or automatically, the continuous series circuit is broken and each cathode becomes a single terminal with the column of low-pressure mercury vapor separating it from the other cathode. In the discussion of inductance in Chapter 4 it was pointed out that a counter E.M.F. is generated by the magnetic field of an inductance coil through which alternating current is flowing, and that this force resents the stopping of the current through the coil after it is once flowing. Thus, when the fluorescent-lamp starting circuit is broken, the tendency of the counter E.M.F. to maintain a flow of current in the ballast coil usually develops an instantaneous surge of high voltage which will more readily start current flowing or ionize the column of mercury vapor between the cathodes and light the lamp. Once the discharge is formed, it tends to draw more and more current so that the lamp would be immediately destroyed unless some means were taken to regulate the current. The ballast coil also serves in this capacity and maintains the proper operating characteristics of the lamp.

If we refer to the discussions of inductance and power factor in Chapter 4, it will be recalled that, when inductance is introduced into a circuit, the current peak occurs after the voltage peak, and a *lagging* power factor exists. Therefore, in the simple fluorescent circuit just described, we find a lagging power factor of around 55 or 60 per cent prevailing. Since this results in a wasteful use of wiring capacity, and since one lamp operating alone produces an objectionable flicker with each alternation of the current flow, it has become general practice to correct both faults by using a two-lamp auxiliary.

In the two-lamp circuits, one lamp operates essentially as described above. The other lamp, however, utilizes a capacitor of proper characteristics in series with its ballast coil so that its total reactance (Chapter 5) is capacitive rather than inductive as with the first lamp. Referring once more to the power-factor paragraphs in Chapter 4, we find an explanation of how with capacitance in a circuit, the current peak will occur before (or ahead of) the voltage peak or lead it, which results in a *leading* power factor. Thus, with one lamp lagging and the other leading by about the same power-factor values, the two-lamp circuit produces a combined power factor of 95 per cent or better.

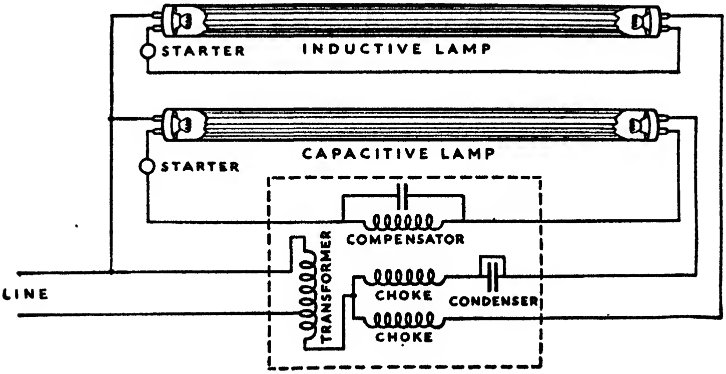


FIG. 109.—Circuit of a two-lamp ballast with built-in starting compensator, for two 30-watt or two 40-watt lamps on 110- to 125-volt circuits.

The smaller sizes of fluorescent lamps (15, 20, 30 and 40 watts) frequently will not start readily when operated on the capacitor circuit because of excessive limiting of the starting current by the capacitor. To offset this, another small choke coil, called a *compensator*, is connected in series with the starter so that it functions only during the lamp-starting process.

The two-lamp circuit does not reduce the A.C. flicker of individual lamps, but it does cause one to reach its higher brightness values while the other is in a state of low brightness, so that illumination resulting from a good blend of the two will show little or no annoying flicker.

Stroboscopic effects are caused when rotating machinery or moving parts are viewed under a single flickering lamp or under two or more which have not been corrected as just described. In extreme cases, when the rotation or vibratory motion of machinery coincides with the frequency of the flicker, the machinery may appear to be stationary. At other times it will appear to be going backward or forward at slower speeds than its actual motion.

There are other methods of correcting unfavorable power-factor conditions with large capacitors for whole lighting systems, and frequently flicker can be overcome by placing adjacent lamps or fixtures on separate phases of a three-phase system. A sequence starting circuit which utilizes a four-lamp ballast is applicable in certain types of installations where either continuous rows of fixtures or adjacent pairs of fixtures, containing two 100-watt fluorescent lamps each, are used on a 460/265-volt three-phase four-wire distribution system of wiring. This circuit saves considerable copper and steel, not only in the ballasts but in the wiring system as well, and has been used to some extent in many of the largest industrial plants. For single-lamp operation, ballasts having a high power factor (90 per cent or more) are available. There is also a method of operating two 14-watt (15-inch) fluorescent lamps in series with a special incandescent lamp which serves as a resistance ballast on either A.C. or

D.C. systems. The larger sizes of lamps may be used on D.C. systems providing resistances having the proper values and are used in series with single-lamp ballasts, but with such a combination the total auxiliary losses are considerably higher than with A.C. operation so that the over-all efficiency is reduced appreciably.

Although these and other methods of operating fluorescent lamps find occasional justification, the use of two-lamp auxiliary equipment seems to have been generally adopted and has proved successful for the large majority of applications. Continual research in fluorescent-lamp circuits and auxiliary design, however, will most likely result in decided improvements.

Fluorescent-lamp Starters.

As explained in the previous section, fluorescent lamps must be started under one set of conditions and operated under another. The change-over consists simply of breaking the circuit in which the two cathode filaments are in series with each other, after they have become sufficiently heated to provide adequate thermionic emission. This circuit breaking can be done manually with a single throw switch of any type (push button, twist, knife blade, etc.), or it can be accomplished automatically by a magnetic or thermal device which will remain closed long enough after the current is turned on to allow the necessary cathode preheating. Such a time-delay switch is called a *starter*, and although there are several satisfactory types, we shall confine this discussion to the one which depends upon electron emission and ionized gas for its operation and therefore is, in a true sense, an electronic device.

Starters of this type are called *glow starters.* The operating parts, which are enclosed in a small, sealed bottle containing argon or neon gas at relatively low pressure, consist of a bimetal strip and a second contact element quite close to it. (A bimetal strip is made up of two pieces of metal having different expansion characteristics, so that when heat is applied to a ribbon or strip having one metal on one face, and the other metal on the other face, the strip will bend or curl.) These contacts are normally apart or open; that is, when the starter is cold and not operating, the bimetal does not touch the other contact. All fluorescent starters are placed across (in parallel with) the lamp, so that when the current is

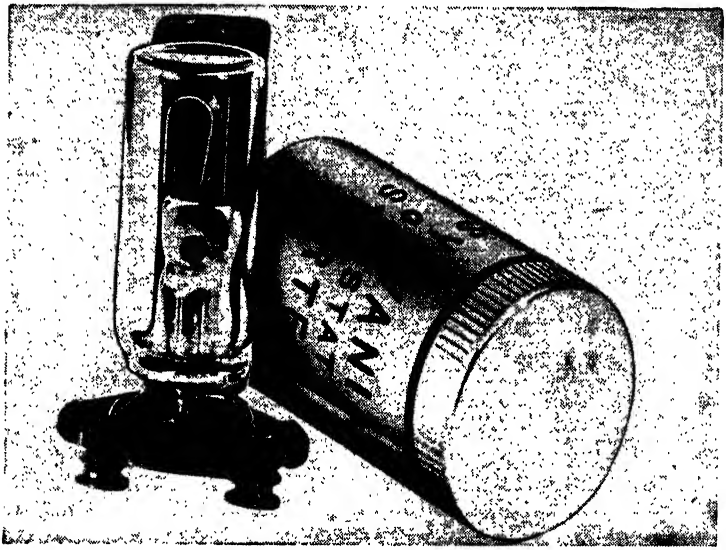


FIG. 110.—One type of glow starter used in conjunction with fluorescent lamps. The curved bimetal strip and second contact can be seen.

first turned on, the line voltage is received across the starter. In the case of 40-watt lamps and 118-volt lines, a transformer is incorporated in the ballast which raises this to about 200 volts.

The voltage necessary to produce a discharge through the argon gas in the bottle is established between 130 and 160 volts (for 30- and 40-watt starters—less in smaller ones), so that the gas ionizes when the current is turned on and a glow discharge takes place. Heat generated by this discharge causes the bimetal strip to move over and make contact with the other element and thus light the two cathodes, which at this point are in series with each other through the contact just established in the starter.

At the instant of contact and as a result of it, the glow discharge stops, thus removing the heat from the bimetal, but there is enough heat lag in the elements to hold them in contact with each other for a sufficient length of time to assure proper cathode-preheating time. When cool, the bimetal moves away from the other element, thus breaking the contact and lighting the lamp. With the lamp lighted, the voltage across the starter is too low to produce a discharge through the gas in the starter bottle, and so the starter remains inactive with the lamp in operation.

Other types of thermal starters operate by means of resistors, a high-resistance contact between carbon and nickel or some method, other than ionized gas, of supplying heat to move the bimetal strip. Magnetic starters, which have been replaced almost entirely by the thermal and glow types, use electromagnetism to move and hold the contacts as required for lamp starting.

Cold-cathode Fluorescent-light Sources.

The basic principle of cold-cathode light sources (sometimes referred to as high-voltage tubing) is identical with that of standard or hot-cathode fluorescent lamps; that is, a low-pressure mercury-vapor discharge is produced to provide the necessary wavelengths of ultra violet which cause fluorescence of the compounds coated on the inside of the tubing. Compounds having the same ingredients in the same proportion as those used in standard fluorescent lamps will produce the same color of light in cold-cathode tubes. The efficiency with which it is produced, however, may not be quite so high at present as with standard fluorescent lamps because of certain operating factors.

Cold-cathode tubes depend upon electron emission from their cathodes to start the discharge, but the emission is not thermionic. Instead, a high potential (voltage) is placed across the column of mercury vapor between the electrodes to force electron emission and current flow. Such potentials may be from 500 or 600 to 15,000 volts, depending upon the length of tubing.

It is highly probable that cold-cathode fluorescent-light sources will be applied to a much greater extent in the near future than at the present time. They have the advantage of instantaneous starting and a relatively simple transformer circuit. Power factor can be corrected, frequency flicker is much less pronounced in single-tube lengths, and tube life is considerably longer due primarily to the fact that cathodes can be made more rugged and durable when electron emission is not obtained from a heated filament. The disadvantage of high-voltage wiring will most likely be overcome by proper design of equipment based upon carefully determined safety requirements.

It is possible that the demands of home lighting upon fluorescent sources will result in a combination of hot- and cold-cathode operating factors, so that the advantages of standardized lengths, colors and higher efficiency will be coupled with instantaneous starting, simpler auxiliary equipment and longer life of the sources.

Bactericidal Tubes.

Chapter 9 was devoted entirely to electromagnetic waves in the ultra violet band, and some discussion was given the bactericidal region within this band. Since the peak of the bactericidal region occurs at wavelengths in the order of 2,537 Angstroms, and since a mercury-vapor discharge at a few microns pressure produces an abundance of radiation at this wavelength, it is obvious that mercury-vapor sources will kill bacteria provided that the radiations can pass through the glass wall of the tube enclosing the discharge.

Bactericidal tubes (or sterilizing lamps) are practically identical with fluorescent sources as far as their electrical and discharge characteristics are concerned. They may operate with either hot or cold cathodes, and the essential difference is the fact that ultra violet transmitting glass (or quartz) is used, and, of course, no fluorescent powder is applied.

With the hot-cathode types, standard fluorescent auxiliary equipment (ballasts) and starters are used, whereas the cold-cathode types require a transformer and operate at voltages ranging from about 300 volts for 10-inch tubes to 500 volts for 30-inch tubes. The hot-cathode types are manufactured in sizes corresponding to 15- and 30-watt T-8 fluorescent lamps, and other standard sizes are possible. There are also on the market several types of special bactericidal tubes having bent shapes and single end special bases—some utilizing quartz for specific applications.

FIG. 111.—Two types of bactericidal tubes. The one at the top employs a hot cathode similar to that used in a fluorescent lamp. The one at the bottom is of the cold-cathode type.

Black-light Sources.

To the average individual, the term *black light* seems to have an ominous and mysterious meaning. Two antithetical words such as these, bound together as a term or phrase, quite naturally cause some amount of subconscious questioning because the words do not seem to belong together. As a matter of fact, black light is neither black nor light, but is invisible ultra violet radiation in the wavelength region of 3,600 Angstroms. The word *light* is used because the radiation is only just beyond visible violet light in the electromagnetic spectrum, and also because it produces fluorescence of certain compounds or pigments which can be mixed with paints, dyes, lacquers, inks and similar products to make them glow with light. The word *black* is associated with *light* because the glass envelope surrounding the mercury-vapor discharge is black (or very deep red-purple in color) and, therefore, opaque to practically all visible light.

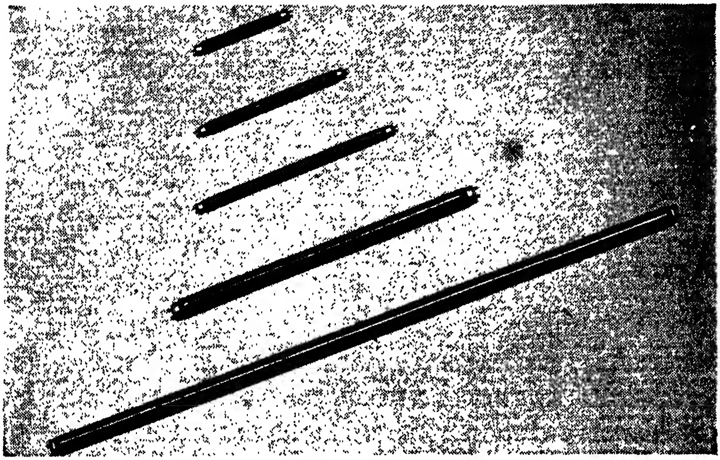


FIG. 112.—Commercially available black-light sources, arranged in size from the 4 watt at the top to the 30 watt at the bottom.

Black light is not new. For several years it has been a theatrical stage-lighting trick. Carbon-arc lamps, which are powerful sources of ultra violet (of all wavelengths) as well as of visible light, are used with heavy red-purple glass filters to hold back all visible light but to permit the longer wavelengths of ultra violet to pass through. Stage scenery and costumes are treated with fluorescent chemicals and glow beautifully and eerily in the nearly invisible "black" beams of the "light."

Although the carbon arc is used to some extent in theatrical work, mercury-vapor-discharge lamps have opened much wider fields. Both high- and low-pressure lamps are employed in a number of applications for commerce, industry, transportation and, most important, war purposes.

High-pressure, high-power sources have the advantage of high output of ultra violet (at 3,600 Angstroms); so they are used when the fluorescent objects are to be located at some distance. They have the disadvantage of producing considerable heat and being relatively short-lived. They also produce an abundance of visible light which must be eliminated with thick red-purple filters if the fluorescence is to be most effective. On the other hand, low-pressure discharges are comparatively weak in 3,600-Angstrom ultra violet, but do not require so much power or generate so much heat, and therefore can be applied to the fluorescent subject at very close range. Such close-range possibilities have resulted in the small 4-watt low-pressure discharge lamp becoming vitally important for wartime applications, one or two of which will be described shortly.

As a rule the high-pressure sources are made with a clear glass or quartz bulb, either enclosed in an outer bulb of red-purple filter glass or placed in a projector having a thick red-purple lens. The mercury-vapor-discharge characteristics are basically the same as those of high-pressure discharge-light sources described earlier in this chapter.

The low-pressure sources operate in the same way as standard fluorescent lamps of comparable wattage and utilize the same ballasts, starters and sockets. The tubular envelope enclosing the discharge, however, is of the red-purple glass, so that no further filtering is required. Low-pressure sources of this type do not depend directly upon the discharge for 3,600-Angstrom wavelength ultra violet potency, since at low pressures the greatest amount of energy is radiated at 2,537 Angstroms.

As was pointed out in the discussion of fluorescent light sources, the 2,537-Angstrom wavelength produces fluorescence of various compounds at different wavelengths of visible light, which we see as green, blue, pink, yellow and other colors. In the case of low-pressure black-light lamps, a compound is used which fluoresces with a considerable amount of 3,600-Angstrom wavelength ultra violet, as well as some visible light of a blue-violet color. If a red-purple envelope is coated with this compound and the low-pressure mercury-vapor discharge produced inside, it can be seen that the 2,537-Angstrom wavelength of the discharge will cause the coating to fluoresce at 3,600 Angstroms plus some visible-light wavelengths, but that only the 3,600 Angstroms will radiate from the lamp as a result of the red-purple tube filtering. With this process we have an efficient source of 3,600 Angstroms near ultra violet (*black light*) for application at close range to those paints, dyes and inks which *excite* to visible light at that wavelength.

Many wartime operations are carried on at night when absolute darkness is essential for their success. At such times, even the tiniest light source becomes a beacon to the enemy. At such times, also, a feeble light can be a source of annoying glare to the dark-adapted eyes of those directing and carrying out the operation.

Yet, modern warfare is machine warfare, and tanks, planes, submarines, surface craft and other mobile units of a fighting body must be operated in conjunction with instruments—and these instruments and dials must be visible to the operators. It is this problem that black light has helped to solve. The numerals, symbols and indicators of many of these instrument dials are treated with a fluorescent material so that they become dimly visible in the presence of black light without producing an undue amount of light to cause detection by the enemy or annoyance to those who must watch the dials as well as the progress of the operation.

There are dozens of other uses in addition to the above, some for war, such as fluorescent maps and marine depth recordings (in conjunction with supersonic impulses, see Chapter 11), and some for industry, which now makes flaws and minute cracks in metal castings more visible with fluorescence and black light.

There are a few other sources of 3,600-Angstrom wavelength ultra violet which in themselves are not black-light sources but which do make use of a red-purple filter at times. Perhaps the best known and certainly the most important of these is a small lamp designated as the *RP*-12.

This source is unique in its cathode-anode construction and in the fact that the discharge occurs in a nearly spherical volume of mercury vapor rather than in a column as with the other low-pressure sources just described. It is a fluorescent lamp depending upon the 2,537-Angstrom wavelength of ultra violet to produce fluorescence of the coating like all others, but unlike black-light sources, clear glass is used so that an appreciable amount of visible light is produced in addition at 3,600-Angstrom wavelength ultra violet.

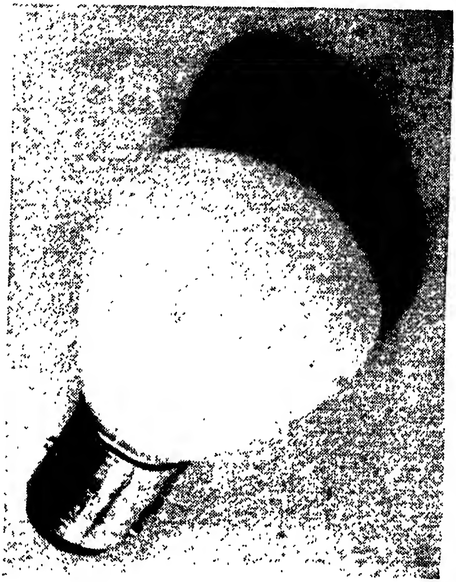


Fig. 113.—The *RP*-12 lamp, described in the text.

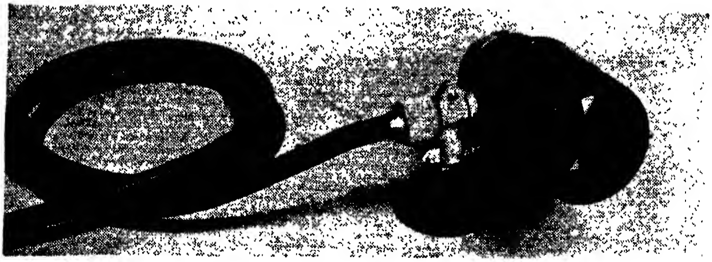


Fig. 114.—Unit employing the *RP*-12 lamp, showing the adjustable red-purple filter on the end.

This lamp was designed specifically for use in airplanes to excite fluorescent dial markings on the instrument panels. It is placed in a fixture having a variable red-purple glass filter so that either 100 per cent black light or 50 per cent black light and 50 per cent visible light may be obtained. Under certain conditions of night combat flying, the pilot wants to have as little light as possible and yet to have certain of his instruments readable. Under other conditions, such as at dusk or dawn, when there is some amount of daylight around him, he needs the visible component in order to see his instruments. There are also several other factors which make such lighting flexibility essential.

Black-light source and application development is continuing, and when the commercial and home markets are opened more fully, this type of illumination will, in all probability, become quite commonplace for specific low-level use.

CHAPTER 14

Strobotrons.

The strobotron first became generally known in conjunction with the science of high-speed photography as developed by Dr. Harold E. Edgerton and his colleagues at the Massachusetts Institute of Technology. Nearly everyone has seen Edgerton's fascinating pictures of a splash of water, a football being kicked, a bullet piercing an incandescent lamp, humming birds in flight and other examples of "stopping" high-speed motion with remarkable photographic detail.

The technique involves many things, not the least of which is a light source capable of extremely rapid and distinct flashes only a few millionths of a second in duration. Incandescent filaments, of course, do not cool sufficiently even at a 60-cycle frequency to show appreciable flickering, and although fluorescent lamps do flicker to some extent at 60 cycles, there is a *holdover*, or *lag*, in the fluorescent compounds which would practically eliminate distinctive flicker at higher frequencies. Therefore, neither of these sources has been used specifically as a source of high-frequency flashing light.

A strobotron is a low-pressure discharge tube utilizing a cold cathode coated with caesium. In the smaller types, neon gas, which produces the characteristic orange-red light, is used. The larger tubes may be filled with argon, krypton or a combination of these and other rare gases and the light produced is usually a brilliant blue-white. The strobotron's primary function, as indicated above, is to provide a source of extremely rapid and distinct flashes of light or, by virtue of the discharge, pulses of current.

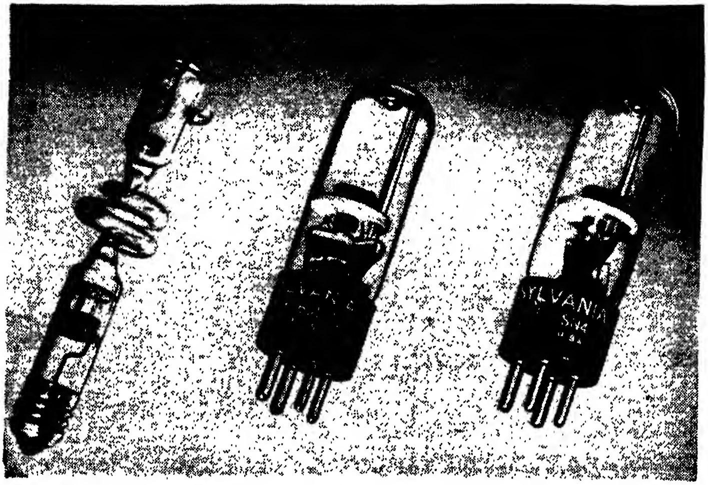


Fig. 115.—Left, one type of discharge tube used to produce stroboscopic light of relatively high intensity, employed in high-speed photographic work. Center and right, two tubes used for the study of stresses and strains in rotating machines.

The frequency of the flashes can be controlled either by rapid mechanical interruption of the circuit or by rapid capacitor discharges. In this way, several thousand separate and distinct flashes or pulses per minute can be obtained, or the frequency can be reduced to 1 per minute or less if desired.

In high-speed photography, the flashes of light act as a camera shutter would, so that it is possible to obtain one exposure of a fast-moving object of only a few millionths of a second in duration or a large number of exposures per second of the same object. Of course, special film and equipment are used, and, when developed and printed, the photographs show the object as it was during the instant of time that the stroboscopic light fell upon it or show the successive positions of the object at each flash of the strobotron.

For the study of rotating or vibrating machinery, the strobotron's flashes are synchronized with the rotation or vibration frequency so that the machine appears motionless. For example, if an electric fan is turning at the rate of 1,200 r.p.m. and a strobotron is made to flash 1,200 times per minute or in multiples of that figure, the flashes will occur when the fan blades are always in the same position. Thus, although the flashing frequency and fan rotation are too fast to be distinguished by the eye, we see the fan always in the same position by virtue of the stroboscopic light, so that it appears to be standing still. Airplane propellers are studied this way so that stresses and strains, which may appear only while they are turning at high speeds, can be determined and corrective measures taken in propeller design. Stroboscopic light is used in hundreds of industries for problems similar to the propeller applications. It has aided considerably in certain ballistics studies.

In the section devoted to supersonics in Chapter 11, mention was made of the strobotron as a means of controlling supersonic impulses for determining marine depths. In applications of this nature, the current of the strobotron's discharge is used rather than the visible light which results from it. Very short packets of supersonic waves are sent to the ocean bottom, where they are echoed back to a receiver. These packets or impulses must be of extremely short duration to be properly timed and individually distinguishable, and the strobotron functions as a *trigger* tube in this respect by controlling the frequency of the impulses as well as their time duration.

Photo-electric Tubes.

Photo-electric tubes are converters of radiant energy into electric current. The radiant-energy wavelengths to which they are sensitive embrace the infra-red, visible-light and ultra violet regions, and the process of conversion bears some resemblance to the reverse of the process by which light is produced in a glow lamp.

A photo-electric tube may be either vacuum or low-pressure gas filled and is comparatively simple in construction. It consists of a cathode which emits electrons when radiant energy impinges upon it. The cathode is usually in the form of a plate, curved so that the greatest amount of electron flow from it will reach the anode, which may be a small rod placed upright at about the focal point of the curve. There are other forms of cathode-anode mounting, but all function in about the same way—to convert radiant energy into electric current.

Radiant energy comes to us in waves of separate and distinct little quantity units called *photons*. There are definite relationships between the energies of these photons at various wavelengths and the number of electrons they cause the cathode to emit when they fall upon it. Since the shorter wavelengths have photons of more energy, ultra violet is basically a better producer of photo-electric emission than visible light, and visible light better than infra-red.

The cathodes used in photo-electric tubes are coated with materials such as caesium, potassium and others which reduce the barrier energy at the cathode surface and allow electrons to be emitted more readily. The coating used depends upon the wavelength of energy to be converted into electron emission (current flow from the cathode to the anode), since the different materials have different characteristics with respect to the wavelength of energy falling upon them. Thus, photoelectric tubes are designed for a number of wavelength regions. Those sensitive to visible light would not be suitable for infra red or ultra violet.

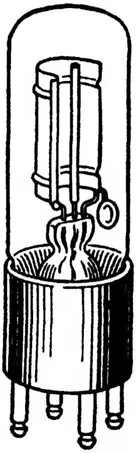


FIG. 116. Typical photo-electric tube construction.

Photo-electric tubes or *electric eyes* as they are popularly called have hundreds of commercial and industrial uses. Since the door-opening application is familiar to a great many people, we can discuss it briefly. A thin beam of light is placed across the path of traffic to a door so that it strikes the cathode of a photo-electric tube (or a photocell) which is on the opposite side of the path from the light source. As long as this light beam remains uninterrupted, an electron current flows from the cathode to the anode in the tube. This current, when amplified, operates sensitive relays, contactors and other mechanism and keeps the door closed. When the beam is interrupted by someone approaching the door, the current ceases to flow and so the door is no longer held closed and an air pressure or mechanical device swings it open.

The same fundamental principle of either interrupting a beam of light or creating one, so that the electron flow from the cathode to the anode of a photo-electric tube is either stopped or created, is the basis for practically all electric-eye installations utilizing a tube to intercept the light. Another method involves a light-sensitive cell called a *photocell.* The photocell is not a tube but consists rather of a plate of some material such as copper oxide or selenium which has the property, when in con-

FIG. 117.—The two photocells mounted on the rear wall of this schoolroom control the illumination within the room in accordance with the degree of natural light available.

junction with other elements making up the cell, of generating small currents when light falls upon it. The movement of electrons occurs when light strikes the sensitive surface. The rest of the circuit is somewhat similar to phototube circuits, consisting of amplification (when necessary) and a series of relays and contactors for controlling the installation.

The use of photo-electric tubes and cells for machinery control, lighting, sorting or inspecting operations, smoke control and hundreds of other operations is rapidly increasing. In Lynn, Massachusetts, three large elementary schools have all their classroom lighting controlled photo-electrically in accordance with the amount of natural daylight available during the day. Two of the buildings are equipped with photo-electric tubes and one with photocells, both types having proved satisfactory. There are dozens of other schools throughout the country similarly equipped.

Widely used instruments such as exposure meters and foot-candle or light meters employ selenium cells to intercept light and convert it into electric current so that readings may be made quickly and accurately.

Cathode-ray Tubes.

Cathode-ray tubes were discussed to some extent in Chapter 11 under the subject of Television Reception. However, since they are used in the oscilloscope and for other purposes, a further discussion here is advisable.

It has been explained how a thin needle-like stream of electrons is shot from the *electron gun* in a cathode-ray tube and how this stream is deflected either electromagnetically or electrostatically by two pairs of plates between which it must pass. (For the sake of simplicity we can call one pair upper and lower, and the other pair left and right.) Electrons, being negative, are repelled from a plate having a negative charge and attracted to one of positive charge.

If an alternating current is connected to the upper and lower reflecting plates, the plates will change their polarity with each alternation, reaching their maximum and minimum values in accordance with the sine-wave characteristics of the generator (see Chapter 3, A.C. Generators). Since the electron stream is being deflected by each of the two plates in accordance with the alternating voltage impressed upon them, it can be seen that the stream will keep tracing a straight vertical line at the center of the fluorescent screen at the end of the tube.

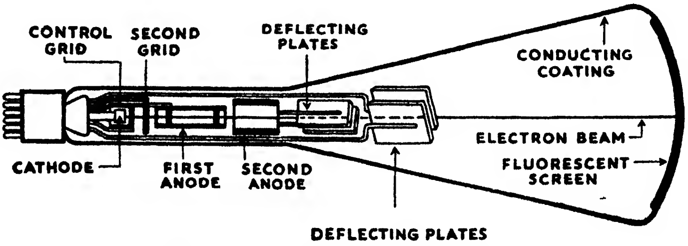


FIG. 118.—Simple diagram showing the principal elements of a cathode-ray tube.

Now if we can deflect the stream from side to side by means of the left and right plates at the same time that it is moving up and down, and do it once for every complete 360° rotation of the generator, the straight vertical line we had before becomes spread out into a wave extending from one side to the other across the fluorescent screen. This wave will be a true indication of the wave form provided by the generator.

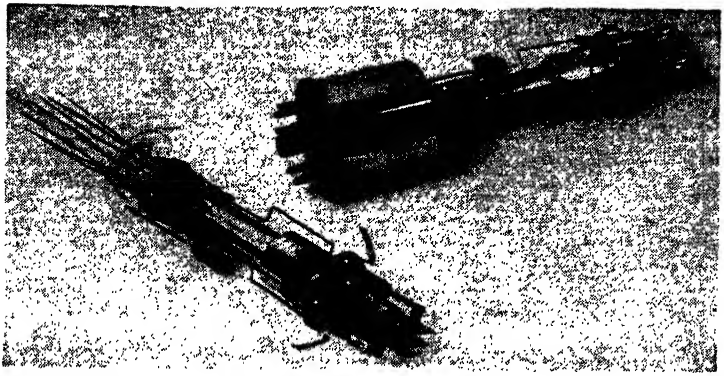


Fig. 119.—Two views of identical mount assemblies used in cathode-ray tubes. In the bottom assembly the cathode is located at the center of the disc nearest the base. The cylinder extending between the cathodes and the plates at the right end is the electron gun, at the end of which can be seen a tiny hole through which a beam of electrons is shot. The two sets of plates at right angles to each other are used to deflect the electron beam from left to right or from top to bottom. The top assembly shows the number of base pins employed.

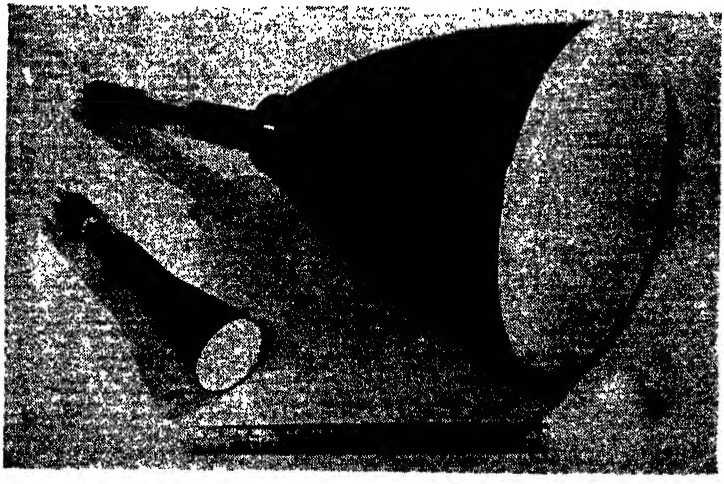


Fig. 120.—Two sizes of cathode-ray tubes available commercially. The small one at the left is used in cathode-ray oscilloscopes, whereas the larger one, with a 12-inch fluorescent screen, is used in television receivers.

The left-to-right sweep of the electron beam is obtained by means of a tube in which the oscillations can be controlled and held at a stable value. In other words, the left and right plates are subjected to controlled oscillations so that the beam will sweep across from left to right, jump back and then retrace the same path again when synchronized with the vertical deflection of the beam. Each sweep takes place in the fraction of a second so that the pattern on the end of the cathode-ray tube appears as a steady wave line.

While this explanation of cathode-ray-oscilloscope operation is considerably simplified and would be subject to much further treatment before a complete picture of the instrument's functions could be obtained, it may serve to provide a basic understanding of how a large amount of the study of electric-current phenomena is carried on.

Iconoscopes and Image-dissector Tubes.

An indication of the method by which visual images are converted into electrical impulses for television transmission was given in Chapter 11. The iconoscope, one type of tube which makes this conversion, is an extremely complicated electron tube involving not only precise control of electron movement in a thin beam, but also a photosensitive screen or plate 3 or 4 inches square called a *mosaic*, as well as several other elements.

The surface of the mosaic is made up of millions of tiny photoemissive units each of which is insulated from the other so that each can acquire a charge independently of its neighbor. Each minute unit consists of a silver globule treated with caesium. When a scene or optical image is focused upon this mosaic surface, each of the tiny units emits electrons in accordance with the intensity of light striking it. Obviously, a focused image will vary

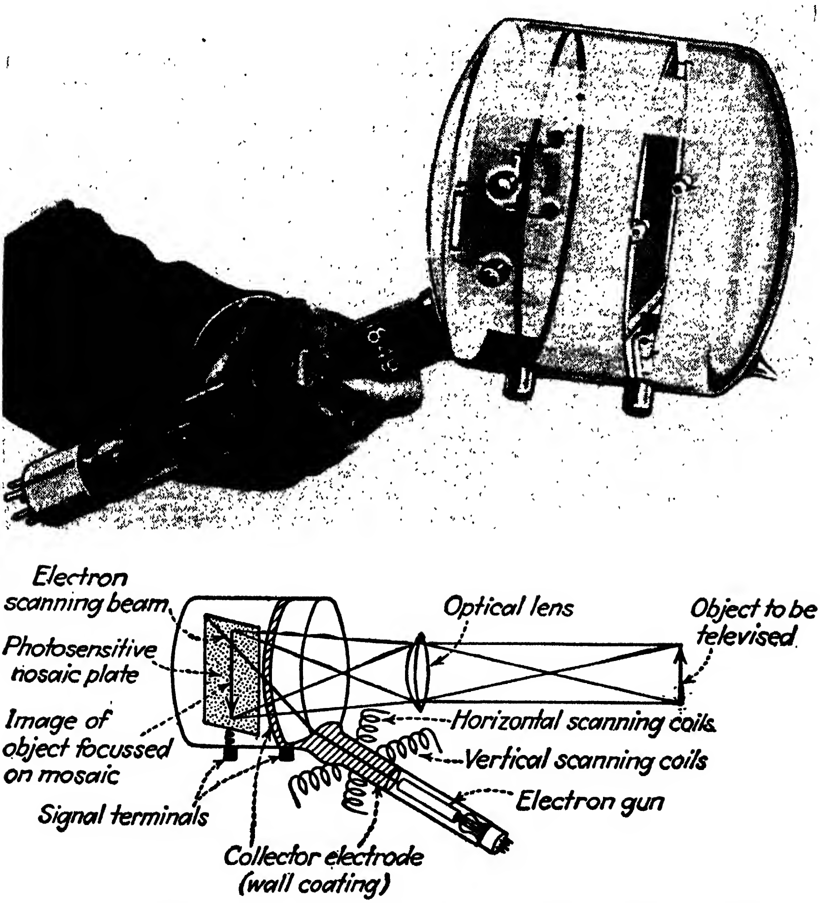


FIG. 121.—Above, commercially available iconoscope. Below, diagram of its construction. The scene to be televised passes through the flat glass window (after passing through lenses to bring it down to proper size) and falls on the mosaic plate shown within the tube. The signal which results passes from the top by means of the two terminals shown at the bottom.

appreciably in its pattern of light, so that there will be a wide range in the emission from different units.

Since electrons are emitted, the units are left positively charged, and the screen becomes a pattern of positively charged units conforming to the optical image focused upon it.

In order to convert this electrical-charge picture into pulses which can be transmitted via electromagnetic waves, an electron beam completely sweeps the plate in successive lines and in so doing effects certain changes in the charge of each unit in the mosaic. These charge changes are then converted into signal pulses and broadcast so that the complete picture is almost instantly reduced to electromagnetic oscillations and at the receiving end just as rapidly traced back into the picture again on the fluorescent screen of a cathode-ray tube.

The image-dissector tube functions quite differently in that the focused image is not broken up on the plate into tiny units as with the iconoscope. In this case the image is emitted intact from a photoemissive plate and scanned by a stationary opening in the end of an electrode within the tube. The scanning is accomplished by movement of the image under the influence of deflection elements, rather than by a moving electron beam, so that electrons, of which the emitted image is constituted, enter the opening as the image passes.

To make a rather crude analogy, the image might be compared to a layer of sand of varying thickness spread out upon a large flat board, and the opening to the hose of a vacuum cleaner. If the board were moved successively back and forth under the hose opening, the sand would be drawn up as it passed the opening, the amount of sand entering at any one moment depending upon its thickness on the board at that point. In a like manner the variations in brilliancy of the electron image become pulses of current entering the opening and, in turn, are broadcast as *video* signals.

Facsimile Recorder Tube.

This particular type of tube has become very widely used as a result of the war. It is the heart of a relatively

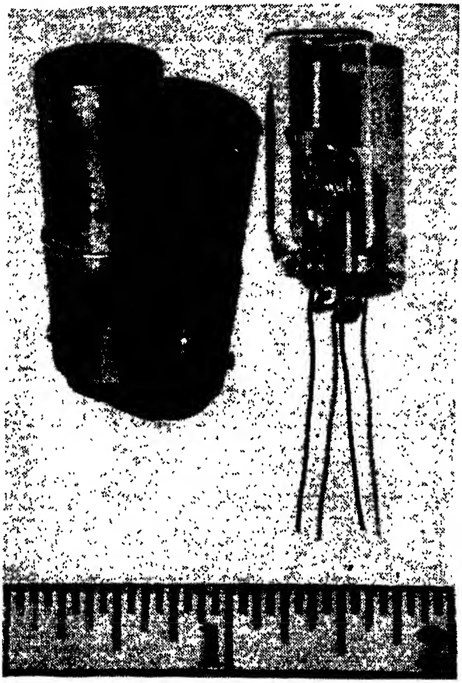


Fig. 122.—An electronic voltage regulator which is used in conjunction with facsimile recording equipment.

new method of receiving photographs transmitted by radio. The photograph is taken by any camera in the usual way and a print (about 8 by 10 inches) made. This print is placed on a cylinder, much like an Ediphone record, and revolved at a moderate rate of speed. A needle-like beam of light is focused on the picture as it revolves. The tiny shaft of light acts about as the needle of an Ediphone record would; that is, it travels laterally along the cylindrical photo as it revolves, until the whole picture has been covered. This pin point of light is reflected from the picture back to a photo-electric tube. It is obvious that the amount of light reflected is dependent upon the variations of black, white or gray on the photograph. Thus, the photo-electric tube generates its current in accordance with the variations of light striking it. This current passes into a radio transmitter and is broadcast; the photo-electric tube taking the place of a microphone.

On the receiving end, possibly thousands of miles away, it is possible actually to "hear" the picture with earphones as it comes in. It sounds like a fluttering high-pitched note, varying in intensity but not in tone.

The next problem is to get the tone back into the form of a picture, and it is in this capacity that the *recorder tube* functions. Instead of earphones or a loud-speaker, the signal, after being amplified, goes to the recorder tube. The tube is sensitive to very slight variations in the energy from the signal, and its light output responds instantly in accordance with these variations. The tube is opaque except for the end where a thin beam of high-intensity light is emitted. This beam of light, which is fluctuating with the radio signal, is high in actinic (photographic) value and is narrowed down to another needle-like shaft by lenses. This pin point of light is focused upon a cylinder like that of the transmitter, except that blank sensitized paper is used. As the cylinder revolves, the recorder tube faithfully records the photograph as it is being broadcast.

Either negatives or positive prints can be sent or received in this way. The potentialities of this method of radioing pictures can be imagined. Not only are we able to read about what happened a few hours before, thousands of miles away, but we see pictures of it as well.

FIG. 123.—A facsimile recorder tube showing the small opening in the top element through which a small beam of light passes. The intensity of this beam varies with the pulsations of the facsimile received by the tube.

Thus, in a facsimile recorder tube we have in effect a slow type of television since the picture is broken up into lines, scanned and reproduced in a manner similar to the operation of a cathode-ray tube.

A tiny electronic tube is used for regulating the voltage in the facsimile recorder. It is essential in this apparatus that the voltage from the amplifier must not fluctuate. If it does, the picture being transmitted or received by radio will be decidedly inaccurate as far as its density is concerned, since a needle-like beam fluctuates as the picture reflects it at the transmitting end and does the recording in the same way on the receiving end, so that fluctuations of light due to unstable voltage cannot be tolerated.

The operating characteristics of this little tube are such that the voltage drop across it remains substantially constant, even though the supply voltage varies, because the drop is independent of the current passing through the tube. A metal can is placed over the top which not only provides protection but also serves as a shield to keep stray electric fields that may be encountered from affecting the actual operation of the tube.

X-ray Tubes.

As explained in Chapter 10, X-rays are electromagnetic waves having wavelengths from a small fraction of an Angstrom to 600 or 800 Angstroms. They are generated when electrons traveling at high speeds through a vacuum tube collide with the solid metallic anode called the *target*.

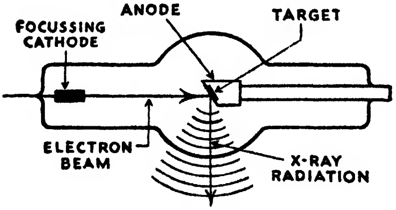


FIG. 124.—Simplified diagram of the fundamental operating elements of an X-ray tube.

In an X-ray tube the electrons are emitted from a hot cathode as in many other types of electron tubes. They are given their high velocity by the application of high potential (voltage) between the cathode and the anode. The higher the potential applied, the greater becomes the speed of the electrons, the shorter become the wavelengths of energy radiating from the tube and the greater their penetrating power.

While an X-ray tube is far from a simple device, its fundamental operation is not so complicated as others we have discussed, and an understanding of it is not difficult. In the massive 1,000,000-volt (and larger) tubes used for industrial metal analysis as well as for the treatment of malignant diseases, a problem of heat control and safety is presented. In such cases, water cooling and oil immersion are sometimes used to overcome the difficulties.

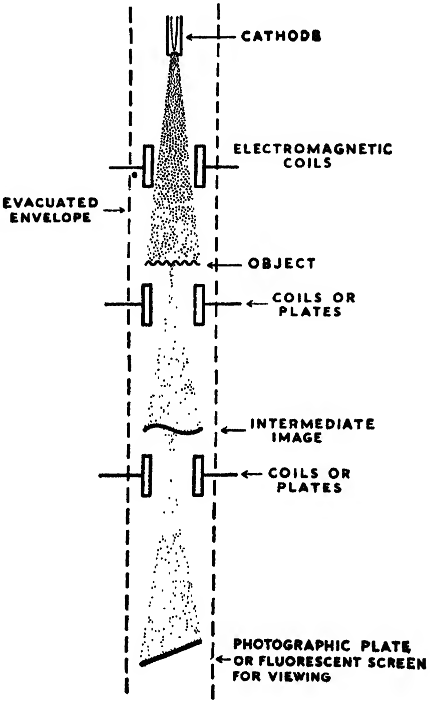
Electron Microscope.

The electron microscope will probably become one of the most important contributions that the science of electronics has made to human welfare. With it we may be able to study the mysteries of fundamental matter so small that the optical or light microscope fails to reveal them by a wide margin.

Visible light, as has been explained in detail, travels in waves of definite length. The waves of deep-yellow light, for example, may be 6,000 Angstroms or a little more than a forty-thousandth of an inch from crest to crest. When objects or particles become small enough to have dimensions approaching the actual lengths of the waves of light, we reach the limit of light's ability to reveal them.

Electrons, on the other hand, together with a nucleus, make up the structure of an atom. Since atoms themselves are something less than a hundred-millionth of an inch in diameter, some idea can be obtained of the size of an electron, although its solid form, if any, is not established with any degree of certainty.

There is a similarity in the behavior of electrons and of light. The latter is refracted when it passes through a transparent medium such as water, air or glass, and the optical microscope is a precise means of controlling this characteristic with glass lenses. Electron behavior, however, is controlled by means of electrostatic or electromagnetic fields (as explained in the discussion of cathode-ray tubes) so that a beam consisting of countless billions of electrons may be deflected in a manner comparable to the refraction of light. The electron microscope is based upon this phenomenon.



PRINCIPLE OF ELECTRON MICROSCOPE OPERATION

Fig. 125

A beam of electrons is provided thermionically. This beam corresponds to the light beam of an optical microscope, but instead of glass lenses for refraction, electric or magnetic fields between plates are used to deflect the electron beam as desired. Thus, a particle to be observed is placed in the path of an electron beam prior to deflection. Electrons will pass through it in accordance with the thickness of the particle at the point of penetration, so that the portion of the beam which has done the penetrating becomes an electronic *likeness* of the particle. By diverging the beam with the deflecting plates, the likeness can be enlarged and directed so that the image will be reproduced on either a fluorescent screen or a photographic plate.

The resolving power of an electron microscope may be as much as a hundred times greater than that of a good optical microscope, which would mean nearly 200,000 diameters, instead of the optical instrument's 1,500 or 2,000, and greater powers are probable in the near future. The highest resolving powers of the electron microscope are the result of electron velocities, which are greater at high than at low resolving powers.

The electron microscope is being used in the study of many industrial materials, as well as in bacteriology and medicine. Its development and use will most certainly unfold a great many aids to medical science in its battle against disease and to physical science in its efforts toward greater comfort and happiness for mankind.

Electron Tubes in General.

Since there are many hundreds of types of electron tubes manufactured today, no attempt could be made in this or any other book adequately to cover all of them. Electron tubes are used to varying extents in practically every branch of industry and commerce. There are so many applications, in fact, that it has been difficult to choose for Part IV those which seemed the most important.

Motor control accomplished through the use of electron tubes, electronic induction heating, the control of resistance welding with thyratrons and ignitrons, rectification, and several other major industrial applications of electronics have been passed over without explanation not because they lacked importance but because they seemed to lack a certain *fundamental* element that it has been the purpose of this primer to present. Basically, electron tubes are devices to produce and control a flow of electrons and nothing else. If an application seems to be intimately associated with this function, it has been discussed here. Where its use has appeared to be more remote from the basic function, even though highly important from the standpoint of industrial efficiency, the discussion has been left to others.

It is hoped that the reader, having completed this book, will be urged by his own interest to peruse other less general and more detailed textbooks on radio, medicine, illumination or whatever other specific branch of electronics appeals most strongly to him. At least, the reader should be better able to discuss electronics than he was when he first read the opening paragraphs of Chapter I.

ACKNOWLEDGMENT

This book is not a first-time presentation of new facts or developments pertaining to electronics and is not intended as a finished and complete treatise on the various subjects discussed. It is, rather, a digest of the very basic principles involved in the study of how electrons behave and how they are controlled, and is so written that the average man will be able to understand these principles and pursue the book with an interest such as he might show in his newspaper or a novel. With this purpose it was advisable to seek a number of authors' concepts, either written or illustrated, so that by fusing them together and sifting out the more complicated and technical factors the fundamental ideas could be expressed without sacrifice of accuracy.

The book was written at the suggestion of Mr. O. Fred Rost, editor of *Wholesaler's Salesman*, a McGraw-Hill publication, who felt as the author did that the men who are charged with bringing business to the manufacturers of electron tubes and equipment should know more about how the products they are selling, and will sell in the future, work.

The author is most grateful to Mr. O. H. Biggs, general manager of *Product Development*, and to Mr. Henry J. McCarthy, research engineer of Sylvania Electric Products, Inc., at Salem, Massachusetts, for reading the manuscript and for offering many helpful suggestions.

Under the pressure of present wartime conditions the time that both took in giving the author their assistance must have been some small fragment of the day that they might have called their own and spent much more pleasantly in needed relaxation.

It is also a pleasure to acknowledge the work done by Dr. Ben Kievit, Mr. W. R. Jones, and their colleagues at the Emporium, Pennsylvania, radio tube plant of Sylvania. Many of the diagrams and ideas in Parts I and II as well as those pertaining to radio tubes as presented in Chapter 12 are due directly to their efforts.

Readers of the "Primer" will doubtless recognize the extensive contributions of many other manufacturers to the science of electronics. To assure this recognition, a few are mentioned: the Bell Telephone Laboratories; the RCA Manufacturing Co., Inc.; the General Electric Company; the Westinghouse Electric & Manufacturing Company; the Corning Glass Works; the Western Electric Co.; and the Farnsworth Television and Radio Corporation.

The courtesy of those companies in contributing illustrations has been acknowledged in the text.

Credit is due Mr. William C. Pirie of Sylvania's advertising department at New York for ably handling much of the production work in connection with drawings and diagrams, and, last but not least, the author is grateful for the patience of his secretary, Miss Doris Gray, whose success in typing from his longhand has been remarkable.

The books listed below are those to which the author referred in checking data and in obtaining considerable factual information during the production of the

"Primer," which, he hopes, will be considered by the authors of those books as a basic training for their more advanced treatments.

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