CHAPTER 8

BASIC ELECTRICITY

GENERAL

Anyone concerned with aircraft maintenance is aware of the increasing use of electricity in modern systems and recognizes the importance to the mechanic of a thorough understanding of electrical principles. While the use of electricity today is so common as to be taken for granted, its widespread use in aircraft electrical systems emphasizes the importance of a sound electrical background for the airframe and powerplant technician.

In the study of physics, the electron theory of the structure of matter was introduced to explain the fundamental nature of matter. A more detailed examination of this theory is necessary to explain the behavior of the electron as it applies to the study of basic electricity.

MATTER

Matter can be defined as anything that has mass (weight) and occupies space. Thus, matter is everything that exists. It may exist in the form of solids, liquids, or gases. The smallest particle of matter in any state or form, that still possesses its identity, is called a molecule.

Substances composed of only one type of atom are called elements. But most substances occur in nature as compounds, that is, combinations of two or more types of atoms. Water, for example is a compound of two atoms of hydrogen and one atom of oxygen. A molecule of water is illustrated in figure 8–1. It would no longer retain the characteristics of water if it was compounded of one atom of hydrogen and two atoms of oxygen.

The Atom

The atom is considered the basic building block of all matter. It is the smallest possible particle that an element can be divided into and still retain its chemical properties. In its simplest form, it consists of one or more electrons orbiting at a high rate of speed around a center, or nucleus, made up of one or more protons, and, in most atoms, one or more neutrons as well. Since an atom is so small that some 200,000 could be placed side by side in a line 1 inch long, it cannot be seen, of course. Nevertheless, a great deal is known about its behavior from various tests and experiments.

The simplest atom is that of hydrogen, which is one electron orbiting around one proton, as shown in figure 8–2. A more complex atom is that of oxygen (see figure 8–3), which consists of eight electrons rotating in two different orbits around a nuclues made up of eight protons and eight neutrons.

An electron is the basic negative charge of electricity and cannot be divided further. Some electrons are more tightly bound to the nucleus of their atom than others and rotate in an imaginary shell or sphere closer to the nucleus, while others are more loosely bound and orbit at a greater distance from the nucleus. These latter electrons are called "free" electrons because they can be freed easily from the positive attraction of the protons in the nucleus to make up the flow of electrons in a practical electrical circuit.

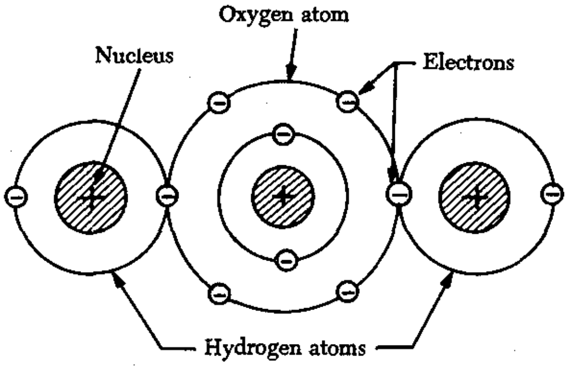


FIGURE 8–1. A water molecule.

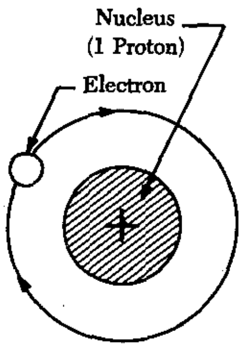


FIGURE 8–2. Hydrogen atom.

The neutrons in a nucleus have no electrical charge. They are neither positive nor negative but are equal in size and weight to the proton. Since a proton weighs approximately 1,845 times as much as an electron, the overall weight of an atom is determined by the number of protons and neutrons in its nucleus. The weight of an electron is not considered in determining the weight of an atom. Indeed, the nature of electricity cannot be defined clearly because it is not certain whether the electron is a negative charge with no mass (weight) or a particle of matter with a negative charge.

Electricity is best understood in terms of its behavior, which is based in part on the charge an atom carries. When the total positive charge of the protons in the nucleus equals the total negative charge of the electrons in orbit around the nucleus, the atom is said to have a neutral charge. If an atom has a shortage of electrons, or negative charges, it is positively charged and is called a positive ion. If it possesses an excess of electrons, it is said to be negatively charged and is called a negative ion.

Electron Movement

In a state of neutral charge, an atom has one electron for each proton in the nucleus. Thus, the number of electrons held by the atoms making up the various elements will vary from one, in the case of hydrogen, to 92 for uranium.

The electrons revolving around a nucleus travel in orbits, sometimes called shells or layers. Each shell can contain a certain maximum number of electrons, and if this number is exceeded, the extra electrons will be forced into the next higher, or outer, shell.

The shell nearest the nucleus can contain no more than two electrons. In an atom containing more than two electrons, the excess electrons will be located in the outer shells. The second shell can have a maximum of eight electrons. The third shell can hold up to 18 electrons, the fourth 32, etc. It should be noted, however, that in some large complex atoms electrons may be arranged in outer shells before some inner shells are filled.

STATIC ELECTRICITY

Electricity is often described as being either static or dynamic. Since all electrons are alike, these words do not actually describe two different types of electricity; rather, they distinguish between electrons at rest and those in motion. The word static means "stationary" or "at rest," and refers to the deficiency or to the excess of electrons. Originally it was thought that static electricity was electricity at rest because electrical energy produced by friction did not move. A simple experiment, such as running a dry comb through hair, will produce cracking or popping sounds, indicating static discharges are taking place. The charges thus built up consist of electrons transferred to the comb as the result of friction. The discharge is caused by the rapid movement of electrons in the opposite direction from the comb to the hair as the charges neutralize each other. In the dark it is possible to see these discharges as tiny sparks.

Static electricity has little practical value, and often causes problems. It is difficult to control and discharges quickly. Conversely, dynamic, or current electricity, is generated and controlled easily and provides energy for useful work.

A summary of that part of the electron theory

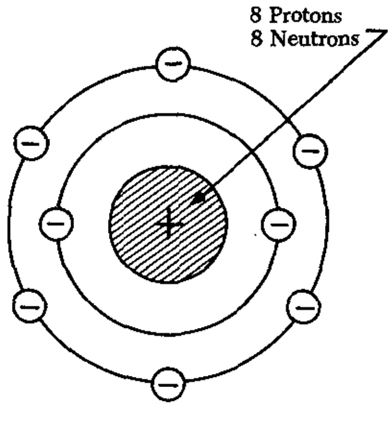


FIGURE 8–3. Oxygen atom.

dealing with charges will help explain static electricity. All electrons are alike and repel each other. Similarly, all protons are alike and repel each other. Electrons and protons are not alike, but attract each other. Hence, the fundamental law of electricity is that like charges repel and unlike charges attract.

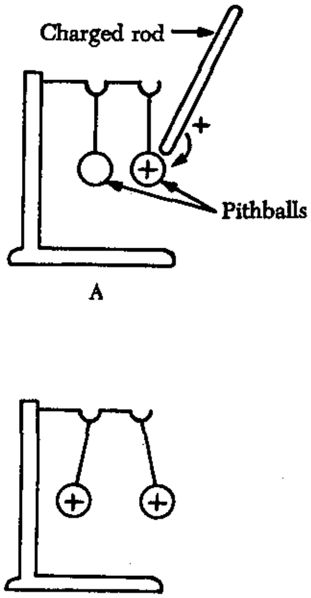
Generation of Static Electricity

Static electricity can be produced by contact, friction, or induction. As an example of the friction method, a glass rod rubbed with fur becomes negatively charged, but if rubbed with silk, becomes positively charged. Some materials that build up static electricity easily are flannel, silk, rayon, amber, hard rubber, and glass.

When two materials are rubbed together, some electron orbits of atoms in one material may cross the orbits or shells of the other, and one material may give up electrons to the other. The transferred electrons are those in the outer shells or orbits and are called free electrons.

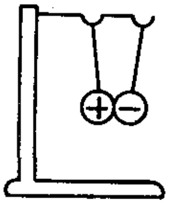
When a glass rod is rubbed with silk, the glass rod gives up electrons and becomes positively charged. The silk becomes negatively charged since it now has excess electrons. The source of these electric charges is friction. This charged glass rod may be used to charge other substances. For example, if two pith balls are suspended, as shown in figure 8–4, and each ball is touched with the charged glass rod, some of the charge from the rod is transferred to the balls. The balls now have similar charges and, consequently, repel each other as shown in part B of figure 8–4. If a plastic rod is rubbed with fur, it becomes negatively charged and the fur is positively charged. By touching each ball with these differently charged sources, the balls obtain opposite charges and attract each other as shown in part C of figure 8–4.

Although most objects become charged with static electricity by means of friction, a charged substance can also influence objects near it by contact. This is illustrated in figure 8–5. If a positively charged rod touches an uncharged metal bar, it will draw electrons from the uncharged bar to the point of contact. Some electrons will enter the rod, leaving the metal bar with a deficiency of electrons (positively charged) and making the rod less positive than it was or, perhaps, even neutralizing its charge completely.



Repulsion

B



Attraction

C

FIGURE 8–4. Reaction of like and unlike charges.

A method of charging a metal bar by induction is demonstrated in figure 8–6. A positively charged rod is brought near, but does not touch, an uncharged metal bar. Electrons in the metal bar are attracted to the end of the bar nearest the positively charged rod, leaving a deficiency of electrons at the opposite end of the bar. If this positively charged end is touched by a neutral object, electrons will flow into the metal bar and neutralize the charge. The metal bar is left with an overall excess of electrons.

Electrostatic Field

A field of force exists around a charged body. This field is an electrostatic field (sometimes called a dielectric field) and is represented by lines extending in all directions from the charged

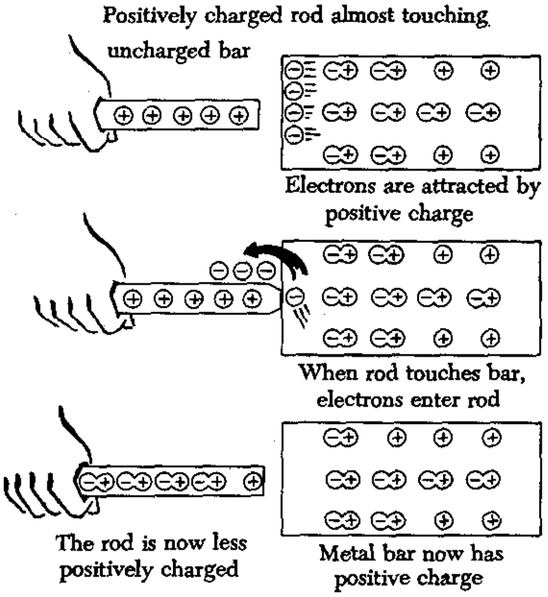


FIGURE 8–5. Charging by contact.

body and terminating where there is an equal and opposite charge.

To explain the action of an electrostatic field, lines are used to represent the direction and intensity of the electric field of force. As illustrated in figure 8–7, the intensity of the field is indicated by the number of lines per unit area, and the direction is shown by arrowheads on the lines pointing in the direction in which a small test charge would move or tend to move if acted upon by the field of force.

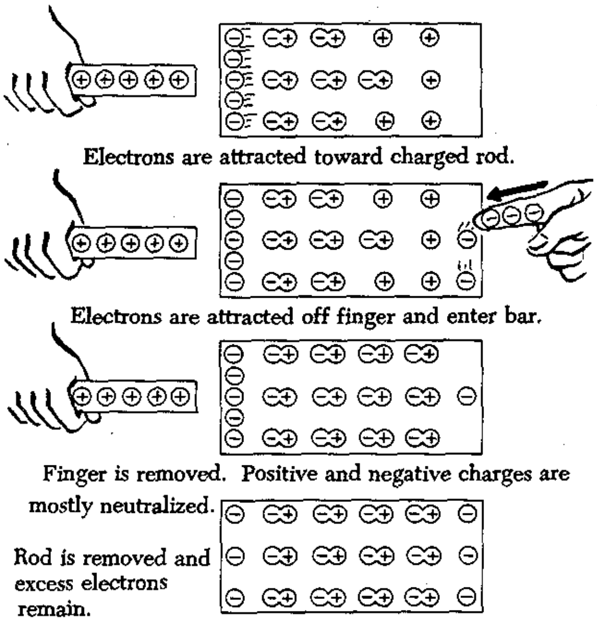


FIGURE 8–6. Charging a bar by induction.

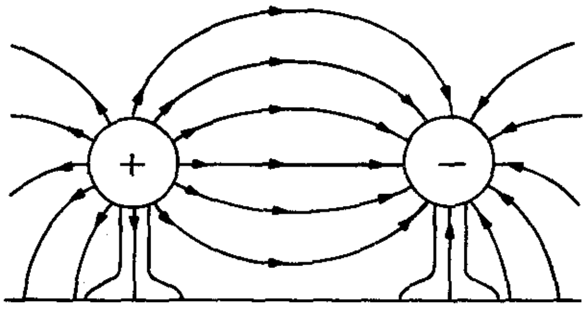


FIGURE 8–7. Direction of electric field around positive and negative charges.

Either a positive or negative test charge can be used, but it has been arbitrarily agreed that a small positive charge will always be used in determining the direction of the field. Thus, the direction of the field around a positive charge is always away from the charge, as shown in figure 8–7, because a positive test charge would be repelled. On the other hand, the direction of the lines about a negative charge is toward the charge, since a positive test charge is attracted toward it.

Figure 8–8 illustrates the field around bodies having like charges. Positive charges are shown, but regardless of the type of charge, the lines of force would repel each other if the charges were alike. The lines terminate on material objects and always extend from a positive charge to a negative charge. These lines are imaginary lines used to show the direction a real force takes.

It is important to know how a charge is distributed on an object. Figure 8–9 shows a small metal disk on which a concentrated negative charge has been placed. By using an electrostatic

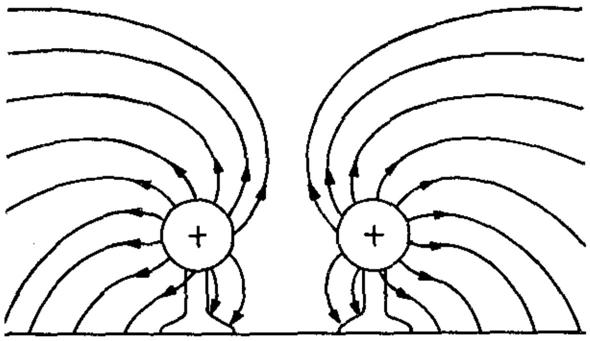


FIGURE 8–8. Field around two positively charged bodies.

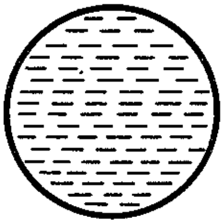


FIGURE 8–9. Even distribution of charge on metal disk.

detector, it can be shown that the charge is spread evenly over the entire surface of the disk. Since the metal disk provides uniform resistance everywhere on its surface, the mutual repulsion of electrons will result in an even distribution over the entire surface.

Another example, shown in figure 8–10, is the charge on a hollow sphere. Although the sphere is made of conducting material, the charge is evenly distributed over the outside surface. The inner surface is completely neutral. This phenomenon is used to safeguard operating personnel of the large Van de Graaff static generators used for atom-smashing. The safest area for the operators is inside the large sphere, where millions of volts are being generated.

The distribution of the charge on an irregularly shaped object differs from that on a regularly shaped object. Figure 8–11 shows that the charge on such objects is not evenly distributed. The greatest charge is at the points, or areas of sharpest curvature, of the objects.

The effects of static electricity must be considered in the operation and maintenance of aircraft. Static interference in the aircraft communication systems and the static charge created by the aircraft's movement through the air are examples of problems created by static electricity. Parts of the aircraft must be "bonded" or joined together to provide a low-resistance (or easy) path for static discharge, and radio parts must be shielded. Static charges must be considered in the refueling of the aircraft to prevent possible igniting of the fuel, and provision must be made to ground the aircraft structure, either by static-conducting tires or by a grounding wire.

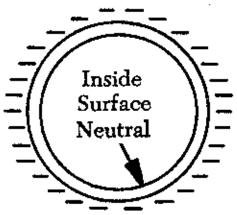


FIGURE 8–10. Charge on a hollow sphere.

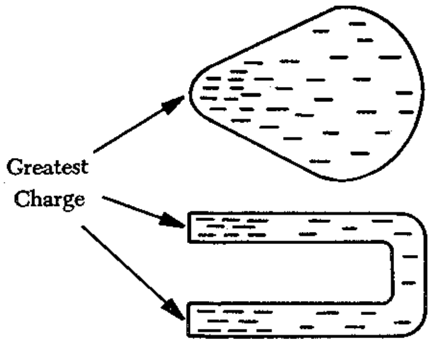


FIGURE 8–11. Charge on irregularly shaped objects.

ELECTROMOTIVE FORCE

The flow of electrons from a negative point to a positive point is called an electric current; this current flows because of a difference in electric pressure between the two points.

If an excess of electrons with a negative charge exists at one end of a conductor and a deficiency of electrons with a positive charge at the other, an electrostatic field exists between the two charges. Electrons are repelled from the negatively charged point and are attracted by the positively charged point.

The flow of electrons of electric current can be compared to the flow of water between two interconnected water tanks when a difference of pressure exists between two tanks. Figure 8–12 shows the level of water in tank A to be at a higher level than the water level in tank B. If the valve in the interconnecting line between the tanks is opened, water will flow from tank A into tank B

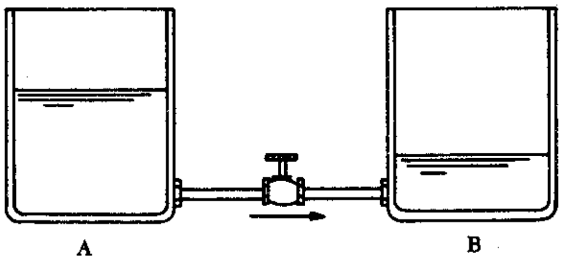


FIGURE 8–12. Difference of pressure.

until the level of water is the same in both tanks. It is important to note that it was not the pressure in tank A that caused the water to flow; rather, it was the difference in pressure between tank A and tank B that caused the flow. When the water in the two tanks are at the same level, the flow of water ceases because there is no longer a difference of pressure.

This comparison illustrates the principle that causes the electrons to move, when a proper path is available, from a point of excess electrons to a point deficient in electrons. The force that causes this movement is the potential difference in electrical energy between the two points. This force is called the electrical pressure or the potential difference or the electromotive force (electron-moving force) which can all be considered the same thing. Electromotive force, abbreviated e.m.f., causes current (electrons) to move in an electric path or circuit. The practical unit of measurement of e.m.f., or potential difference, is the volt. The symbol for e.m.f. is the capital letter "E."

If the water pressure in tank A of figure 8–12 is 10 p.s.i. and the pressure in tank B is 2 p.s.i., there is a difference in pressure of 8 p.s.i. Similarly, it can be said that an electromotive force of 8 volts exists between two electrical points. Since potential difference is measured in volts, the word "voltage" can also be used to describe amounts of potential difference. Thus, it is correct to say that the voltage of a certain aircraft battery is 24 volts, another means of indicating that a potential difference of 24 volts exists between two points connected by a conductor.

CURRENT FLOW

Electrons in motion make up an electric current. This electric current is usually refered to as "current" or "current flow," no matter how many electrons are moving. When the current flow is in one direction only, it is called direct current. Later in the study of electrical fundamentals, current that reverses itself periodically, called alternating current, will be discussed. In the present study all references are to direct current.

Since an electric current may consist of varying numbers of electrons, it is important to know the number of electrons flowing in a circuit in a given time. Electrons can be counted by measuring the basic electrical charge on each electron. Since this charge is very small, a practical unit, the coulomb, is used to measure an amount, or quantity, of electrical charge. The accumulated charge on 6.28 billion billion electrons is called one coulomb. When this quantity of electrons flows past a given point in an electrical circuit, one ampere of current is said to be flowing in the circuit. Current flow is measured in amperes or parts of amperes by an electrical instrument called an ammeter. The symbol used to indicate current in formulas or on schematics is the capital letter "I," which stands for the intensity of current flow.

FIGURE 8–13. Electron movement.

The drift of free electrons must not be confused with the concept of current flow that approaches the speed of light. When a voltage is applied to a circuit, the free electrons travel but a short distance before colliding with atoms. These collisions usually knock other electrons free from their atoms, and these electrons travel on toward the positive terminal of the wire, colliding with other atoms as they drift at a comparatively slow rate of speed. To understand the almost instantaneous speed of the effect of electric current, it is helpful to visualize a long tube filled with steel balls as shown in figure 8–13.

It can be seen that a ball introduced in one end of the tube, which represents a conductor, will immediately cause a ball to be emitted at the opposite end of the tube. Even if the tube were long enough to reach clear across the country, this effect could still be visualized as being instantaneous. Thus, electric current flow can be viewed as occurring instantaneously, even though it is a result of a comparatively slow drift of electrons.

RESISTANCE

The property of a conductor of electricity that limits or restricts the flow of electric current is called its resistance. Electrical pressure is required to overcome this resistance, which is the attractive force holding the electrons in their orbits. The materials from which electrical conductors are manufactured, usually in the form of extruded wire, are materials that offer very little resistance to current flow. While wire of any size or resistance value may be used, the word "conductor" usually refers to materials which offer low resistance to current flow, and the word "insulator" describes materials that offer high resistance to current. There is no distinct dividing line between conductors and insulators; under the proper conditions, all types of material conduct some current. Materials offering a resistance to current flow midway between the best conductors and the poorest conductors (insulators) are sometimes referred to as "semiconductors," and find their greatest application in the field of transistors.

The best conductors are materials, chiefly metals, which possess a large number of free electrons; conversely, insulators are materials having few free electrons. The best conductors are silver, copper, gold, and aluminum, but some nonmetals, such as carbon and water, can be used as conductors. Materials such as rubber, glass, ceramics, and plastics are such poor conductors that they are usually used as insulators. The current flow in some of these materials is so low that it is usually considered zero.

The unit used to measure resistance is called the ohm. The symbol for the ohm is the Greek letter omega(Ω). In mathematical formulas, the capital letter "R" refers to resistance. The resistance of a conductor and the voltage applied to it determine the number of amperes of current flowing through the conductor. Thus, 1 ohm of resistance will limit the current flow to 1 ampere in a conductor to which a voltage of 1 volt is applied.

Factors Affecting Resistance

Among the four major factors affecting the resistance of a conductor, one of the most important is the type of conductor material. It has been pointed out that certain metals are commonly used as conductors because of the large number of free electrons in their outer orbits. Copper is usually considered the best available conductor material, since a copper wire of a particular diameter offers a lower resistance to current flow than an aluminum wire of the same diameter However, aluminum is much lighter than copper, and for this reason as well as cost considerations, aluminum is often used when the weight factor is important.

A second resistance factor is the length of the conductor. The longer the length of a given size of wire, the greater the resistance. Figure 8–14 pictures two wire conductors of different lengths. If 1 volt of electrical pressure is applied across the two ends of the conductor that is 1 foot in length and the resistance to the movement of free electrons is assumed to be 1 ohm, the current flow is limited to 1 ampere. If the same size conductor is doubled in length, the same electrons set in motion by the 1 volt applied now find twice the resistance; consequently, the current flow will be reduced by one-half.

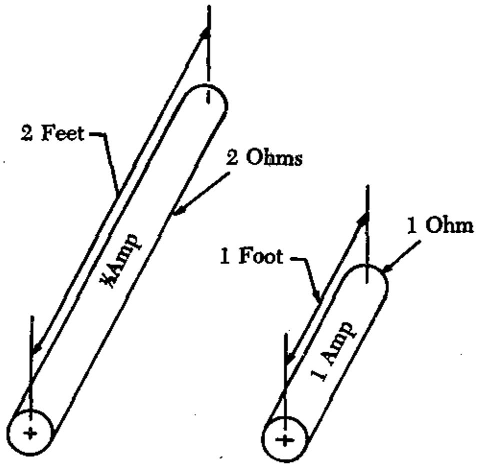


FIGURE 8–14. Resistance varies with length of conductor.

A third factor affecting the resistance of a conductor is cross-sectional area, or the end surface of a conductor. This area may be triangular or even square, but is usually circular. If the cross-sectional area of a conductor is doubled, the resistance to current flow will be reduced in half. This is true because of the increased area in which an electron can move without collision or capture by an atom. Thus, the resistance varies inversely with the cross-sectional area of a conductor.

To compare the resistance of one conductor with that of another having greater cross-sectional area, a standard, or unit, size of conductor must be established. The most convenient unit of measurement of wire diameter is the mil (0.001 of an inch). The most convenient unit of wire length is the foot. Using these standards, the unit of size will be the mil-foot. Thus, a wire will have unit size if it has a diameter of 1 mil and the length of 1 foot. The resistance specified in ohms of a unit conductor of a certain material is called the

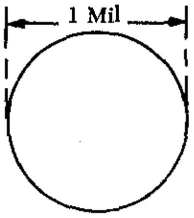


FIGURE 8–15. Circular mil.

specific resistance, or specific resistivity, of the substance.

The square mil is a convenient unit of cross-sectional area for square or rectangular conductors. A square mil is the area of a square, each side of which measures 1 mil.

To compute the cross-sectional area of a conductor in square mils, the length in mils of one side is squared. In the case of a rectangular conductor, the length of one side is multiplied by the length of the other. For example, a common rectangular bus bar (large, special conductor) is ⅜ inch thick and 4 inches wide. The ⅜ inch thickness may be expressed as 0.375 inch. Since 1,000 mils equals 1 inch, the width in inches can be converted to 4,000 mils. The cross-sectional area of the rectangular conductor is .375 × 4,000 or 1,500 square mils.

More common than the square or rectangular shape is the circular conductor. Because the diameters of round conductors may be only a fraction of an inch, it is convenient to express these diameters in mils to avoid the use of decimals. The circular mil is the standard unit of wire cross-sectional area used in American and English wire tables. Thus, the diameter of a wire that is 0.025 inch may be more conveniently expressed as 25 mils.

Figure 8–15 illustrates a circle having a diameter of 1 mil. The area in circular mils is obtained by squaring the diameter measured in mils. Thus, a wire with a diameter of 25 mils has an area of 25 squared, or 25 × 25, or 625 circular mils.

In comparing square and round conductors, it should be noted that the circular mil is a smaller unit of area than the square mil. To determine the circular-mil area when the square-mil area is known, the area in square mil is divided by 0.7854. Conversely, to find the square-mil area when the circular-mil area is known, the area in circular mils is multiplied by 0.7854.

Wires are manufactured in sizes numbered according to a table known as the American wire gage (AWG). Wire diameters become smaller as the gage numbers become larger. This table is available to aviation technicians for reference, not only on wire size but also resistance and cross-sectional area.

The last major factor influencing the resistance of a conductor is temperature. Although some substances, such as carbon, show a decrease in resistance as the ambient (surrounding) temperature increases, most materials used as conductors increase in resistance as temperature increases. The resistance of a few alloys, such as constantan and maganin, change very little as the temperature changes. The amount of increase in the resistance of a 1-ohm sample of a conductor per degree rise in temperature above 0° Centigrade (C.), the assumed standard, is called the temperature coefficient of resistance. For each metal this is a different value; for example, for copper the value is approximately 0.00427 ohm. Thus, a copper wire having a resistance of 50 ohms at a temperature of 0° C. will have an increase in resistance of 50 × 0.00427, or 0.214 ohm, for each degree rise in temperature above 0° C. The temperature coefficient of resistance must be considered where there is an appreciable change in temperature of a conductor during operation. Charts listing the temperature coefficient of resistance for different materials are available.

BASIC CIRCUIT COMPONENTS AND SYMBOLS

An electrical circuit consists of: (1) A source of electrical pressure or e.m.f.; (2) resistance in the form of an energy-consuming electrical device; and (3) conductors, usually in the form of copper or aluminum wires, to provide a path for electron flow from the negative side of the power source through the resistance and back to the positive side of the power source. Figure 8–16 is a pictorial representation of a practical circuit.

This circuit contains a source of e.m.f. (storage battery), a conductor to provide a path for the flow of electrons from the negative to the positive terminal of the battery, and a power-dissipating device (lamp) to limit the current flow. Without some resistance in the circuit the potential difference between the two terminals would be neutralized very quickly or the flow of electrons would become so heavy that the conductor would become overheated and burn.

At the same time that the lamp acts as a

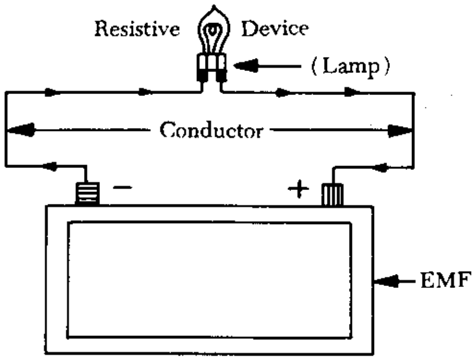


FIGURE 8–16. A practical circuit.

current-limiting resistance in the circuit, it is also accomplishing the desired funtion of creating light.

Figure 8–17 is a schematic representation of figure 8–16, in which symbols rather than pictures are used to represent the circuit components.

All components used in electrical circuits are represented in drawings, blueprints, and illustrations in schematic form by symbols. The components commonly used in basic circuits, together with their schematic symbols, are discussed to provide the necessary background for interpretation of circuit diagrams.

Source of Power

The source of power, or applied voltage, for a circuit may be any one of the common sources of e.m.f., such as a mechanical source (generator), a chemical source (battery), a photoelectric source (light), or a thermal source (heat). Figure 8–18 illustrates two schematic symbols for a generator. Most electrical components have only one symbol; however, in the case of the generator and a few others, more than one symbol has been developed to represent a single electrical component. These symbols are normally very similar in design. Figure 8–18 illustrates that the two symbols for a generator are so nearly alike there is little chance for confusion.

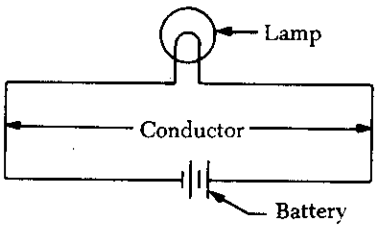


FIGURE 8–17. Circuit components represented by symbols.

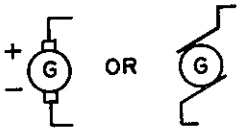


FIGURE 8–18. Electrical symbols for a d.c. generator.

Another common source for the voltage applied to a circuit is the battery, a chemical source of power. Figure 8–19 shows symbols for a single-cell battery and a three-cell battery.

The following statements are true of battery symbols used in schematic diagrams (refer to figure 8–19):

(1) The shorter vertical line represents the negative terminal.
(2) The longer vertical line is the positive terminal.
(3) The horizontal lines represent the conductors connected to the terminals.
(4) Each cell of a battery has one negative and one positive terminal.

Dry cell batteries, such as those used to operate flashlights, are called primary cells. The larger storage batteries containing several primary cells are called secondary cells. The schematic symbol for the primary cell is shown in figure 8–20. The center rod is the positive terminal of the cell, and the case of the cell is the negative terminal. When more than 1.5 volts are required, cells are connected in series. To connect the cells in series, the negative terminal of each cell is connected to the positive terminal of the succeeding cell as shown in A of figure 8–21. The voltage is then equal to the sum of the voltages of the individual cells. Since the same current must flow through each cell in succession, the current that the battery can supply is equal to the current rating of a single cell. Thus, a battery composed of cells in series provides a higher voltage, but not a greater current capacity.

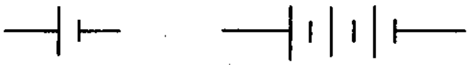


FIGURE 8–19. One-cell and three-cell battery symbols.

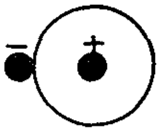


FIGURE 8–20. Schematic symbol for a dry cell battery.

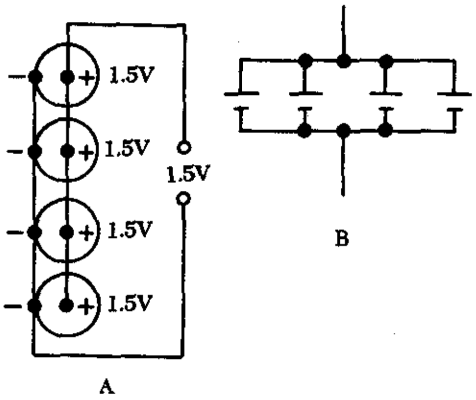


FIGURE 8–22. Cells connected in parallel.

To obtain a greater current flow than one cell is able to supply, the cells are connected in parallel. The total current available is equal to the sum of the individual currents from each cell, but the voltage is equal to the voltage of a single cell. To connect cells in parallel, all positive terminals are connected together and all negative terminals are connected together. In A of figure 8–22, a schematic diagram of cells connected in parallel is shown. B of figure 8–22 illustrates the symbol used to represent this group of cells connected in parallel. Each cell must have the same voltage; otherwise, a cell with higher voltage will force current through the lower voltage cells.

Another method of arranging cells is to connect them in series-parallel. In this method, shown in figure 8–23, two groups of cells are connected in series, and then these two groups are connected in parallel. This arrangement provides both a greater voltage and a greater current output.

Conductor

Another basic requirement of a circuit is the conductor or wire connecting the various electrical components. This is always represented in schematic diagrams as a line. Figure 8–24 illustrates two different symbols used to indicate wires (conductors) that cross but are not connected. While either of these symbols may be used, the symbol shown in B of figure 8–24 is now found more often, since it is less likely to be misinterpreted.

Figure 8–25 illustrates the two different symbols used to represent connected wires. Either of these two symbols may be used, but it is important that no conflict exists with the symbol selected to represent unconnected wires. For example, if the symbol for unconnected wires shown in A of figure 8–24 is selected, the symbol for connected wires must be that shown in A of figure 8–25.

A circuit component found in all practical circuits is the fuse. This is a safety or protective device used to prevent damage to the conductors and circuit components by excessive current flow.

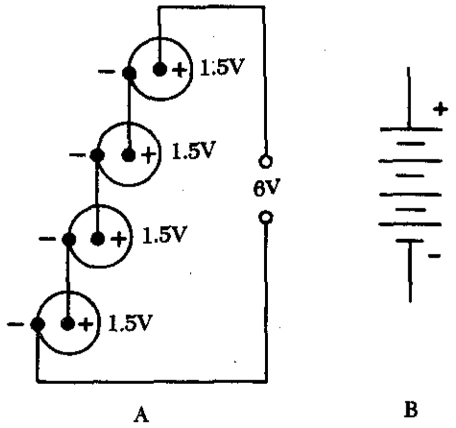


FIGURE 8–21. Schematic diagram and symbol of cells connected in series.

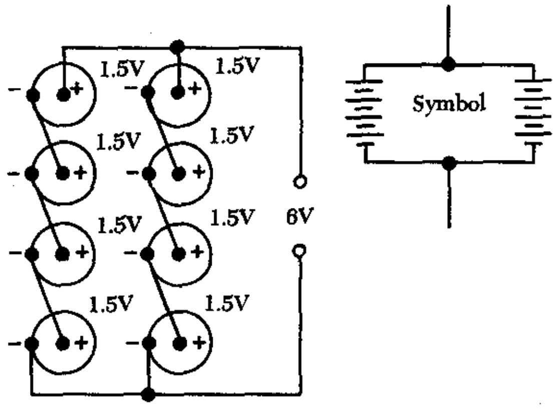


FIGURE 8–23. Cells in series-parallel arrangement.

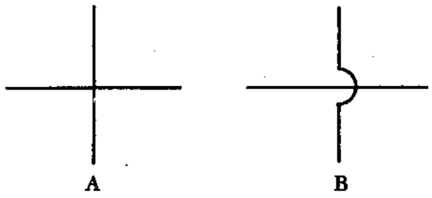


FIGURE 8–24. Unconnected crossed-over wires.

The schematic symbol for a fuse is shown in figure 8–26.

Another symbol found in basic circuit schematics is the symbol for the switch, shown in figure 8–27. The open switch symbol is shown in A of figure 8–27, and in B of figure 8–27 the closed switch symbol is shown connected in a circuit. There are many different types of switches, but these symbols can represent all but the most complex.

Figure 8–28 illustrates the symbol for "ground" or the common reference point in a circuit. This is the reference point from which most circuit voltages are measured. This point is normally considered to be at zero potential.

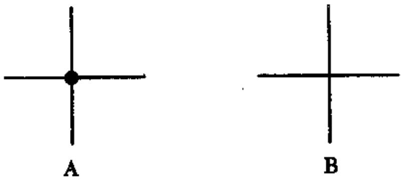


FIGURE 8–25. Connected wires.

Sometimes meters for measuring current flow or voltage are temporarily connected to the circuit, and in some circuits these meters are permanent components. In figure 8–29, the symbols for an ammeter and a voltmeter are used in a simple circuit. It is important that these components be connected properly. The ammeter, which measures current flow, is always connected in series with the power source and circuit resistances. The voltmeter, which measures the voltage across a circuit component, is always connected across (in parallel with) a circuit component, never in a series arrangement.

FIGURE 8–26. Schematic symbol for a fuse.

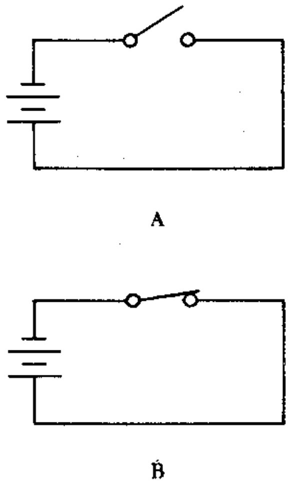


FIGURE 8–27. Open and closed switch symbols.

Resistors

The last of the basic component requirements of a complete circuit can be grouped under the single heading of resistance. Resistance in a practical circuit may take the form of any electrical device, such as a motor or a lamp, which uses electrical power and produces some useful function. On the other hand, the resistance of a circuit may be in the form of resistors inserted in the circuit to limit current flow.

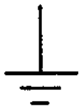


FIGURE 8–28. Ground or common reference point symbol.

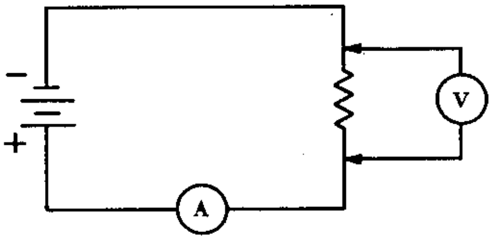


FIGURE 8–29. Ammeter and voltmeter symbols.

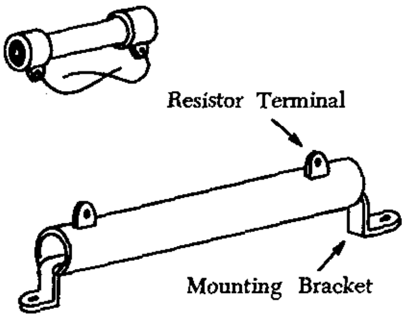


FIGURE 8–30. Fixed wire-wound resistors.

A wide variety of resistors are available. Some have a fixed ohmic value and others are variable. They are manufactured from special resistance wire, graphite (carbon), or metal film. Wire-wound resistors control large currents, while carbon resistors control relatively small currents. Wire-wound resistors are constructed by winding resistance wire on a porcelain base, attaching the wire ends to metal terminals, and coating the wire for protection and heat conduction. (See figure 8–30.)

Wire-wound resistors are available with fixed taps which can be used to change the resistance value in increments or steps. They may also be provided with sliders which can be adjusted to change the resistance to any fraction of the total resistance. (See figure 8–31.) Still another type is the precision wire-wound resistors (figure 8–32) made of manganin wire. They are used where the resistance value must be very accurate.

Carbon resistors are manufactured from a rod of compressed graphite and binding material, with wire leads, called "pigtail" leads, attached to each end of the resistor. (See figure 8–33.)

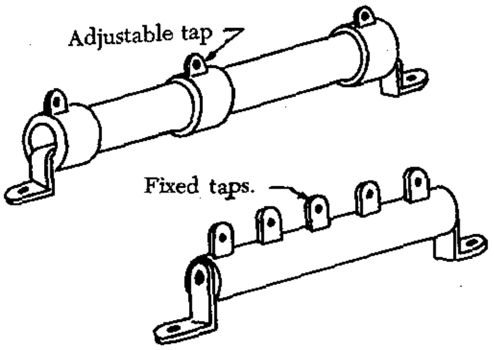


FIGURE 8–31. Wire-wound resistors with fixed and adjustable taps.

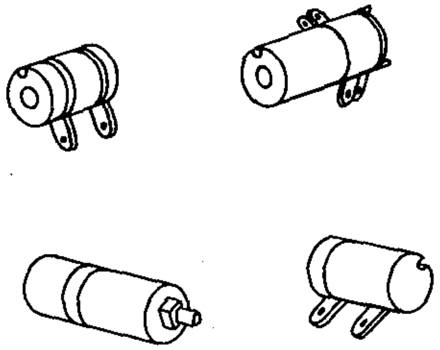


FIGURE 8–32. Precision wire-wound resistors.

Variable resistors are used to vary the resistance while the equipment is in operation. Wire-wound variable resistors control large currents, and carbon variable resistors control small currents. Wire-wound variable resistors are constructed by winding resistance wire on a porcelain or bakelite circular form. A contact arm which can be adjusted to any position on the circular form by means of a rotating shaft is used to select resistance settings. (See figure 8–34.)

Carbon variable resistors (see figure 8–35), used to control small currents, are constructed of a carbon compound deposited on a fiber disk. A contact on a movable arm varies the resistance as the arm shaft is turned.

The two symbols used on a schematic or circuit diagram to represent variable resistors are shown in figure 8–36.

The schematic symbol for a fixed resistor is shown in A of figure 8–37. A variation of this

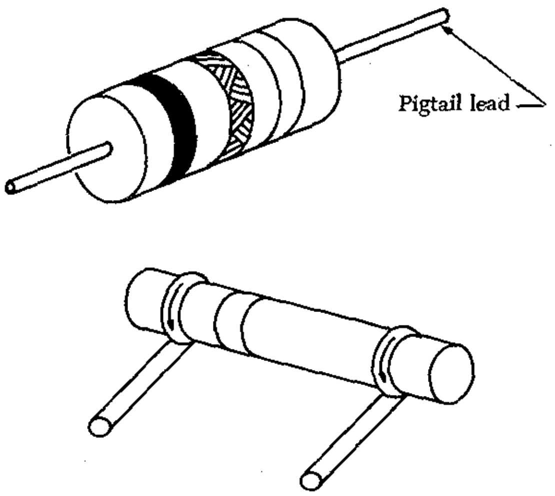


FIGURE 8–33. Carbon resistors.

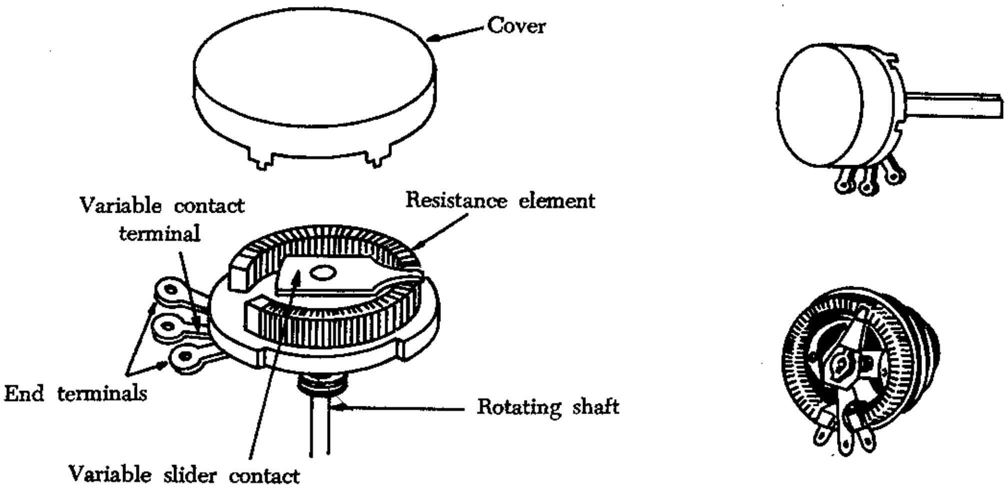


FIGURE 8–34. Wire-wound variable resistor.

symbol represents the tapped resistor, which has a fixed value but is provided with taps from which selected amounts of resistance can be obtained. (See B of figure 8—37.)

Resistor Color Code

The resistance value of any resistor can be measured by using an ohmmeter. But this is seldom necessary. Most wire-wound resistors have their resistance value in ohms printed on the body of the resistor. Many carbon resistors are similarly marked, but are often mounted in such a manner that it is difficult or impossible to read the resistance value. Additionally, heat often discolors the resistor body, making the printed marking illegible, and many carbon resistors are so small that a printed marking cannot be used. Thus, a color code marking is used to identify the resistance value of carbon resistors.

There is only one color code for carbon resistors, but there are two systems or methods used to paint this color code on resistors. One is the body-end-dot system, and the other is the end-to-center band system.

In each color code system, three colors are used to indicate the resistance value in ohms, and a fourth color is sometimes used to indicate the tolerance of the resistor. By reading the colors in the correct order and by substituting numbers from the color code, the resistance value of a resistor can be determined.

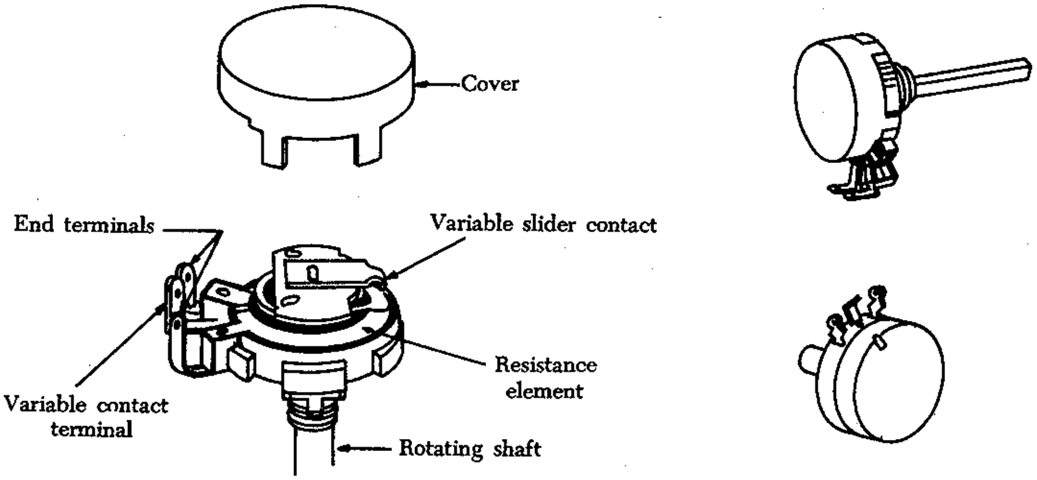


FIGURE 8–35. Carbon variable resistor.

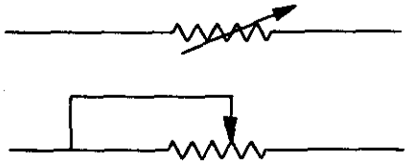


FIGURE 8–36. Symbols for variable resistors.

It is very difficult to manufacture a resistor to an exact standard of ohmic values. Fortunately, most circuit requirements are not extremely critical. For many uses the actual resistance in ohms can be 20 percent higher or lower than the value marked on the resistor without causing difficulty. The percentage variation between the marked value and the actual value of a resistor is known as the "tolerance" of a resistor. A resistor coded for a 5-percent tolerance will not be more than 5 percent higher or lower than the value indicated by the color code.

The resistor color code (see figure 8–38) is made up of a group of colors, numbers, and tolerance values. Each color is represented by a number and in most cases by a tolerance value.

When the color code is used with the end-to-center band marking system, the resistor is normally marked with bands of color at one end of the resistor. The body or base color of the resistor has nothing to do with the color code, and in no way indicates a resistance value. To prevent confusion, this body will never be the same color as any of the bands indicating resistance value.

When the end-to-center band marking system is used, the resistor will be marked by either three or four bands. The first color band (nearest the end of the resistor) will indicate the first digit in the numerical resistance value. This band will never be gold or silver in color.

The second color band (refer to figure 8–39) will always indicate the second digit of ohmic value. It will never be gold or silver in color. The third color band indicates the number of zeros to be added to the two digits derived from the first and second bands, except in the following two cases:

(1) If the third band is gold in color, the first two digits must be multiplied by 10 percent.

(2) If the third band is silver in color, the first two digits must be multiplied by 1 percent.

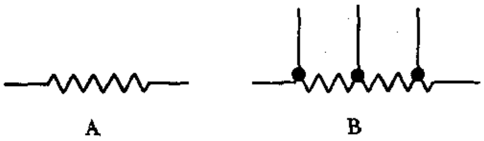


FIGURE 8–37. Symbols for fixed resistors.

Resistor color code		
Color	Number	Tolerance
Black	0	......
Brown	1	1%
Red	2	2%
Orange	3	3%
Yellow	4	4%
Green	5	5%
Blue	6	6%
Violet	7	7%
Gray	8	8%
White	9	9%
Gold	....	5%
Silver	....	10%
No color	....	20%

FIGURE 8–38. Resistor color code.

If there is a fourth color band, it is used as a multiplier for percentage of tolerance, as indicated in the color code chart in figure 8-38. If there is no fourth band, the tolerance is understood to be 20 percent.

Figure 8–39 illustrates the rules for reading the resistance value of a resistor marked with the end-to-center band system. This resistor is marked with three bands of color, which must be read from the end toward the center.

These are the values that should be obtained:

Color	Numerical Value	Significance
1st band—Red	2	1st digit
2nd band—Green	5	2nd digit
3rd band—Yellow	4	No. of zeros to add

There is no fourth color band, so the tolerance is understood to be 20 percent. 20 percent of 250,000 = 50,000.

Since the 20 percent tolerance is plus or minus,

Maximum resistance = 250,000 + 50,000
= 300,000 ohms
Minimum resistance = 250,000 − 50,000
= 200,000 ohms.

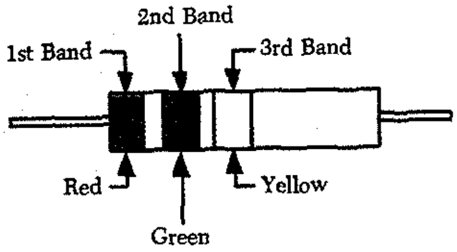


FIGURE 8–39. End-to-center band marking.

Figure 8–40 contains a resistor with another set of colors. This resistor code should be read as follows:

The resistance of this resistor is 86,000 ±10 percent ohms. The maximum resistance is 94,600 ohms and the minimum resistance is 77,400 ohms.

As another example, the resistance of the resistor in figure 8–41 is 960 ± 5 percent ohms. The maximum resistance is 1,008 ohms, and the minimum resistance is 912 ohms.

Sometimes circuit considerations dictate that the tolerance must be smaller than 20 percent. Figure 8–42 shows an example of a resistor with a 2 percent tolerance. The resistance value of this resistor is 2,500 ± 2 percent ohms. The maximum resistance is 2,550 ohms, and the minimum resistance is 2,450 ohms.

Figure 8–43 contains an example of a resistor with a black third color band. The color code value of black is zero, and the third band indicates the number of zeros to be added to the first two digits.

In this case, a zero number of zeros must be added to the first two digits; therefore, no zeros are added. Thus, the resistance value is 10 ± 1 percent ohms. The maximum resistance is 10.1 ohms, and the minimum resistance is 9.9 ohms.

There are two exceptions to the rule stating the third color band indicates the number of zeros. The first of these exceptions is illustrated in figure 8–44. When the third band is gold in color,

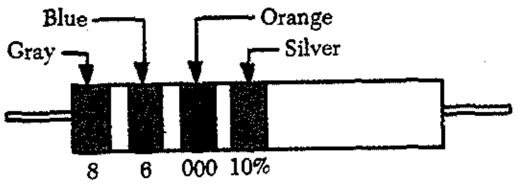


FIGURE 8-40. Resistor color code example.

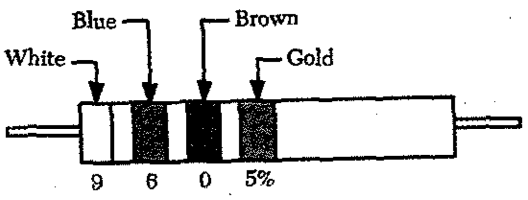


FIGURE 8-41. Resistor color code example.

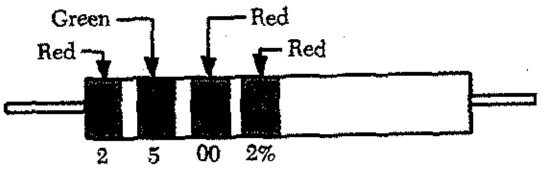


FIGURE 8-42. Resistor with 2 percent tolerance.

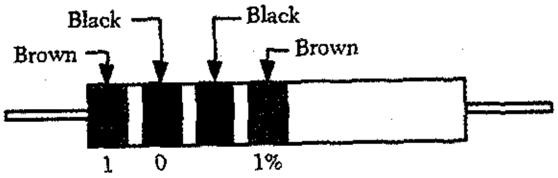


FIGURE 8-43. Resistor with black third color band.

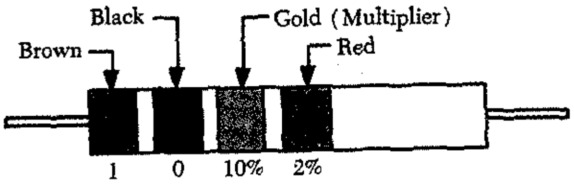


FIGURE 8-44. Resistor with a gold third band.

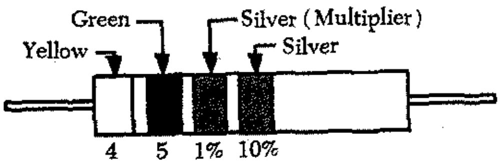


FIGURE 8-45. Resistor with a silver third band.

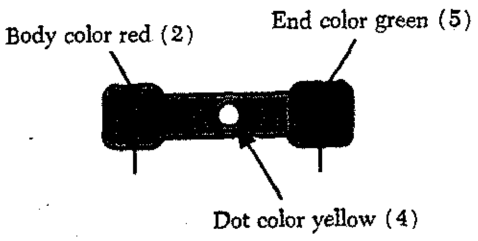


FIGURE 8-46. Resistor coded with body-end-dot system.

it indicates that the first two digits must be multiplied by 10 percent. The value of this resistor is

$$10 \times .10 \pm 2\% = 1 \pm .02 \text{ ohms.}$$

When the third band is silver, as is the case in figure 8–45, the first two digits must be multiplied by 1 percent. The value of the resistor is .45 ± 10 percent ohms.

Body-End-Dot System

The body-end-dot system of marking is rarely used today. A few examples will explain it. The location of the colors has the following significance:

Body color . . . . 1st digit of ohmic value

End color . . . . 2nd digit of ohmic value

Dot color . . . . Number of zeros to be added

If only one end of the resistor is painted, it indicates the second figure of the resistor value, and the tolerance will be 20 percent. The other two tolerance values are gold (5 percent) and silver (10 percent). The opposite end of the resistor will be painted to indicate a tolerance other than 20 percent. Figure 8–46 shows a resistor coded by the body-end-dot system.
The values are as follows:

Body—1st digit—2.

End—2nd digit—5.

Dot—No. of zeros—0000 (4).

The resistor value is 250,000 ± 20 percent ohms. The tolerance is understood to be 20 percent because no second dot is used.

If the same color is used more than once, the body, end, and dot may all be the same color, or any two may be the same; but the color code is used in exactly the same way. For example, a 33,000-ohm resistor will be entirely orange.

OHM'S LAW

The most important law applicable to the study of electricity is Ohm's law. This law, which outlines the relationship between voltage, current, and resistance in an electrical circuit, was first stated by the German physicist, George Simon Ohm (1787–1854). This law applies to all direct-current circuits. In a modified form it may be applied to the alternating circuits to be studied later in this text. Ohm's experiments showed that current flow in an electrical circuit is directly proportional to the amount of voltage applied to the circuit. Stated in different words, this law says that as the voltage increases, the current increases; and when the voltage decreases, the current flow decreases. It should be added that this relationship is true only if the resistance in the circuit remains constant. For it can be readily seen that if the resistance changes, current also changes.

Ohm's law may be expressed as an equation, as follows:

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

Where I is current in amperes, E is the potential difference measured in volts, and R is the resistance measured in ohms (designated by the Greek letter omega, whose symbol is Ω).

If any two of these circuit quantities are known, the third may be found by simple algebraic transposition.

The circuit shown in figure 8–47 contains a voltage source of 24 volts and a resistance of 3 ohms.

If an ammeter is inserted in the circuit, as shown in figure 8–47, the intensity of current flowing in the circuit can be read directly. Assuming that no ammeter is available, the intensity of current flow can be determined by using Ohm's law as follows:

$$I = \frac{E}{R} \qquad I = \frac{24\text{ V}}{3\Omega} \qquad I = 8 \text{ amperes.}$$

Some features of figure 8–47 that are typical of all electrical circuits drawn in schematic form should be reviewed. The electrical pressure or potential difference appiled to the circuit is rep-

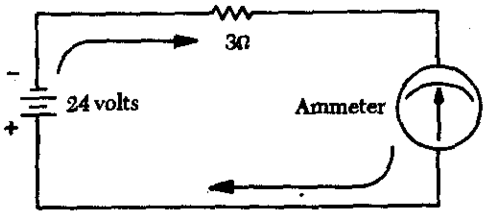


FIGURE 8–47. Electrical circuit demonstrating Ohm's law.

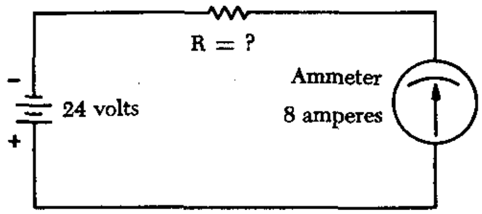


FIGURE 8–48. A circuit with unknown resistance.

resented in schematic form by the symbol for a battery. The negative sign is located near one side to indicate the negative terminal of the source, or battery. The opposite side is marked positive with a + symbol. Arrows are sometimes used to indicate the direction of current flow from the negative terminal, through the conducting wires and other circuit devices, to the positive terminal of the source.

Figure 8–48 shows that the values of voltage and current are known. To find the quantity of resistance in the circuit, Ohm's law can be transposed to solve for R.

Transposing the basic formula $I = \frac{E}{R}$ to $R = \frac{E}{I}$, and substituting the known circuit values in the equation, $R = \frac{24 \text{ volts}}{8 \text{ amperes}} = 3$ ohms, or 3 Ω.

Ohm's law can also be transposed to determine the voltage applied to a circuit when current flow and resistance are known, as shown in figure 8–49.

In this circuit the unknown circuit quantity, the voltage, is represented by the symbol E. The value of resistance is 3 ohms, and the current flow is 8 amperes. (The word amperes is often shortened to "amps.")

Transposing Ohm's law from its basic formula, the equation to solve for E becomes $E = I \times R$.

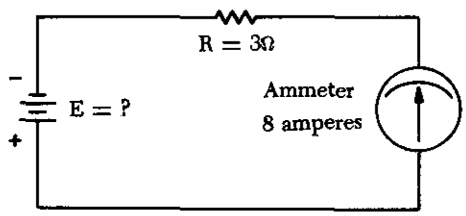


FIGURE 8–49. Circuit with unknown voltage.

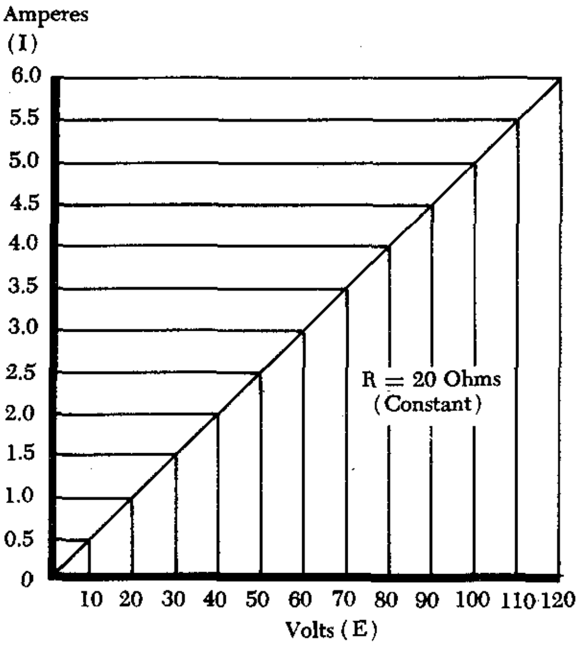


FIGURE 8–50. Voltage vs. current in a constant-resistance circuit.

Substituting the known values in the equation,

$$E = 8 \times 3$$

$$E = 24 \text{ volts or } 24 \text{ V.}$$

The relationship between the various circuit quantities can be further demonstrated if the resistance in a circuit is held constant. In such a case, the current will increase or decrease in direct proportion to the increase or decrease of voltage applied to the circuit. For example, if the voltage applied to a circuit is 120 volts and the resistance of the circuit is 20 ohms, the current flow will be $\frac{120}{20}$, or 6 amperes. If this resistance remains constant at 20 ohms, a graph of voltage-current relationship, as shown in figure 8–50, can be ploted.

The relationship between voltage and current in this example shows voltage plotted horizontally along the X axis in values from 0 to 120 volts, and the corresponding values of current are plotted vertically in values from 0 to 6.0 amperes along the Y axis. A straight line drawn through all the points where the voltage and current lines meet represents the equation $I = \frac{E}{20}$ and is called a linear relationship. The constant,

$$\text{Current} = \frac{\text{Electromotive force}}{\text{Resistance}}$$

$$I = \frac{E}{R} \qquad \text{Amperes} = \frac{\text{Volts}}{\text{Ohms}}$$

$$\text{Resistance} = \frac{\text{Electromotive force}}{\text{Current}}$$

$$R = \frac{E}{I} \qquad \text{Ohms} = \frac{\text{Volts}}{\text{Amperes}}$$

$$\text{Electromotive force} = \text{current} \times \text{resistance}$$

$$E = IR \qquad \text{Volts} = \text{amperes} \times \text{ohms}$$

FIGURE 8–51. Ohm's law.

20, represents the resistance, which is assumed not to change in this example. This graph represents an important characteristic of the basic law, that the current varies directly with the applied voltage if the resistance remains constant.

The basic equations derived from Ohm's law are summarized, together with the units of measurements of circuit quantities, in figure 8–51.

The various equations which may be derived by transposing the basic law can be easily obtained by using the triangles in figure 8–52.

The triangles containing E, I, and R are divided into two parts, with E above the line and $I \times R$ below it. To determine an unknown circuit quantity when the other two are known, cover the unknown quantity with a thumb. The location of the remaining uncovered letters in the triangle will indicate the mathematical operation to be performed. For example, to find I, refer to (a) of figure 8–52, and cover I with the thumb. The uncovered letters indicate that E is to be divided by R, or $I = \frac{E}{R}$. To find R, refer to (b) of figure 8–52, and cover R with the thumb. The result indicates that E is to be divided by I,or $R = \frac{E}{I}$. To find E, refer to (c) of figure 8–52, and cover E with the thumb. The result indicates I is to be multiplied by R, or $E = I \times R$.

This chart is useful when learning to use Ohm's law. It should be used to supplement the beginner's knowledge of the algebraic method.

Power

In addition to the volt, ampere, and ohm, there is one other unit frequently used in electrical circuit calculations. This is the unit of power.

The unit used to measure power in d.c. electrical circuits is the watt. Power is defined as the rate of doing work and is equal to the product of the voltage and current in a d.c. circuit. When the current in amperes (I) is multiplied by e.m.f. in volts (E), the result is power measured in watts (P). This indicates that the electrical power delivered to a circuit varies directly with the applied voltage and current flowing in the circuit. Expressed as an equation, this becomes

$$P = IE.$$

This equation may be transposed to determine any one of the three circuit quantities as long as the other two are known. Thus, if the power is read directly from a wattmeter and the voltage is measured with a voltmeter, the intensity of the current (I) flowing in the circuit can be determined by transposing the basic equation to $I = \frac{P}{E}$.

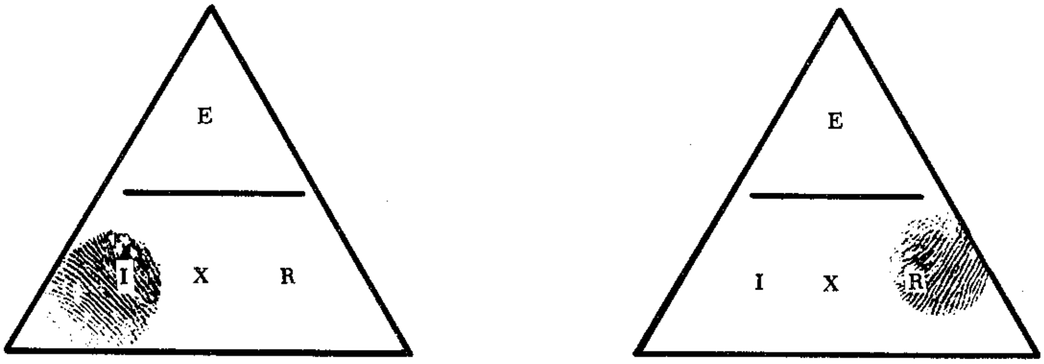
Similarly, the voltage (E) can be found by transposing the basic power formula to $E = \frac{P}{I}$.

Since some of the values used to determine the power delivered to a circuit are the same as those used in Ohm's law, it is possible to substitute Ohm's law values for equivalents in the power formula.

In Ohm's law, $I = \frac{E}{R}$. If this value $\frac{E}{R}$ is substituted for I in the power formula, it becomes

$$P = I \times E; P = E \times \frac{E}{R}; \text{ or } P = \frac{E^2}{R}.$$

This equation, $P = \frac{E^2}{R}$, illustrates that the power in watts delivered to a circuit varies directly with the square of the applied voltage and inversely with the circuit resistance.

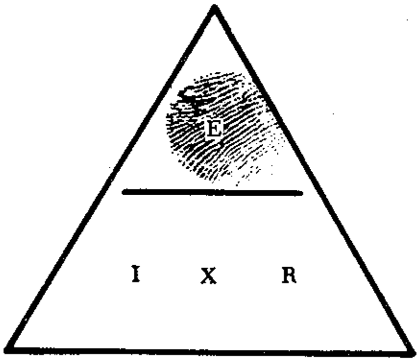


To find I (amperes) place thumb over I and divide E by R as indicated.

(a)

To find R (ohms) place thumb over R and divide as indicated.

(b)



To find E (volts) place thumb over X and multiply as indicated.

(c)

E = volts I = amperes R = ohms

FIGURE 8–52. Ohm's law chart.

The watt is named for James Watt, the inventor of the steam engine. Watt devised an experiment to measure the power of a horse in order to find a means of measuring the mechanical power of his steam engine. One horsepower is required to move 33,000 pounds 1 foot in 1 minute. Since power is the rate of doing work, it is equivalent to the work divided by time. Stated as a formula, this is

$$\text{Power} = \frac{33{,}000 \text{ ft.-lb.}}{60 \text{ sec. (1 min.)}}, \text{ or}$$

$$P = 550 \text{ ft.-lb./sec.}$$

Electrical power can be rated in a similar manner. For example, an electric motor rated as a 1-horsepower motor requires 746 watts of electrical energy. But the watt is a relatively small unit of power. Much more common is the kilowatt or 1,000 watts. (The prefix kilo means 1,000.) In measuring amounts of electrical energy consumed, the kilowatt hour is used. For example, if a 100-watt bulb consumes electrical energy for 20 hours, it has used 2,000 watt hours or 2 kilowatt hours of electrical energy.

Electrical power that is lost in the form of heat when current flows through an electrical device is often referred to as power loss. This heat is usually dissipated into the surrounding air and serves no useful purpose, except when used for heating. Since all conductors possess some resistance, circuits are designed to reduce these losses. Referring again to the basic power formula, $P = I \times E$, it is possible to substitute the Ohm's law values for E in the power formula to obtain a power formula that directly reflects the power losses in a resistance.

$$P = I \times E; E = I \times R.$$

Substituting the Ohm's law value for E ($I \times R$) in the power formula,

$$P = I \times I \times R.$$

Collecting terms, this gives,

$$P = I^2 R.$$

From this equation, it can be seen that the power in watts in a circuit varies as the square of the circuit current in amperes and varies directly with the circuit resistance in ohms.

Finally, the power delivered to a circuit can be expressed as a function of current and resistance by transposing the power equation $P = I^2 R$. Transposing to solve for current gives

$$I^2 = \frac{P}{R}$$

and by extracting the square root of both sides of the equation, $I = \sqrt{\frac{P}{R}}$.

Thus, the current through a 500-watt, 100-ohm load (resistance) is as follows:

$$I = \sqrt{\frac{P}{R}} = \frac{500}{100} = 2.24 \text{ amperes.}$$

The electrical equations derived from Ohm's law and the basic power formula do not reveal all about the behavior of circuits. They do indicate the numerical relation between the volt, ampere, ohm, and watt. Figure 8–53 provides a summary of all the possible transpositions of these formulas in a 12-segment circle.

SERIES D. C. CIRCUITS

The series circuit is the most basic of electrical circuits. All other types of circuits are elaborations or combinations of series circuits. Figure 8–54 is an example of a simple series circuit. It is a circuit because it provides a complete path for current to flow from the negative to the positive terminal of the battery. It is a series circuit because there is only one possible path in which current can flow, as indicated by the arrows showing the direction of electron movement. It is also called a series circuit because current must pass through the circuit components, the battery and the resistor, one after the other, or "in series."

The circuit shown in figure 8–55 contains the basic components required for any circuit: a source of power (battery), a load or current-limiting resistance (resistor), and a conductor (wire). Most practical circuits contain at least two other items: a control device (switch) and a safety device (fuse). With all five components in the circuit it would appear as shown in figure 8–55, which is a d.c. series circuit.

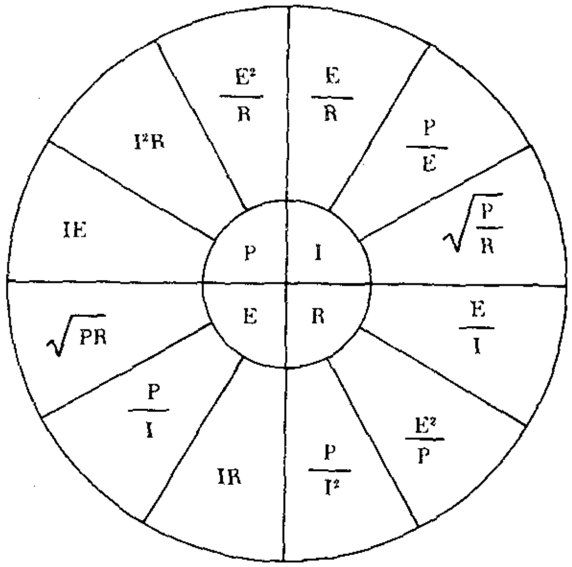


FIGURE 8–53. Summary of basic equations using the volt, ampere, ohm, and watt.

In the d.c. or direct-current circuit, current flows in one direction from the negative terminal of the battery through the switch (which must be closed) through the load resistance and the fuse to the positive terminal of the battery.

To discuss the behavior of electric current in a d.c. series circuit, figure 8–56 is redrawn in figure 8–57 to include three ammeters and two resistors. Since an ammeter measures the intensity of current flow, three have been located in the circuit to measure the current flowing at various points in the circuit.

With the switch closed to complete the circuit, all three ammeters will indicate the same amount of current. This is an important characteristic of all series circuits: No matter how many components are included in a series circuit, the current is the same intensity throughout the circuit. While it is true that an increase in the number of circuit components will increase the resistance to current flow in the circuit, whatever the value of current flowing in the circuit, it will be the same value at all points in the circuit.

In figure 8–56, the current through resistor R_1 is labeled I_1 and the current through resistor R_2 is labeled I_2. If the total current in the circuit is I_T, the formula describing the current flow is,

$$I_T = I_1 = I_2.$$

If the number of resistors is increased to five, the formula will be

$$I_T = I_1 = I_2 = I_3 = I_4 = I_5.$$

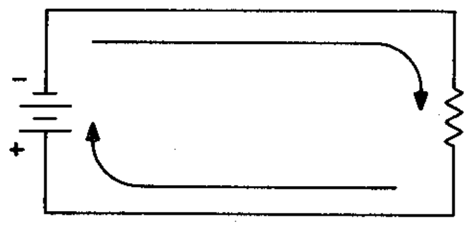


FIGURE 8–54. A series circuit.

Without indicating how much current is flowing, it will always be true that the current through any resistor in a series circuit will be the same as that through any other resistor.

Figure 8–57 is a series circuit containing two resistances. In order to determine the amount of current flow in this circuit, it is necessary to know how much resistance or opposition the current flow will encounter. Thus, the second characteristic of series circuits is: Total resistance in a series circuit is the sum of the separate resistances in the circuit. Stated as a formula, this becomes

$$R_T = R_1 + R_2.$$

In figure 8–57, this is

$$R_T = R_1\ (5\ \Omega) + R_2\ (10\ \Omega) \text{ or}$$

$$R_T = 5 + 10 = 15\ \Omega.$$

The total resistance of the circuit in figure 8–57 is 15 ohms. It is important to remeber that, if the circuit were altered to include 10, 20, or even 100 resistors, the total resistance would still be the sum of all the separate resistances. It is also true that there is a certain negligible resistance in the battery, as well as in the fuse and the switch. These small values of resistance will not be considered in determining the value of current flow in this circuit.

The Ohm's law formula for finding current is $I = E/R$. Since the battery voltage is 30 volts and the total circuit resistance is 15 ohms, the equation becomes

$$I = \frac{30\ \text{V}}{15\ \Omega} = 2 \text{ amperes.}$$

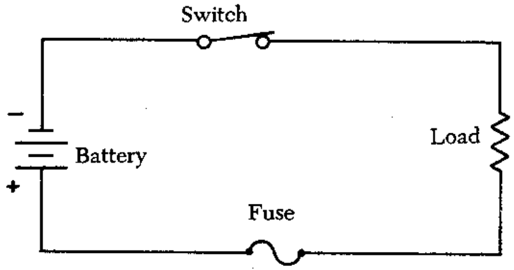


FIGURE 8–55. A d.c. series circuit.

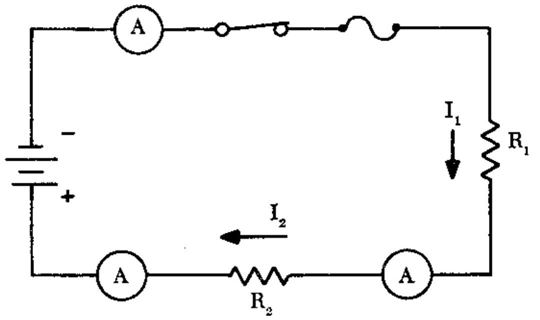


FIGURE 8–56. Current flow in a series circuit.

The current flow is 2 amperes (sometimes the word amperes is shortened to amps), and this value of current is everywhere in the circuit.

To consider what effect a change in resistance will have on current flow when the voltage remains constant, the total resistance is doubled to 30 ohms. Using Ohm's law

$$I = \frac{E}{R}, I = \frac{30\ \text{V}}{30\ \Omega} = 1 \text{ ampere.}$$

It can be seen that current will be reduced to half its former value when resistance is doubled. On the other hand, if voltage remains constant, and resistance is reduced to half its former value the current will double its original value.

$$I = \frac{E}{R} = I = \frac{30\ \text{V}}{7.5\ \Omega} = 4 \text{ amperes.}$$

Thus, if voltage remains constant and resistance increases, current must decrease. Conversely, if resistance decreases, current must increase.

However, if resistance is held constant and voltage is doubled, the current flow will double its original value. If the voltage applied to the circuit in figure 8–58 is doubled to 60 volts and the original value of resistance is maintained at

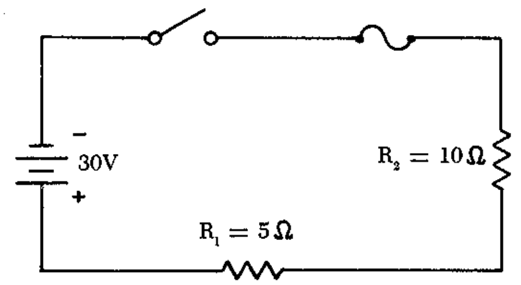


FIGURE 8–57. A series circuit with two resistors.

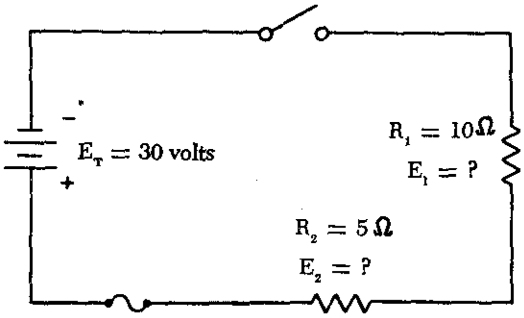


FIGURE 8–58. Voltage drops in a circuit.

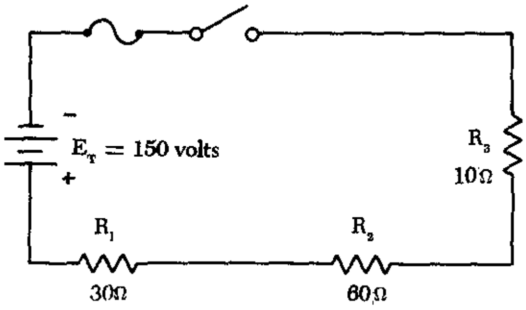


FIGURE 8–59. Applying Ohm's law.

15 ohms,

$$I = \frac{E}{R} = \frac{60\text{ V}}{15\ \Omega} = 4\text{ amperes,}$$

and if voltage is reduced to half its original value, with resistance constant, current will decrease to half its original value.

$$I = \frac{E}{R} = \frac{15\text{ V}}{15\ \Omega} = 1\text{ ampere.}$$

Thus, if resistance remains constant, and voltage increases, current must also increase. If voltage decreases, current decreases also.

It is important to distinguish between the terms "voltage" and "voltage drop" in discussing series circuits. Voltage drop refers to the loss in electrical pressure caused by forcing electrons through a resistance. In figure 8–58, the applied voltage (the battery) is 30 volts and is labeled E_T.

Since there are two resistances in the circuit, there will be two separate voltage drops. These two voltage drops will be the loss in electrical pressure used to force electrons through the resistances. The amount of electrical pressure required to force a given number of electrons through a resistance is proportional to the size of the resistance. Thus, the voltage drop across R_1 will be twice that across R_2 since R_1 has two times the resistance value of R_2. The drop across R_1 is labeled E_1, and that across R_2 is E_2. The current, I, is the same throughout the circuit.

Using:

$$\begin{array}{ll} E = IR & E_2 = IR_2 \\ E_1 = IR_1 & E_2 = 2a \times 5 \\ E_1 = 2a \times 10 & E_2 = 10\text{ V.} \\ E_1 = 20\text{ V} & \end{array}$$

If the voltage drops (used) across the two resistors are added (10 V + 20 V), a value equal to the applied voltage, 30 volts, is obtained. This confirms the basic formula for series circuits:

$$E_T = E_1 + E_2.$$

In any d.c. series circuit, a missing quantity such as voltage, resistance, or current can be calculated by using Ohm's law if any two of the quantities are known.

Figure 8–59 is a series circuit containing three known values of resistance and an applied voltage of 150 volts. Using these values, the unknown circuit quantities can be determined by applying Ohm's law as follows:

$R_1 = 30\ \Omega$

$R_2 = 60\ \Omega$

$R_3 = 10\ \Omega$

R_T = ________

I_T = ________

E_{R_1} = ________

E_{R_2} = ________

E_{R_3} = ________

Total resistances:

$$\begin{aligned} R_T &= R_1 + R_2 + R_3 \\ &= 30 + 60 + 10 \\ &= 100\ \Omega. \end{aligned}$$

Total Current:

$$\begin{aligned} I_T &= \frac{E_T}{R_T} \\ &= \frac{150\text{ V}}{100\ \Omega} \\ &= 1.5\text{ amperes.} \end{aligned}$$

Voltage Drops:

$$E = IR$$

$$E_{R_1} = I_T \times R_1$$

$$= 1.5 \text{ amps} \times 30$$

$$= 45 \text{ V.}$$

$$E_{R_2} = I_T \times R_2$$

$$= 1.5 \text{ amps} \times 60$$

$$= 90 \text{ V.}$$

$$E_{R_3} = I_T \times R_3$$

$$= 1.5 \text{ amps} \times 10$$

$$= 15 \text{ V.}$$

Do these values for voltage drops equal the applied voltage?

$$E_T = E_{R_1} + E_{R_2} + E_{R_3}$$

$$E_T = 150 \text{ volts}$$

$$150 \text{ V} = 45 \text{ V} + 90 \text{ V} + 15 \text{ V.}$$

The sum of the voltage drops equals the applied voltage.

Kirchhoff Laws

In 1847, a German physicist, G. R. Kirchhoff, elaborated on Ohm's law and developed two statements that are known as Kirchhoff's laws for current and voltage. An understanding of these laws enables the aircraft technician to gain a better understanding of the behavior of electricity. Using Kirchhoff's laws, it is possible to find: (1) The current in each branch of a network circuit when both the resistance and the electromotive force in each branch are known, or (2) the electromotive force in each branch when both the resistance of, and the current in, each branch are known. These laws are stated as follows:

Current Law—The algebraic sum of the currents at any junction of conductors in a circuit is zero. This means that the amount of current flowing away from a point in a circuit is equal to the amount flowing to that point.

Voltage Law—The algebraic sum of the applied voltage and the voltage drop around any closed circuit is zero, which means that the voltage drop around any closed circuit is equal to the applied voltage.

When applying Kirchhoff's laws, use the following procedures to simplify the work:

1. When the direction of current is not apparent, assume a direction of flow. If the assumption is wrong, the answer will be numerically correct but preceded by a negative sign.
2. Place polarity markings (plus and minus signs) on all resistors and batteries in the circuit being solved. The assumed direction of current flow will not affect the polarities of the batteries, but it will affect the polarity of the voltage drop on resistors. Therefore, the voltage drop should be marked so that the end of a resistor into which the current is assumed to flow is negative, and the end from which it leaves is positive.

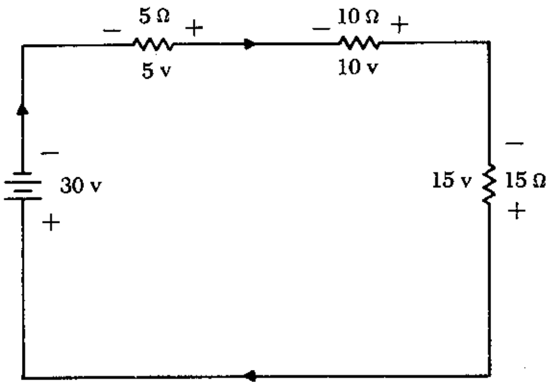


FIGURE 8–60. Polarity of voltage drops.

In the statements of Kirchhoff's laws, the term algebraic sum was used. An algebraic sum differs from an arithmetic sum in that both the magnitude and the sign of each number must be considered. In electrical circuits a voltage drop occurs when current flows through a resistor. The magnitude of the voltage is determined by the size of the resistor and the amount of current flow. The polarity (sign) of the voltage drop is determined by the direction of the current flow. For example, observe the polarities of the applied electromotive force (e.m.f.) and the voltage drop as shown in figure 8–60. The applied e.m.f. causes electrons to flow through the opposition offered by the resistances. The voltage drop across each resistance is therefore opposite in polarity to that of the applied e.m.f. Note that the side of each resistor where the current enters is labeled the negative side.

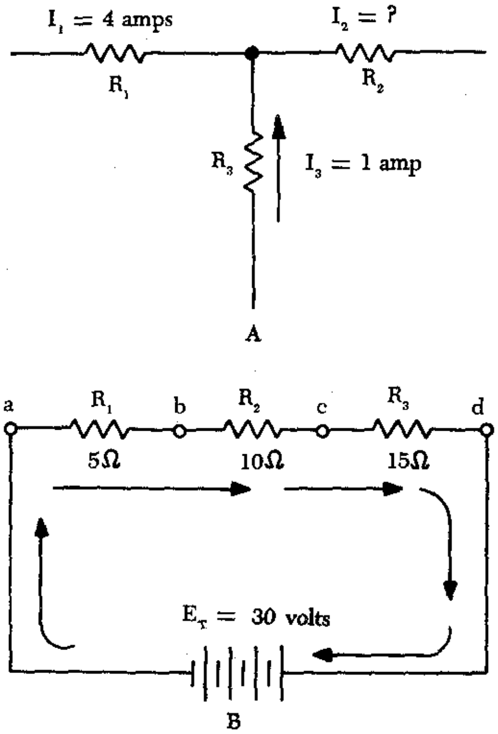


FIGURE 8–61. Circuit demonstrating Kirchhoff's laws, (A) current law and (B) voltage law.

A portion of a circuit which illustrates Kirchhoff's current law is shown in figure 8–61.

The current flowing through resistor R_1 has an intensity of four amperes. The current flowing through resistor R_3 has a magnitude of one ampere and is flowing into the same junction as the current through R_1. Using Kirchhoff's current law, it is possible to determine how much current is flowing through R_2 and whether it is flowing toward or away from the common junction. This is expressed in equation form as:

$$I_1 + I_2 + I_3 = 0.$$

Substituting the current values in the equation gives

$$4 + I_2 + (-1) = 0$$

$$I_2 = 1 + 4$$

$$I_2 = 5$$

$$-4 + (-1) + 5 = 0.$$

Kirchhoff's current law finds a wider application in more complex parallel or series-parallel circuits.

Figure 8-61(B) is a series d.c. circuit which is used to demonstrate Kirchhoff's voltage law. The total resistance is the sum of R_1, R_2, and R_3 which is 30 ohms. Since the applied voltage is 30 volts, the current flowing in the circuit is 1 ampere. Therefore, the voltage drops across R_1, R_2, and R_3 are 5 volts, 10 volts, and 15 volts, respectively. The sum of the voltage drops is equal to the applied voltage of 30 volts.

This circuit may also be solved by using the polarities of the voltages and showing that the algebraic sum of the voltages is zero. Consider voltages positive if the (+) sign is met first and negative if the (−) sign is met first when tracing the current flow. By starting at the battery and going in the direction of current flow (as indicated by the arrows) the following equation may be set up:

$$\text{Total voltage } (E_t) = +30 - 5 - 10 - 15$$

$$E_t = 0.$$

The point to start around the circuit and the polarity to use are arbitrary and are a matter of choice for each circuit.

PARALLEL D. C. CIRCUITS

A circuit in which two or more electrical resistances, or loads, are connected across the same voltage source is a parallel circuit. The parallel circuit differs from the series circuit in that more than one path is provided for current flow—the more paths added in parallel, the less opposition to flow of electrons from the source. In a series circuit the addition of resistance increases the opposition to current flow. The minimum requirements for a parallel circuit are the following:

(1) a power source.
(2) conductors.
(3) a resistance or load for each current path.
(4) two or more paths for current flow.

Figure 8–62 shows a parallel circuit with three paths for current flow. Points A, B, C, and D are connected to the same conductor and are at the same electrical potential. In a similar manner, points E, F, G, and H are at the same potential. Since the applied voltage appears between points A and E, the same voltage is applied between points B and F, points C and G, and between points D and H. Thus, when resistors are connected in parallel across a voltage source, each resistor has the same applied voltage, although the currents through the resistors may differ de-

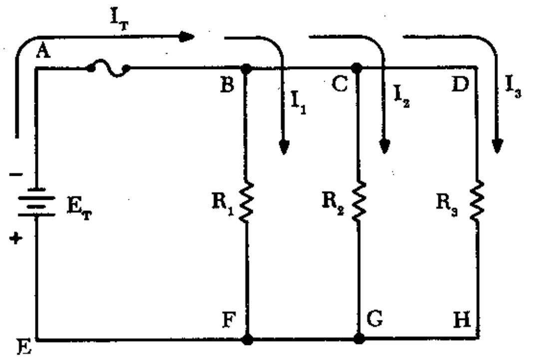


FIGURE 8–62. A parallel circuit.

pending on the values of resistance. The voltage in a parallel circuit may be expressed as follows:

$$E_T = E_1 = E_2 = E_3.$$

Where E_T is the applied voltage, E_1 is the voltage across R_1, E_2 is the voltage across R_2, and E_3 is the voltage across R_3 (figure 8–62).

The current in a parallel circuit divides among the various branches in a manner depending on the resistance of each branch (see figure 8–63). A branch containing a small value of resistance will have a greater current flow than a branch containing a high resistance. Kirchhoff's current law states that the current flowing toward a point is equal to the current flowing away from that point. Thus, the current flow in a circuit may be expressed mathematically as follows:

$$I_T = I_1 + I_2 + I_3$$

where I_T is the total current and I_1, I_2, and I_3 are the currents through R_1, R_2, and R_3, respectively.

Kirchhoff's and Ohm's law can be applied to find the total current flow in the circuit shown in figure 8–63.

The current flow through the branch containing resistance R_1 is

$$I_1 = \frac{E}{R_1} = \frac{6}{15} = .4 \text{ amps.}$$

The current through R_2 is

$$I_2 = \frac{E}{R_2} = \frac{6}{25} = .24 \text{ amps.}$$

The current through R_3 is

$$I_3 = \frac{E}{R_3} = \frac{6}{12} = .5 \text{ amps.}$$

The total current, I_T, is

$$I_T = I_1 + I_2 + I_3$$

$$I_T = .4 \text{ amps} + .24 \text{ amps} + .5 \text{ amps}$$

$$I_T = 1.14 \text{ amps.}$$

In a parallel circuit, $I_T = I_1 + I_2 + I_3$. By Ohm's law the following relationships can be obtained:

$$I_T = \frac{E_T}{R_T},\ I_1 = \frac{E_1}{R_1},\ I_2 = \frac{E_2}{R_2},\ \text{and } I_3 = \frac{E_3}{R_3}.$$

Substituting these values in the equation for total current,

$$\frac{E_T}{R_T} = \frac{E_1}{R_1} + \frac{E_2}{R_2} + \frac{E_3}{R_3}.$$

In a parallel circuit $E_T = E_1 = E_2 = E_3$. Therefore,

$$\frac{E}{R_T} = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}.$$

Dividing through by E gives,

$$\frac{I}{R_T} = \frac{I}{R_1} + \frac{I}{R_2} + \frac{I}{R_3}.$$

This equation is the reciprocal formula for finding the total or equivalent resistance of a parallel circuit. Another form of the equation may be derived by solving for R_T.

$$R_T = \frac{1}{\frac{I}{R_1} + \frac{I}{R_2} + \frac{I}{R_3}}.$$

An analysis of the equation for total resistance in a parallel circuit shows that R_T is always less

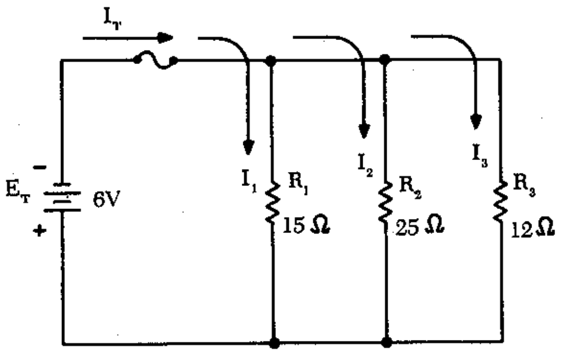


FIGURE 8–63. Current flow in a parallel circuit.

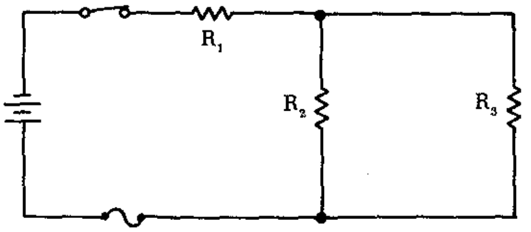


FIGURE 8–64. A series-parallel circuit.

than the smallest resistance in a parallel circuit. Thus a 10-ohm, a 20-ohm, and a 40-ohm resistor connected in parallel have a total resistance of less than 10 ohms.

If there are only two resistors in a parallel circuit, the reciprocal formula is

$$\frac{I}{R_T} = \frac{I}{R_1} + \frac{I}{R_2}.$$

Simplified, this becomes:

$$R_T = \frac{R_1 R_2}{R_1 + R_2}.$$

This simplified, shorter formula can be used when two resistances are in parallel. Another method can be used for any number of resistors in parallel if they are of equal resistance. The resistance value of one resistor is divided by the number of resistors in parallel to determine the total resistance. Expressed mathematically this becomes:

$$R_T = \frac{R}{N}.$$

Where R_T is the total resistance, R is the resistance of one resistor, and N is the number of resistors.

SERIES-PARALLEL D. C. CIRCUITS

Most circuits in electrical equipment are not series or parallel circuits. They are usually series-parallel circuits, which are combinations of series and parallel circuits. A series-parallel circuit consists of groups of parallel resistors connected in series with other resistors. An example of a series-parallel circuit is shown in figure 8–64.

The requirements for a series-parallel circuit are as follows:

(1) power source (battery).
(2) conductors (wires).

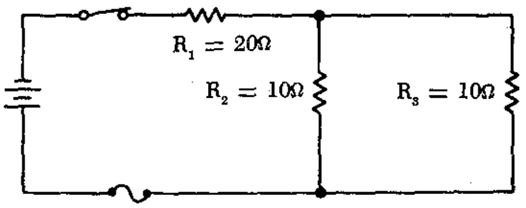


FIGURE 8–65. A series-parallel circuit.

(3) load (resistances).
(4) more than one path for current flow.
(5) a control (switch).
(6) safety device (fuse).

While series-parallel circuits may appear extremely complex, the same rule used for series and parallel circuits can be applied to simplify and solve them.

The easiest method of handling series-parallel circuits is to break them apart and redraw them as equivalent circuits. The circuit in figure 8–65 is an example of a simple series-parallel circuit that can be redrawn to illustrate this procedure.

In this circuit the same voltage is applied to R_2 and R_3; thus they are in parallel. The equivalent resistance of these two resistors is equal to the value of one resistor divided by the number of resistors in parallel. This is true only when the parallel resistors have the same ohmic value. If this rule is applied, the circuit can be redrawn as shown in figure 8–66.

This has converted the original series-parallel circuit into a simple series circuit containing two resistances. To further simplify the circuit, the two series resistances can be added, and the circuit can be redrawn as shown in figure 8–67.

Although the last redrawing of the circuit could have been omitted and the calculations done mentally, this circuit illustrates clearly that one 25-ohm resistor is the resistive equiv-

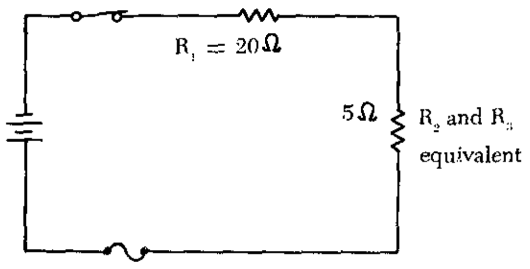


FIGURE 8–66. A redrawn series-parallel circuit.

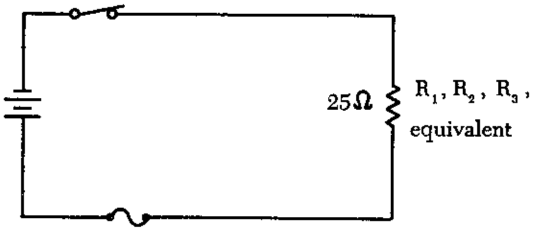


FIGURE 8–67. An equivalent series-parallel circuit

alent of the three resistors of the original circuit. Figure 8–68 contains a more complex series-parallel circuit.

The first step in simplifying this circuit is to reduce each group of parallel resistors to a single equivalent resistor. The first group is the parallel combination of R_2 and R_3. Since these resistors have unequal values of resistance, the formula for two parallel resistances is used:

$$R_a = \frac{R_2\,R_3}{R_2 + R_3} = \frac{120 \times 40}{120 + 40} = \frac{4800}{160} = 30\ \Omega.$$

Then the parallel combination of R_2 and R_3 can be replaced with a single 30 Ω resistor, as shown in figure 8–69.

Next, the equivalent resistance of the parallel combination of R_4, R_5, and R_6 can be determined using the formula $R_b = R/N$: where, R_b is the equivalent resistance of R_4, R_5, and R_6, R is the value of one of the resistors, and N is the number of resistors in parallel,

$$R_b = \frac{R}{N} = \frac{60}{3} = 20\ \Omega.$$

The parallel combination of R_4, R_5, and R_6 can now be redrawn as a single 20 Ω resistor, as shown in figure 8–70.

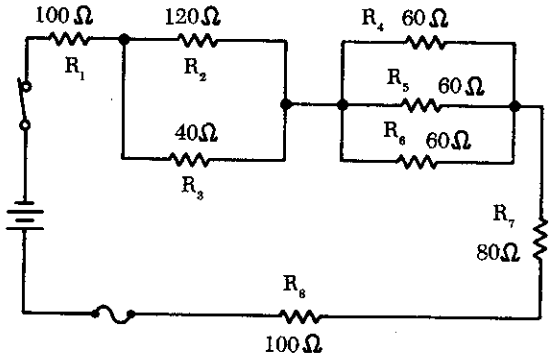


FIGURE 8–68. A more complex series-parallel circuit.

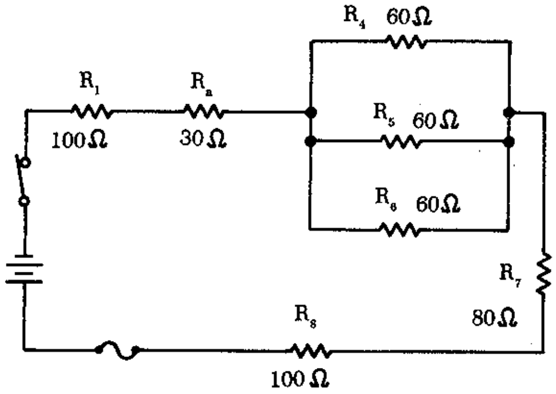


FIGURE 8–69. Series-parallel circuit with one equivalent resistance.

The original series-parallel circuit has now been replaced with its equivalent series circuit. This circuit could be redrawn again to replace the five resistors in series with one 330-ohm resistor.

This can be proved by using the total resistance formula for series circuits:

$$R_T = R_1 + R_a + R_b + R_7 + R_8$$
$$= 100 + 30 + 20 + 80 + 100$$
$$= 330 \text{ ohms.}$$

The first series-parallel circuit used is redrawn to discuss the behavior of current flow (figure 8–71).

Unlike the parallel circuit, the branch currents, I_1 and I_2, cannot be established using the applied voltage. Since R_1 is in series with the parallel combination of R_2 and R_3, a portion of the applied voltage is dropped across R_1. In order to find the branch currents, total resistance and total current must be found first. Since R_2 and R_3 are

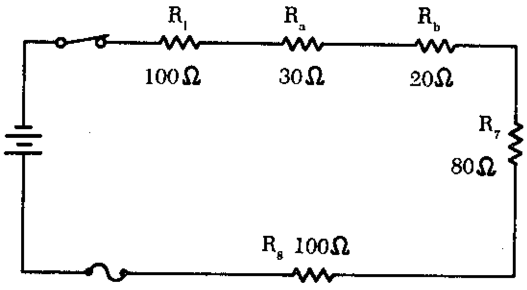


FIGURE 8–70. Series-parallel equivalent circuit.

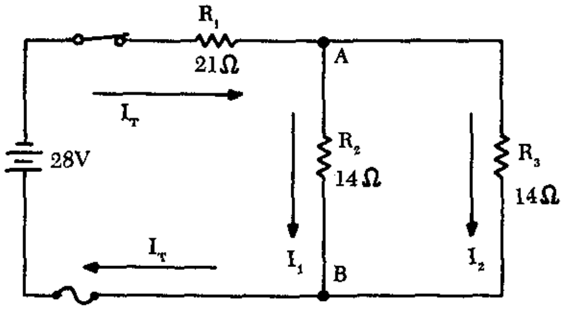


FIGURE 8–71. Current flow in a series-parallel circuit.

equal resistance,

$$R_{\text{equiv.}} = \frac{R}{N} = \frac{14}{2} = 7\ \Omega.$$

Total resistance is

$$\begin{aligned} R_T &= R_1 + R_{\text{equiv.}} \\ &= 21\ \Omega + 7\ \Omega \\ &= 28\ \Omega. \end{aligned}$$

Using Ohm's law, total current is

$$I_T = \frac{E_T}{R_T} = \frac{28\ \text{V}}{28\ \Omega} = 1 \text{ ampere.}$$

The total current, 1 ampere, flows through R_1 and divides at point A, with part of the current flowing through R_2, and the other part through R_3. Since R_2 and R_3 are of equal size, it is obvious that half of the total current, or .5 amps, will flow through each branch.

The voltage drops in the circuit are determined by Ohm's law:

$$\begin{aligned} E &= IR. \\ E_{R_1} &= I_T R_1 \\ &= 1 \times 21 \\ &= 21 \text{ Volts.} \\ E &= IR. \\ E_{R_2} &= I_1 R_2 \\ &= .5 \times 14 \\ &= 7 \text{ Volts.} \\ E &= IR. \\ E_{R_3} &= I_2\, R_3 \\ &= .5 \times 14 \\ &= 7 \text{ Volts.} \end{aligned}$$

The voltage drops across parallel resistors are always equal. It should also be remembered that, when the voltage is held constant and the resistance of any resistor in a series-parallel circuit is increased, the total current will decrease. This should not be confused as adding another parallel resistor to a parallel combination, which could reduce total resistance and increase total current flow.

VOLTAGE DIVIDERS

Voltage dividers are devices which make it possible to obtain more than one voltage from a single power source.

A voltage divider usually consists of a resistor, or resistors connected in series, with fixed or movable contacts and two fixed terminal contacts. As current flows through the resistor, different voltages can be obtained between the contacts. A typical voltage divider is shown in figure 8–72.

A load is any device which draws current. A heavy load means a heavy current drain. In addition to the current drawn by the various loads, there is a certain amount drawn by the voltage divider itself. This is known as bleeder current.

To understand how a voltage divider works, examine the illustration in figure 8–73 carefully and observe the following:

Each load draws a given amount of current: I_1, I_2, I_3. In addition to the load currents, some bleeder current (I_B) flows. The current I_t is drawn from the power source and is equal to the sum of all currents.

The voltage at each point is measured with respect to a common point. Note that the common

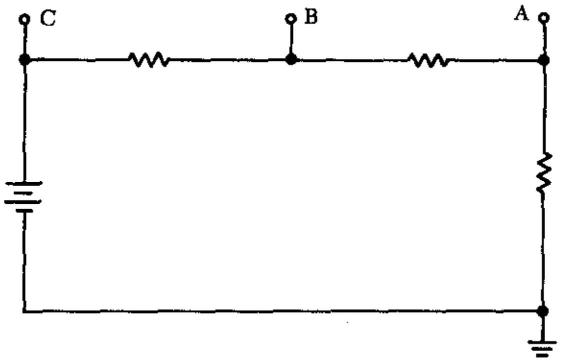


FIGURE 8–72. A voltage divider circuit.

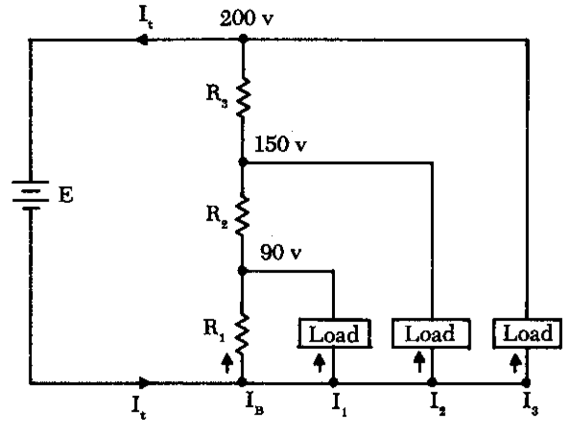


FIGURE 8–73. A typical voltage divider.

point is the point at which the total current (I_t) divides into separate currents (I_1, I_2, I_3).

Each part of the voltage divider has a different current flowing in it. The current distribution is as follows:

Through R_1—bleeder current (I_B)
Through R_2—I_B plus I_1
Through R_3—I_B plus I_1, plus I_2.

The voltage across each resistor of the voltage divider is:

90 volts across R_1
60 volts across R_2
50 volts across R_3.

The voltage divider circuit discussed up to this point has had one side of the power supply (battery) at ground potential. In figure 8–74 the common reference point (ground symbol) has been moved to a different point on the voltage divider.

The voltage drop across R_1 is 20 volts; however, since tap A is connected to a point in the circuit that is at the same potential as the negative side of the battery, the voltage between tap A and the reference point is a negative (−) 20 volts. Since resistors R_2 and R_3 are connected to the positive side of the battery, the voltages between the reference point and tap B or C are positive.

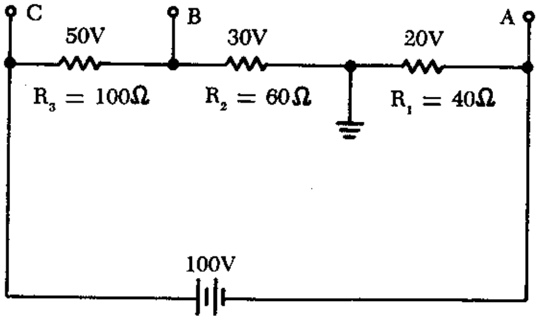


FIGURE 8–74. Positive and negative voltage on a voltage divider.

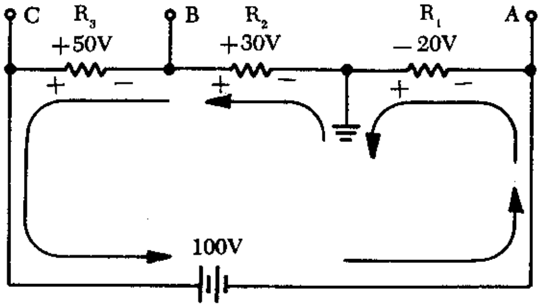


FIGURE 8–75. Current flow through a voltage divider.

A simple method of determining negative and positive voltages is provided by the following rules: (1) If current enters a resistance flowing away from the reference point, the voltage drop across that resistance is positive in respect to the reference point; (2) if current flows out of a resistance toward the reference point, the voltage drop across that resistance is negative in respect to the reference point. It is the location of the reference point that determines whether a voltage is negative or positive.

Tracing the current flow provides a means for determining the voltage polarity. Figure 8–75 shows the same circuit with the polarities of the voltage drops and the direction of current flow indicated.

The current flows from the negative side of the battery to R_1. Tap A is at the same potential as the negative terminal of the battery since the slight voltage drop caused by the resistance of the conductor is disregarded; however, 20 volts of the source voltage are required to force the current through R_1 and this 20-volt drop has the polarity indicated. Stated another way, there are only 80 volts of electrical pressure left in the circuit on the ground side of R_1.

When the current reaches tap B, 30 more volts have been used to move the electrons through R_2, and in a similar manner the remaining 50 volts are used for R_3. But the voltages across R_2 and R_3 are positive voltages, since they are above ground potential.

Figure 8–76 shows the voltage divider used

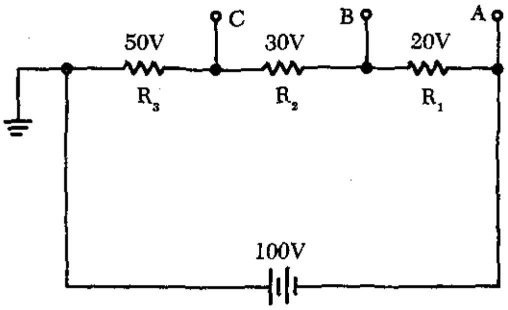


FIGURE 8-76. Voltage divider with changed ground.

previously. The voltage drops across the resistances are the same; however, the reference point (ground) has been changed. The voltage between ground and tap A is now a negative 100 volts, or the applied voltage. The voltage between ground and tap B is a negative 80 volts, and the voltage between ground and tap C is a negative 50 volts.

RHEOSTATS AND POTENTIOMETERS

The voltage dividers discussed thus far have consisted of resistors of various sizes across which a variety of voltage drops were developed. Rheostats and potentiometers are variable resistors which are sometimes used in connection with voltage dividers.

A rheostat is a variable resistor used to vary the amount of current flowing in a circuit. The rheostat is represented schematically as a two-terminal resistance with a sliding arm contact. Figure 8-77 shows a rheostat connected in series with an ordinary resistance in a series circuit. As the slider arm moves from point A to B, the amount of rheostat resistance (AB) is increased. Since the rheostat resistance and the fixed resistance are in series, the total resistance in the circuit also increases, and the current in the circuit decreases. On the other hand, if the slider arm is moved toward point A, the total resistance decreases and the current in the circuit increases.

The potentiometer is a variable resistor which has three terminals. Two ends and a slider arm are connected in a circuit. A potentiometer is used to vary the amount of voltage in a circuit and is one of the most common controls used in electrical and electronic equipment. Some examples are the volume control in radio receivers and the brightness control in television receivers.

In A of figure 8-78 a potentiometer is used to obtain a variable voltage from a fixed voltage source to apply to an electrical load. The voltage applied to the load is the voltage between points B and C. When the slider arm is moved to point A, the entire voltage is applied to the electrical device (load); when the arm is moved to point C, the voltage applied to the load is zero. The potentiometer makes possible the application of any voltage between zero and full voltage to the load.

The current flowing through the circuit of figure 8-78 leaves the negative terminal of the battery and divides, one part flowing through the lower portion of the potentiometer (points C to B) and the other part through the load. Both parts combine at point B and flow through the upper portion of the potentiometer (points B to A) back to the positive terminal of the battery. In B of figure 8-78, a potentiometer and its schematic symbol are shown.

In choosing a potentiometer resistance, consideration should be given to the amount of current drawn by the load as well as the current flow through the potentiometer at all settings of the slider arm. The energy of the current through the potentiometer is dissipated in the form of

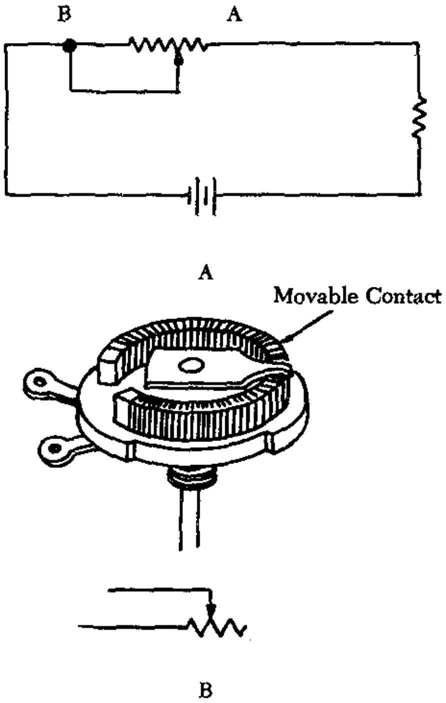
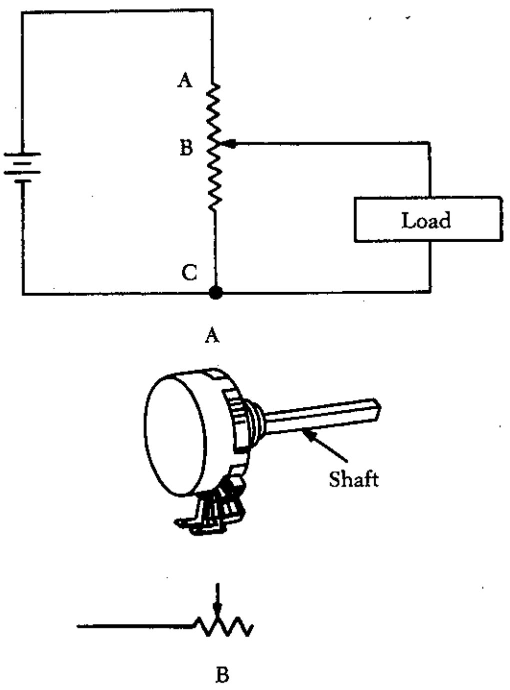


FIGURE 8-77. Rheostat.



FIGURER 8–78. Potentiometer.

heat. It is important to keep this wasted current as small as possible by making the resistance of the potentiometer as large as practicable. In most cases, the resistance of the potentiometer can be several times the resistance of the load.

Rheostats and potentiometers are constructed of a circular resistance material over which a sliding contact moves. The resistance may be distributed in many ways, and the method used determines the classification as either linear or tapered. The linear type provides a resistance evenly distributed over its entire length, while the tapered has more resistance per unit length at one end than at the other. As an example, a one-half turn of a linear rheostat places one half of the total resistance between either end and the slider, while a one-half turn of a tapered rheostat places one-tenth (or any desired fraction) of the total resistance between one end and the slider.

Prefixes

In any system of measurements, a single set of units is usually not sufficient for all the computations involved in electrical repair and maintenance. Small distances, for example, can usually be measured in inches, but larger distances are more meaningfully expressed in feet, yards, or miles. Since electrical values often vary from numbers that are a millionth part of a basic unit of measurement to very large values, it is often necessary to use a wide range of numbers to represent the values of such units as volts, amperes, or ohms. A series of prefixes which appear with the name of the unit have been devised for the various multiples or submultiples of the basic units. There are 12 of these prefixes, which are also known as conversion factors. Six of the most commonly used prefixes with a short definition of each are as follows:

Mega means one million (1,000,000).

Kilo means one thousand (1,000).

Centi means one-hundredth (1/100).

Milli means one-thousandth (1/1000).

Micro means one-millionth (1/1,000,000).

Micro micro means one-millionth-millionth (1/1,000,000,000,000).

One of the most extensively used conversion factors, kilo, can be used to explain the use of prefixes with basic units of measurement. Kilo means 1,000, and when used with volts is expressed as kilovolt, meaning 1,000 volts. The symbol for kilo is the letter "K". Thus, 1,000 volts is one kilovolt or 1KV. Conversely, one volt would equal one-thousandth of a KV, or 1/1000 KV. This could also be written 0.001 KV.

Similarly, the word "milli" means one-thousandth, and thus, 1 millivolt equals one-thousandth (1/1000) of a volt.

These prefixes may be used with all electrical units. They provide a convenient method for writing extremely large or small values. Most electrical formulas require the use of values expressed in basic units; therefore, all values must usually be converted before computation can be made. Figure 8–79 contains a conversion table which lists a number of the most commonly used electrical values.

1 ampere = 1,000,000 microamperes.
1 ampere = 1,000 milliamperes.
1 farad = 1,000,000,000,000 micromicrofarads.
1 farad = 1,000,000 microfarads.
1 farad = 1,000 millifarads.
1 henry = 1,000,000 microhenrys.
1 henry = 1,000 millihenrys.
1 kilovolt = 1,000 volts.
1 kilowatt = 1,000 watts.
1 megohm = 1,000,000 ohms.
1 microampere = .000001 ampere.
1 microfarad = .000001 farad.
1 microhm = .000001 ohm.
1 microvolt = .000001 volt.
1 microwatt = .000001 watt.
1 micromicrofarad = .000000000001 farad.
1 milliampere = .001 ampere.
1 millihenry = .001 henry.
1 millimho = .001 mho.
1 milliohm = .001 ohm.
1 millivolt = .001 volt.
1 milliwatt = .001 watt.
1 volt = 1,000,000 microvolts.
1 volt = 1,000 millivolts.
1 watt = 1,000 milliwatts.
1 watt = .001 kilowatt.

FIGURE 8–79. Conversion table.

Figure 8–80 contains a complete list of the multiples used to express electrical quantities, together with the prefixes and symbols used to represent each number.

MAGNETISM

Magnetism is so closely allied with electricity in the modern industrial world it can be safely stated that without magnetism the electrical world would not be possible. Knowledge of magnetism has existed for many centuries, but it was not until the eighteenth century that this stream of knowledge was joined with that of electricity by the discoveries of science.

The earliest known magnetism was the lodestone, a natural mineral found in Asia Minor. Today this substance is called magnetite or magnetic oxide of iron. When a piece of this ore is suspended horizontally by a thread or floated on wood in undisturbed water, it will align itself in a north-south direction. This characteristic led to its use as a compass and the name lodestone, meaning leading stone. Other than the earth itself, the lodestone is the only natural magnet. All other magnets are produced artifically.

From the earliest times a great deal was known about the elementary behavior of magnets. For example, it was known that the property of magnetism could be induced in an iron bar by stroking it with a lodestone. In addition, it was known that if the north-seeking end of a suspended magnet was brought near the north-seeking end of another, the magnets would repel each other. On the other hand, they found that a north-seeking and a south-seeking end would attract each other.

Magnetism is defined as the property of an object to attract certain metallic substances. In general, these substances are ferrous materials; that is, materials composed of iron or iron alloys, such as soft iron, steel, and alnico. These materials, sometimes called magnetic materials, today include at least three nonferrous materials: nickel, cobalt and gadolinium, which are magnetic to a limited degree. All other substances are considered nonmagnetic, and a few of these nonmagnetic substances can be classified as diamagnetic since they are repelled by both poles of a magnet.

Magnetism is an invisible force, the ultimate nature of which has not been fully determined.

Number	Prefix	Symbol
1,000,000,000,000	tera	t
1,000,000,000	giga	g
1,000,000	mega	m
1,000	kilo	k
100	hecto	h
10	deka	dk
0.1	deci	d
0.01	centi	c
0.001	milli	m
0.000,001	micro	u
0.000,000,001	nano	n
0.000,000,000,001	pico	p

FIGURE 8–80. Prefixes and symbols for multiples of basic quantities.

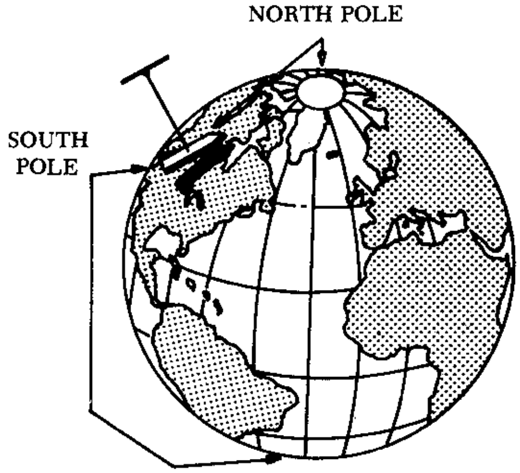


FIGURE 8-81. One end of magnetized strip points to the magnetic north pole.

It can best be described by the effects it produces. Examination of a simple bar magnet similar to that illustrated in figure 8-81 discloses some basic characteristics of all magnets. If the magnet is suspended to swing freely, it will align itself with the earth's magnetic poles. One end is labelled "N," meaning the north-seeking end or pole of the magnet. If the "N" end of a compass or magnet is referred to as north-seeking rather than north, there will be no conflict in referring to the pole it seeks, which is the north magnetic pole. The opposite end of the magnet, marked "S," is the south-seeking end and points to the south magnetic pole. Since the earth is a giant magnet, its poles attract the ends of the magnet. These poles are not located at the geographic poles.

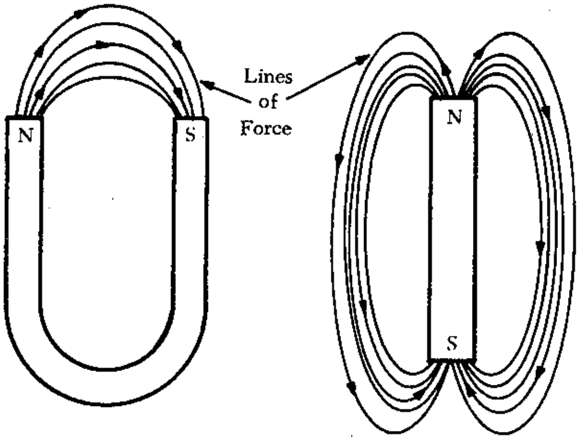
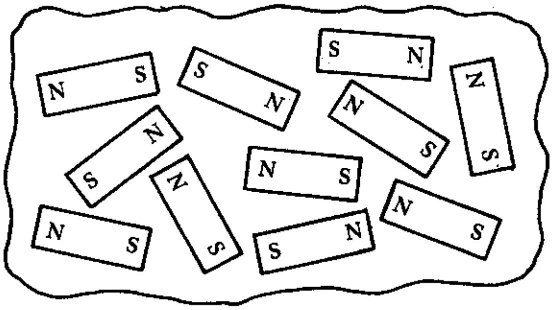
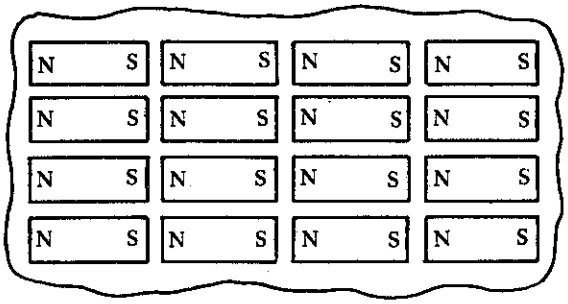


FIGURE 8-82. Magnetic field around magnets.



(A) Unmagnetized



(B) Magnetized

FIGURE 8-83. Arrangement of molecules in a piece of magnetic material.

The somewhat mysterious and completely invisible force of a magnet depends on a magnetic field that surrounds the magnet as illustrated in figure 8-82. This field always exists between the poles of a magnet, and will arrange itself to conform to the shape of any magnet.

The theory that explains the action of a magnet holds that each molecule making up the iron bar is itself a tiny magnet, with both north and south poles as illustrated in A of figure 8-83. These molecular magnets each possess a magnetic field, but in an unmagnetized state the molecules are arranged at random throughout the iron bar. If a magnetizing force, such as stroking with a lodestone, is applied to the unmagnetized bar, the molecular magnets rearrange themselves in line with the magnetic field of the lodestone, with all north ends of the magnets pointing in one direction and all south ends in the opposite direction. This is illustrated in B of figure 8-83. In such a configuration, the

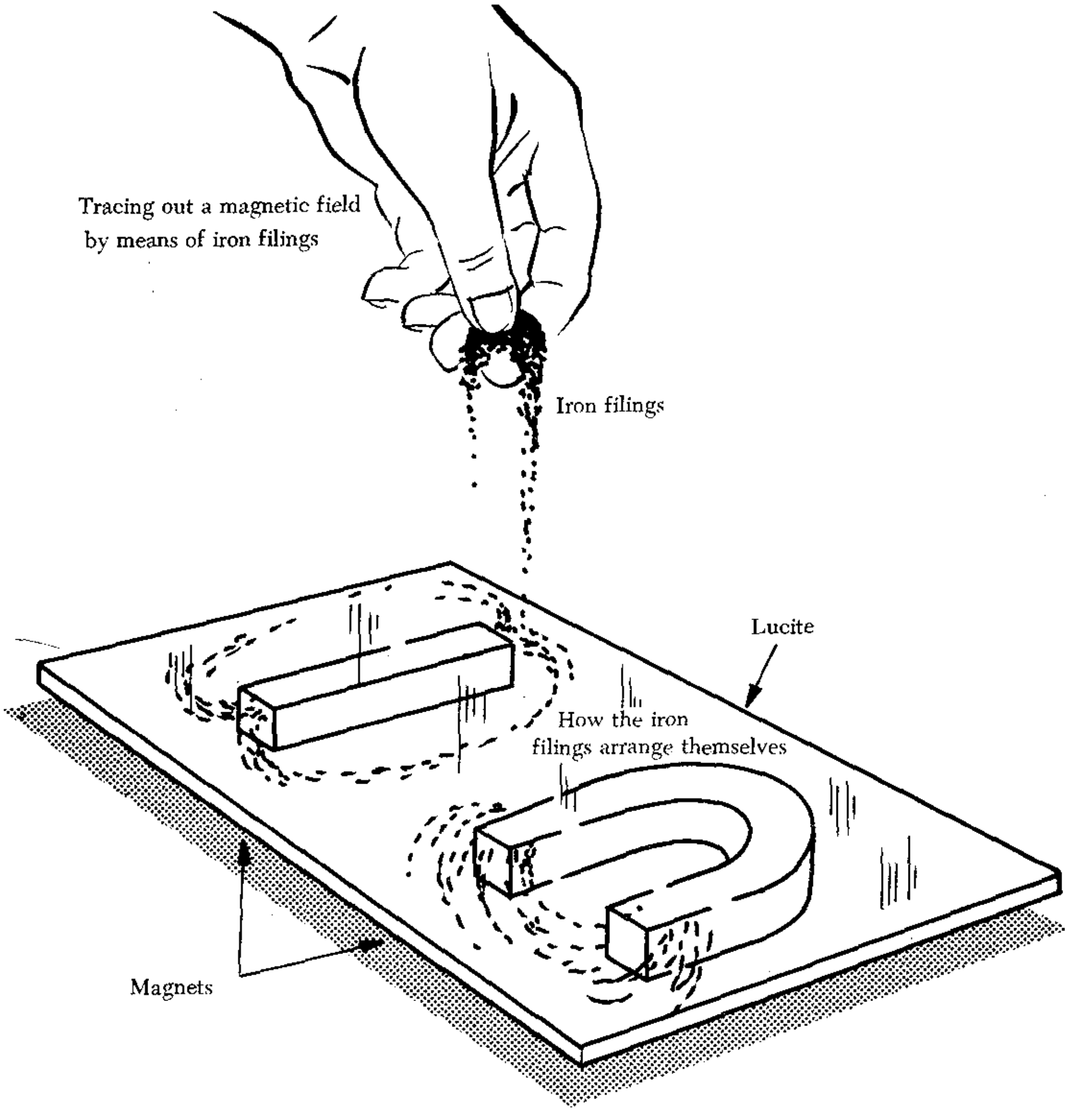


FIGURE 8–84. Tracing out a magnetic field with iron filings.

magnetic fields of the magnets combined to produce the total field of the magnetized bar.

When handling a magnet, avoid applying direct heat, or hammering or dropping it. Heating or sudden shock will cause misalignement of the molecules, causing the strength of a magnet to decrease. When a magnet is to be stored, devices known as "keeper bars" are installed to provide an easy path for flux lines from one pole to the other. This promotes the retention of the molecules in their north-south alignement.

The presence of the magnetic force or field around a magnet can best be demonstrated by the experiment illustrated in figure 8–84. A sheet of transparent material such as glass or lucite is placed over a bar magnet and iron filings are sprinkled slowly on this transparent shield. If the glass or lucite is tapped lightly, the iron filings will arrange themselves in a definite pattern around the bar, forming a series of lines from the north to south end of the bar to indicate the pattern of the magnetic field.

As shown, the field of a magnet is made up of many individual forces that appear as lines in the iron-filing demonstration. Although they are not "lines" in the ordinary sense, this word is used to describe the individual nature of the separate forces making up the entire magnetic field. These lines of force are also referred to as magnetic flux. They are separate and individual forces,

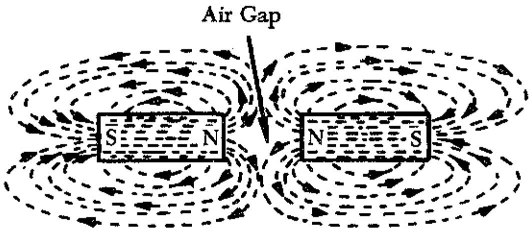


FIGURE 8–85. Like poles repel.

since one line will never cross another; indeed, they actually repel one another. They remain parallel to one another and resemble stretched rubber bands, since they are held in place around the bar by the internal magnetizing force of the magnet.

The demonstration with iron filings further shows that the magnetic field of a magnet is concentrated at the ends of the magnet. These areas of concentrated flux are called the north and south poles of the magnet. There is a limit to the number of lines of force that can be crowded into a magnet of a given size. When a magnetizing force is applied to a piece of magnetic material, a point is reached where no more lines of force can be induced or introduced. The material is then said to be saturated.

The characteristics of the magnetic flux can be demonstrated by tracing the flux patterns of two bar magnets with like poles together, as shown in figure 8–85. The two like poles repel one another because the lines of force will not cross each other. As the arrows on the individual lines indicate, the lines turn aside as the two like poles are brought near each other and travel in a path parallel to each other. Lines moving in this manner repel each other, causing the magnets as a whole to repel each other.

By reversing the position of one of the magnets, the attraction of unlike poles can be demonstrated, as shown in figure 8–86.

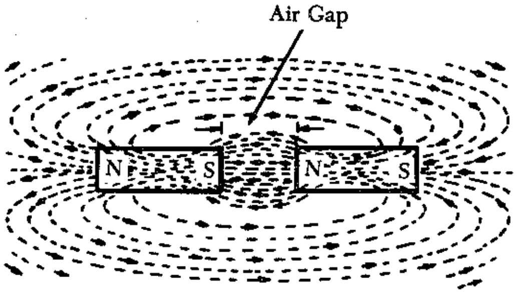


FIGURE 8–86. Unlike poles attract.

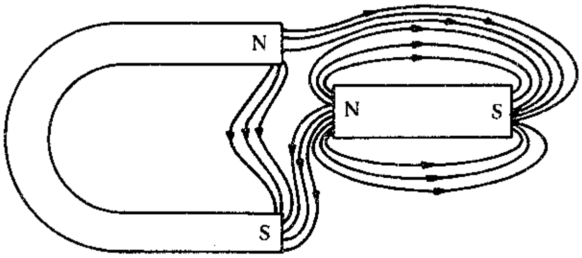


FIGURE 8–87. Bypassing flux lines.

As the unlike poles are brought near each other, the lines of force rearrange their paths and most of the flux leaving the north pole of one magnet enters the south pole of the other. The tendency of lines of force to repel each other is indicated by the bulging of the flux in the air gap between the two magnets.

To further demonstrate that lines of force will not cross one another, a bar magnet and a horseshoe magnet can be positioned to display a magnetic field similar to that of figure 8–87. The magnetic fields of the two magnets do not combine, but are re-arranged into a distorted flux pattern.

The two bar magnets may be held in the hands and the north poles brought near each other to demonstrate the force of repulsion between like poles. In a similar manner the two south poles can demonstrate this force. The force of attraction between unlike poles can be felt by bringing a south and a north end together, These experiments are illustrated in figure 8–88.

Figure 8–89 illustrates another characteristic of magnets. If the bar magnet is cut or broken into pieces, each piece immediately becomes a magnet itself, with a north and south pole. This feature supports the theory that each molecule is a magnet, since each successive division of the magnet produces still more magnets.

Since the magnetic lines of force form a continuous loop, they form a magnetic circuit. It is impossible to say where in the magnet they originate or start. Arbitrarily, it is assumed that all lines of force leave the north pole of any magnet and enter at the south pole.

There is no known insulator for magnetic flux, or lines of force, since they will pass through all materials. However, it has been found that they will pass through some materials more easily than others. Thus, it is posible to shield certain areas, such as instruments, from the effects

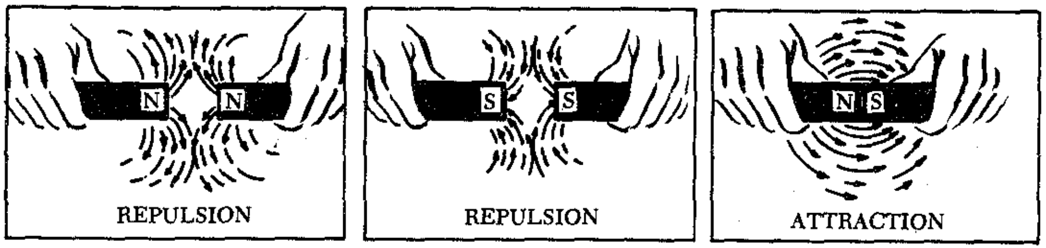


FIGURE 8–88. Repulsion and attraction of magnet poles.

of the flux by surrounding them with a material that offers an easier path for the lines of force. Figure 8–90 shows an instrument surrounded by a path of soft iron, which offers very little opposition to magnetic flux. The lines of force take the easier path, the path of greater permeability, and are guided away from the instrument.

Materials, such as soft iron and other ferrous metals, are said to have a high permeability, the measure of the ease with which magnetic flux can penetrate a material. The permeability scale is based on a perfect vacuum with a rating of one. Air and other nonmagnetic materials are so close to this that they are also considered to have a rating of one. The nonferrous metals having a permeability greater than one, such as nickel and cobalt, are called paramagnetic, while the term ferromagnetic is applied to iron and its alloys, which have by far the greatest permeability. Any substance, such as bismuth, having a permeability of less than one, is considered diamagnetic.

Reluctance, the measure of opposition to the lines of force through a material, can be compared to the resistance of an electrical circuit. The reluctance of soft iron, for instance, is much lower than that of air. Figure 8–91 demonstrates that a piece of soft iron placed near the field of a magnet can distort the lines of force, which follow the path of lowest reluctance through the soft iron.

The magnetic circuit can be compared in many respects to an electrical circuit. The magnetomotive force (m.m.f.), causing lines of force in the magnetic circuit, can be compared to the electromotive force or electrical pressure of an electrical circuit. The m.m.f. is measured in gilberts, symbolized by the capital letter "F." The symbol for the intensity of the lines of force, or flux, is the Greek letter phi (ϕ), and the unit of field intensity is the gauss. An individual line of force, called a maxwell, in an area of one square centimeter produces a field intensity of one gauss. Using reluctance rather than permeability, the law for magnetic circuits can be stated: A magnetomotive force of one gilbert will cause one maxwell, or line of force, to be set up in a material when the reluctance of the material is one.

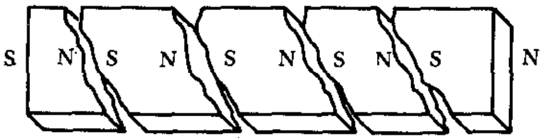


FIGURE 8–89. Magnetic poles in a broken magnet.

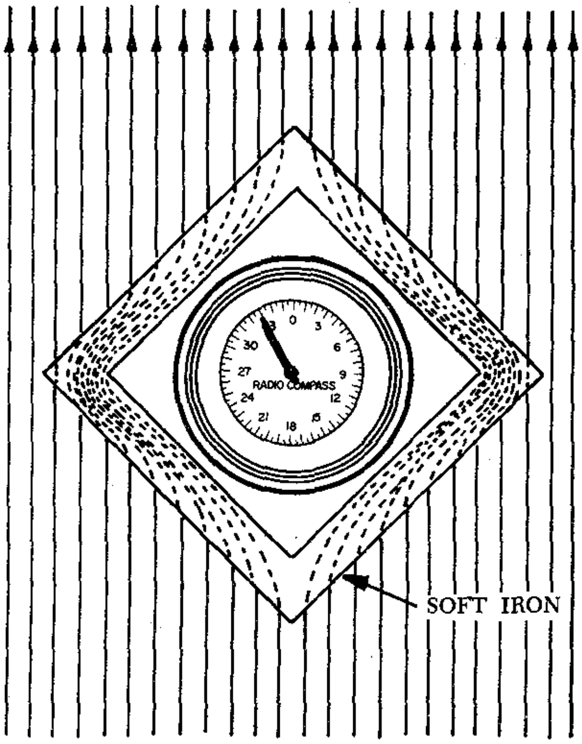


FIGURE 8–90. Magnetic shield.

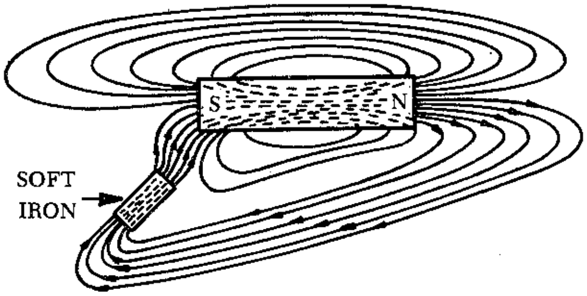


FIGURE 8–91. Effect of a magnetic substance in a magnetic field.

Types of Magnets

Magnets are either natural or artifical. Since naturally occurring magnets or lodestones have no practical use, all magnets considered in this study are artifical or man-made. Artifical magnets can be further classified as permanent magnets, which retain their magnetism long after the magnetizing force has been removed, and temporary magnets, which quickly lose most of their magnetism when the external magnetizing force is removed.

Hard steel has long been used to make permanent magnets, but magnets of even better quality are now available from various alloys. Alnico, an alloy of iron, alluminum, nickel and cobalt, is considered one of the very best. Others with excellent magnetic qualities are alloys such as Remalloy and Permendur.

The old method of producing a magnet by stroking a piece of steel or iron with a natural magnet has been replaced by other means. A piece of metal placed in contact with, or even near, a magnet will become magnetized by induction and the process can be accelerated by heating the metal and then placing it in a magnetic field to cool. Magnets can also be produced by placing the metal to be magnetized in a strong magnetic field and striking it several times with a hammer, This process can be used to produce permanent magnets from metals such as hard steel.

The ability of a magnet to hold its magnetism varies greatly with the type of metal and is known as retentivity. Magnets made of soft iron are very eaily magnetized but quickly lose most of their magnetism when the external magnetizing force is removed. The small amount of magnetism remaining, called residual magnetism, is of great importance in such electrical applications as generator operation.

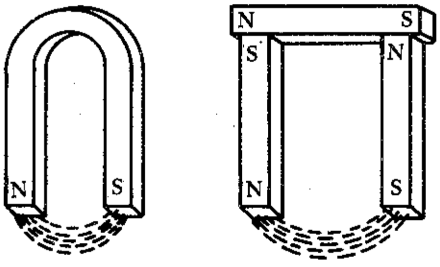


FIGURE 8–92. Two forms of horseshoe magnets.

Horseshoe magnets are commonly manufactured in two forms, as shown in figure 8–92. The most common type is made from a long bar curved into a horseshoe shape, while a variation of this type consists of two bars connected by a third bar, or yoke.

Magnets can be made in many different shapes, such as balls, cylinders, or disks. One special type of magnet is the ring magnet, or Gramme ring, often used in instruments. This is a closed-loop magnet, similar to the type used in transformer cores, and is the only type that has no poles.

Sometimes special applications require that the field of force lie through the thickness rather than the length of a piece of metal. Such magnets are called flat magnets and are used as pole pieces in generators and motors.

Electromagnetism

In 1819, the Danish physicist, Hans Christian Oersted, discovered that the needle of a compass brought near a current-carrying conductor would be deflected. When the current flow stopped, the compass needle returned to its original position. This important discovery demonstrated a relationship between electricity and magnetism that led to the electromagnet and to many of the inventions on which modern industry is based.

Oersted discovered that the magnetic field had no connection with the conductor in which the electrons were flowing, because the conductor was made of nonmagnetic copper. The magnetic field around the conductor was created by the electrons moving through the wire. Since a magnetic field accompanies a charged particle, the greater the current flow the greater the magnetic field. Figure 8–93 illustrates the magnetic field around a current-carrying wire. A series of concentric circles around the conductor represent the field, which,

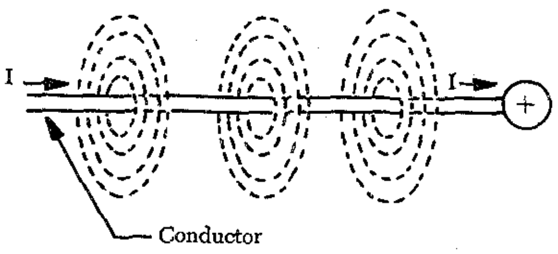


FIGURE 8–93. Magnetic field formed around a conductor in which current is flowing.

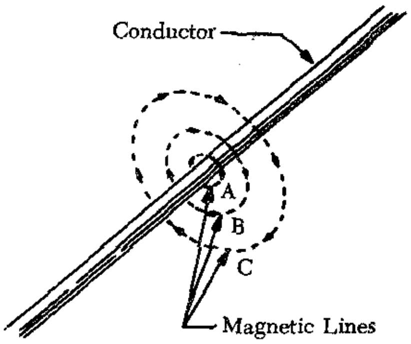


FIGURE 8–94. Expansion of magnetic field as current increases.

if all the lines were shown, would appear more as a continuous cylinder of such circles around the conductor.

As long as current flows in the conductor, the lines of force remain around it, as shown in figure 8–94. If a small current flows through the conductor, there will be a line of force extending out to circle A. If the current flow is increased, the line of force will increase in size to circle B, and a further increase in current will expand it to circle C. As the original line (circle) of force expands from circle A to B, a new line of force will appear at circle A. As the current flow increases, the number of circles of force increases, expanding the outer circles farther from the surface of the current-carrying conductor.

If the current flow is a steady nonvarying direct current, the magnetic field remains stationary. When the current stops, the magnetic field collapses and the magnetism around the conductor disappears.

A compass needle is used to demonstrate the direction of the magnetic field around a current-carrying conductor. A of figure 8–95 shows a compass needle positioned at right angles to, and approximately one inch from, a current-carrying conductor. If no current were flowing, the north-seeking end of the compass needle would point toward the earth's magnetic pole. When current flows, the needle lines itself up at right angles to a radius drawn from the conductor. Since the compass needle is a small magnet, with lines of force extending from south to north inside the metal, it will turn until the direction of these lines agrees with the direction of the lines of force around the conductor. As the compass needle is moved around the conductor, it will maintain itself in a position at right angles to the conductor, indicating that the magnetic field around a current-carrying conductor is circular. As shown in B of figure 8–95, when the direction of current flow through the conductor is reversed, the compass needle will point in the opposite direction, indicating the magnetic field has reversed its direction.

A method used to determine the direction of the lines of force when the direction of the current flow is known, is shown in figure 8–96. If the conductor is grasped in the left hand, with the thumb pointing in the direction of current flow, the fingers will be wrapped around the conductor in the same direction as the lines of the magnetic field. This is called the left-hand rule.

Although it has been stated that the lines of force have direction, this should not be construed to mean that the lines have motion in a circular direction around the conductor. Although the lines of force tend to act in a clockwise or counterclockwise direction they are not revolving around the conductor.

Since current flows from negative to positive, many illustrations indicate current direction with a dot symbol on the end of the conductor when the electrons are flowing toward and a plus sign when the current is flowing away from the observer. This is illustrated in figure 8–97.

When a wire is bent into a loop and an electric current flows through it, the left-hand rule remains valid, as shown in figure 8–98.

If the wire is coiled into two loops, many of the lines of force become large enough to include both loops. Lines of force go through the loops in the same direction, circle around the outside of the two coils, and come in at the opposite end. (See figure 8–99.)

When a wire contains many such loops, it is called a coil. The lines of force form a pattern

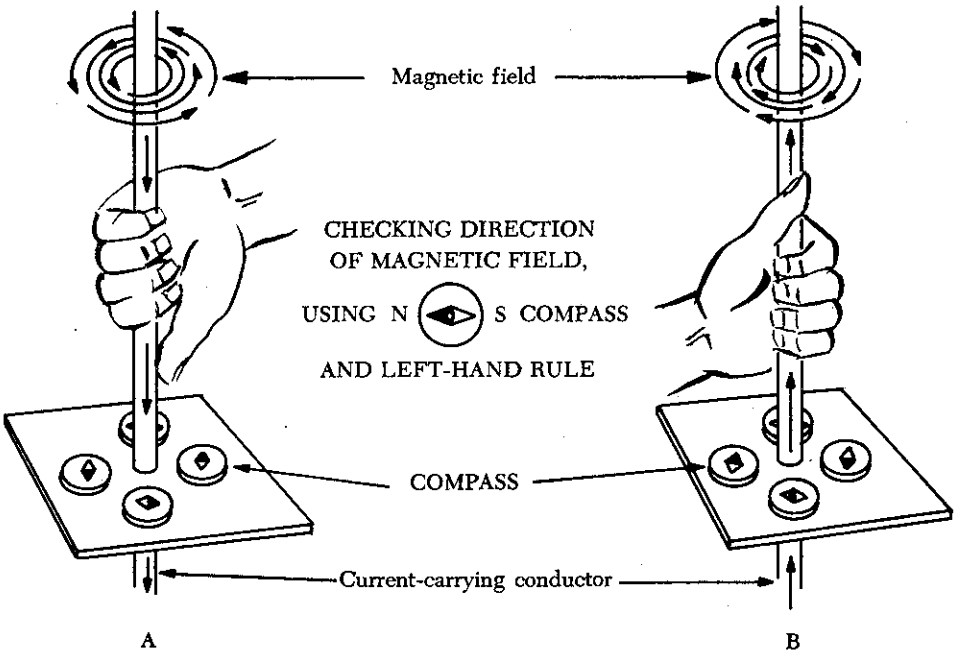


FIGURE 8–95. Magnetic field around a current-carrying conductor.

through all the loops, causing a high concentration of flux lines through the center of the coil. (See figure 8–100.)

In a coil made from loops of a conductor, many of the lines of force are dissipated between the loops of the coil. By placing a soft iron bar inside the coil, the lines of force will be concentrated in the center of the coil, since soft iron has a greater permeability than air. (See figure 8–101.) This combination of an iron core in a coil of wire loops, or turns, is called an electromagnet, since the poles (ends) of the coil possess the characteristics of a bar magnet.

The addition of the soft iron core does two things for the current-carrying coil. First, the magnetic flux is increased, and second, the flux lines are more highly concentrated.

When direct current flows through the coil, the core will become magnetized with the same polarity (location of north and south poles) as the coil would have without the core. If the current is reversed, the polarity will also be reversed.

The polarity of the electromagnet is determined by the left-hand rule in the same manner as the polarity of the coil without the core was determined. If the coil is grasped in the left hand in such a manner that the fingers curve around the coil in the direction of electron flow (minus to plus), the thumb will point in the direction of the north pole. (See figure 8–102.)

The strength of the magnetic field of the electromagnet can be increased by either increasing the flow of current or the number of loops in the wire. Doubling the current flow approximately doubles the strength of the field, and in a similar manner, doubling the number of loops approximately doubles magnetic field strength. Finally, the type metal in the core is a factor in the field strength of the electromagnet.

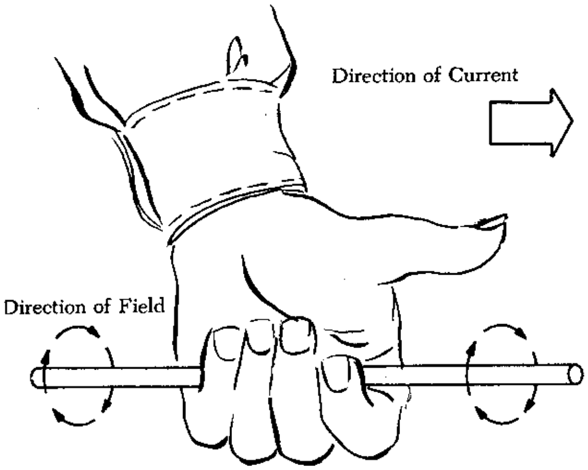


FIGURE 8–96. Left-hand rule.

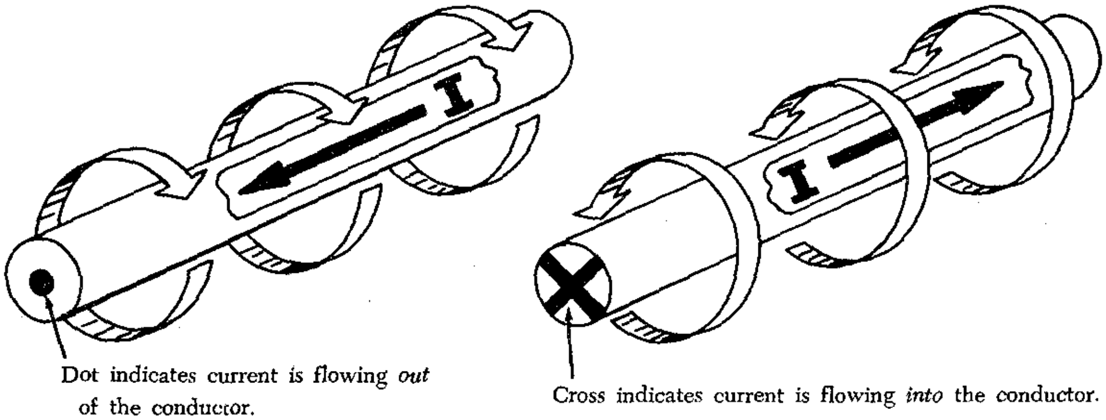


FIGURE 8–97. Direction of current flow in a conductor.

A soft-iron bar is attracted to either pole of a permanent magnet and, likewise, is attracted by a current-carrying coil. As shown in figure 8–103, the lines of force extend through the soft iron, magnetizing it by induction and pulling the iron bar toward the coil. If the bar is free to move, it will be drawn into the coil to a position near the center where the field is strongest.

Electromagnets are used in electrical instruments, motors, generators, relays, and other devices. Some electromagnetic devices operate on the principle that an iron core held away from the center of a coil will be rapidly pulled into a center position when the coil is energized. This principle is used in the solenoid, also called solenoid switch or relay, in which the iron core is spring-loaded off center and moves to complete a circuit when the coil is energized.

The application of the solenoid is shown in figure 8–104, where it is a solenoid relay. When the cockpit switch is closed, the energized coil pulls the core switch down, which completes the circuit to the motor. Since this solenoid relay operates on low current, it eliminates high-amperage wiring in the cockpit of the aircraft.

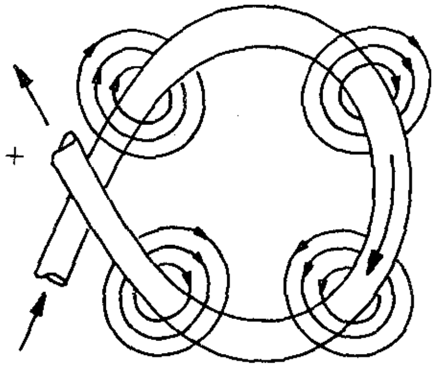


FIGURE 8–98. Magnetic field around a looped conductor.

The solenoid-and-plunger type of magnet in various forms is used extensively to open circuit breakers automatically, when the load current becomes excessive, and to operate valves, magnetic brakes, and many other devices. The armature-type of electromagnet also has extensive applications. For this type of magnet, the coil is wound on and insulated from the iron core; the core is not movable. When current flows through the coil, the iron core becomes magnetized and causes a pivoted soft-iron armature located near the electromagnet to be attracted to it. These magnets are used in doorbells, relays, circuit breakers, telephone receivers, and many other devices.

STORAGE BATTERIES

There are two sources of electrical energy in an aircraft: (1) The generator, which converts mechanical energy into electrical energy, and (2) the battery, which converts chemical energy into electrical energy. During normal engine operation, electrical energy is taken from the engine-driven generator. The storage battery is used as an auxiliary source of power when the generator is not operating.

When the generators are operating at a speed too low to supply electrical energy for the airplane, electrical power is taken from the battery and the battery discharges, losing some of the chemical energy stored in it. During flight, the airplane

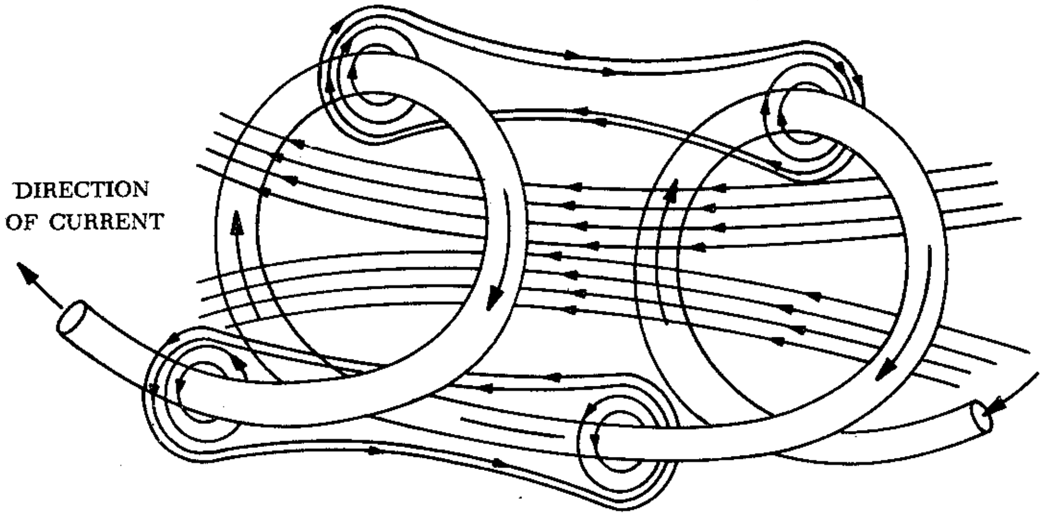


FIGURE 8–99. Magnetic field around a conductor with two loops.

generator charges the battery over a long period of time and restores the chemical energy. Lead-acid and nickel-cadmium batteries are the types of storage batteries in general use.

LEAD-ACID BATTERIES

Lead-acid batteries used in aircraft are similar to automobile batteries. The cells of a battery are connected in series. Each cell contains positive plates of lead peroxide, negative plates of spongy lead, and electrolyte (sulphuric acid and water). In discharging, the chemical energy stored in the battery is changed to electrical energy; in charging, the electrical energy supplied to the battery is changed to chemical energy and stored. It is possible to charge a storage battery many times before it deteriorates permanently.

Lead-acid Cell Construction

The components of a typical lead-acid cell are shown in figure 8–105. Each plate consists of a framework called a grid, made of lead and antimony, to which the active material (spongy lead or lead peroxide) is attached. The positive and negative plates, (1) of figure 8–105, are so assembled that each positive plate is between two negative plates. Thus, the end plate in each cell is a negative plate. Between the plates are

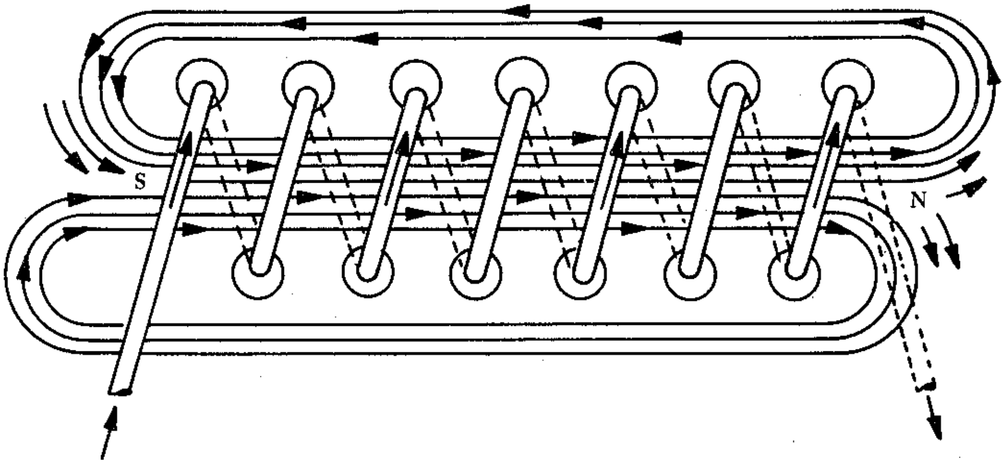


FIGURE 8–100. Magnetic field of a coil.

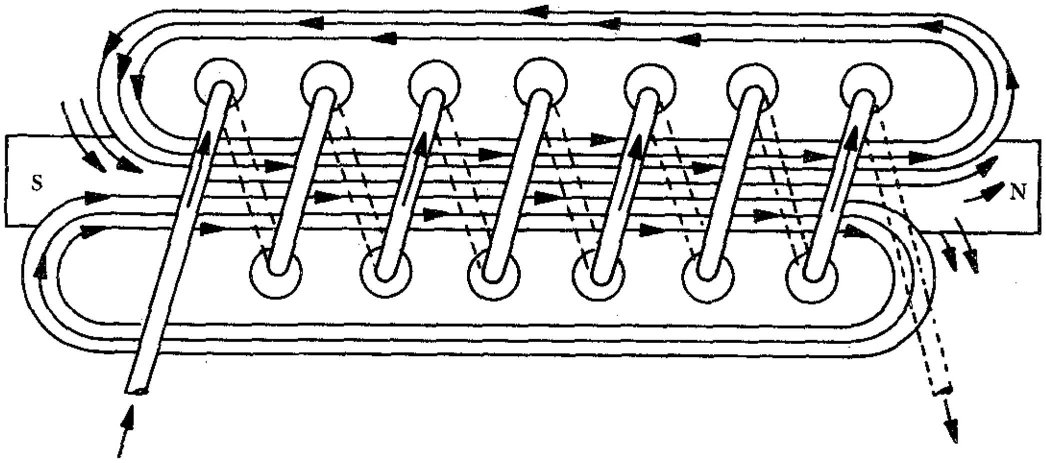


FIGURE 8–101. Electromagnet.

porous separators (7) which keep the positive and negative plates from touching each other and and shorting out the cell. The separators have vertical ribs on the side facing the positive plate. This construction permits the electrolyte to circulate freely around the plates. In addition, it provides a path for sediment to settle to the bottom of the cell.

Each cell is sealed in a hard rubber casing through the top of which are terminal posts and a hole into which is screwed a nonspill vent cap (4). The hole provides access for testing the strength of the electrolyte and adding water. The vent plug permits gases to escape from the cell with a minimum of leakage of electrolyte, regardless of the position the airplane might assume. In figure 8–106, the construction of the vent plug is shown. In level flight, the lead weight permits venting of gases through a small hole. In inverted flight, this hole is covered by the lead weight.

The individual cells of the battery are connected in series by means of cell straps, as illustrated in figure 8–107. The complete assembly is enclosed in an acid-resisting metal container (battery box), which serves as electrical shielding and mechanical protection. The battery box has a removable top. It also has a vent-tube nipple at each end. When the battery is installed in an airplane, a vent tube is attached to each nipple. One tube is the intake tube and is exposed to the slipstream. The other is the exhaust vent tube and is attached to the battery drain sump, which is a glass jar containing a felt pad moistened with a concentrated solution of sodium bicarbonate (baking soda). With this arrangement, the airstream is directed through the battery case where battery gases are picked up, neutralized in the sump, and then expelled overboard without damage to the airplane.

To facilitate installation and removal of the battery in some aircraft, a quick-disconnect assembly is used to connect the power leads to the

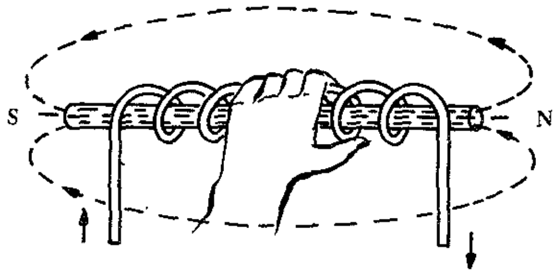


FIGURE 8–102. Left-hand rule applied to a coil.

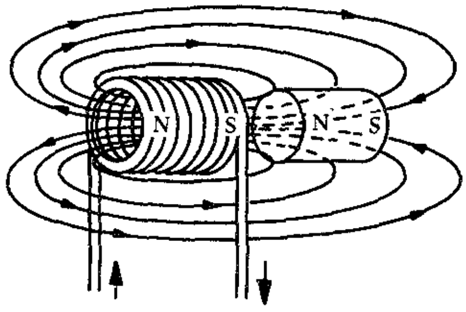


FIGURE 8–103. Solenoid with iron core.

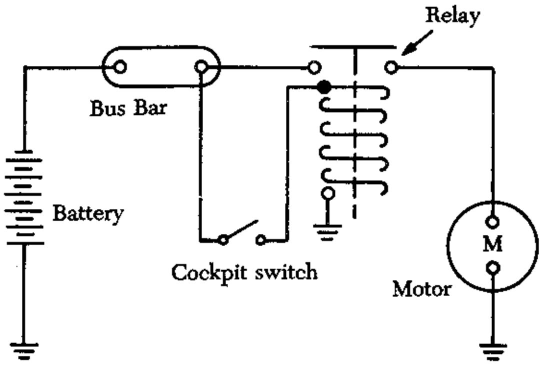
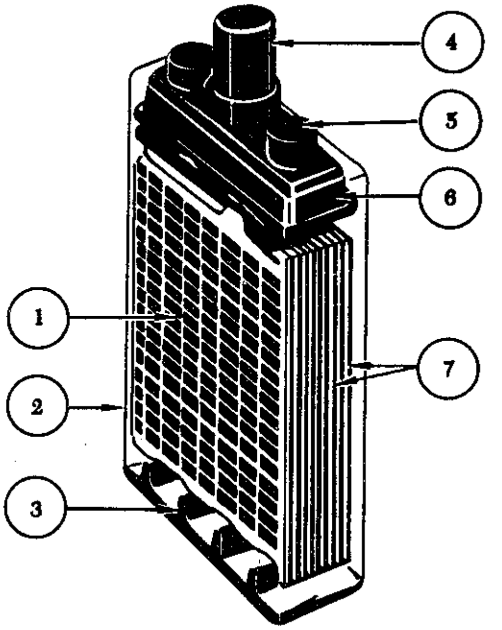


FIGURE 8–104. Use of a solenoid in a circuit.

battery. This assembly, which is shown in figure 8–108, attaches the battery leads in the aircraft to a receptacle mounted on the side of the battery. The receptacle covers the battery terminal posts and prevents accidental shorting during the installation and removal of the battery. The plug consists of a socket and a handwheel with a course-pitch thread. It can be readily connected to the receptacle by the handwheel. Another advantage of this assembly is that the plug can be installed in only one position, eliminating the possibility of reversing the battery leads.



1. Plates
2. Cell container
3. Supporting ribs
4. Vent cap
5. Terminal post
6. Cell cover
7. Separators

FIGURE 8–105. Lead-acid cell construction.

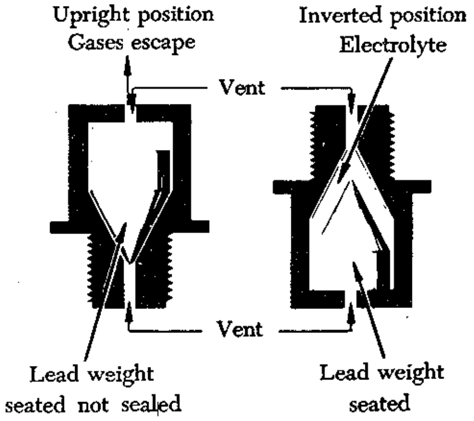


FIGURE 8–106. Nonspill battery vent plug.

Operation of Lead-acid Cells

A lead-acid cell contains positive plates coated with lead peroxide (PbO_2); negative plates made of lead (Pb); and a liquid electrolyte, consisting of sulphuric acid (H_2SO_4) and water (H_2O). During discharge, lead sulfate ($PbSO_4$) is formed on both the positive and negative plates, the acid content of the electrolyte is decreased, and its water content is increased. As discharge continues, the amount of lead sulfate on the plates increases until the sulfate coatings become so thick that the weakened electrolyte cannot effectively reach the active materials (lead and lead peroxide). When this happens, chemical reaction is retarded and the output of the cell is reduced. In practice, the cell is not permitted to be discharged to this extent because thick coatings of lead sulfate are difficult to remove in charging. Additionally, a cell ap-

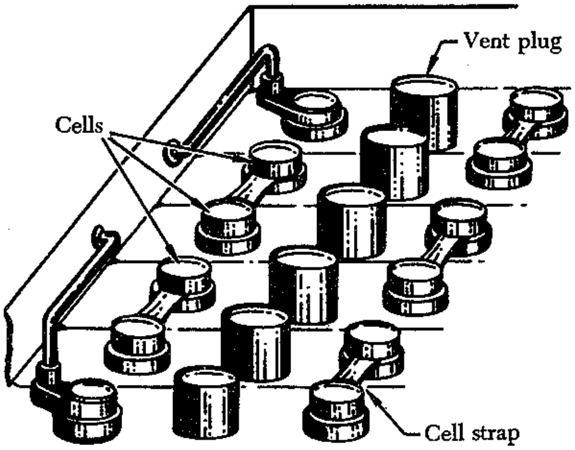


FIGURE 8–107. Connection of storage battery.

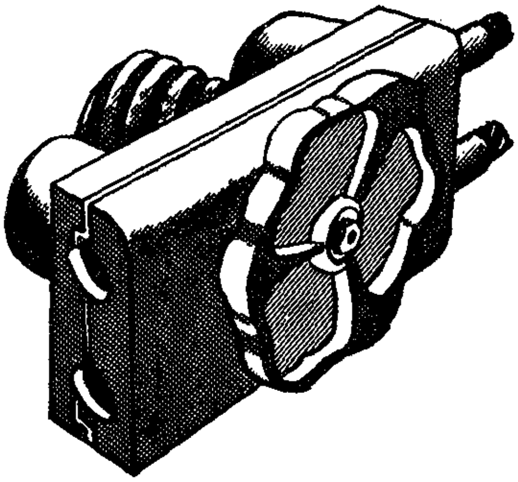


FIGURE 8–108. A battery quick-disconnect assembly.

proaching a state of total discharge is of little use because the high internal resistance (*IR*) caused by the sulfate coatings on its plates reduces the current to a value too low for practical use.

When a cell is being charged, lead sulfate is removed from both the positive and negative plates, and sulphuric acid is again formed. In the process, the water content of the electrolyte is decreased and the density of the electrolyte is increased.

The open-circuit voltage of a lead-acid cell, that is, its voltage when there is no load drawing current, is approximately 2.2 volts. This voltage is the same for every lead-acid cell regardless of its plate size and remains at this value until the cell is practically dead, regardless of its state of discharge. When the cell approaches total discharge, its voltage begins to drop rapidly.

The closed-circuit voltage of a cell, that is, its voltage under load, decreases gradually as the cell is discharged. This gradual decrease in terminal voltage is due to a gradual increase in the internal resistance of the cell caused by sulphation of the plates. At the end of normal discharge, the internal resistance of a lead-acid cell is more than twice as high as it is when fully charged. The difference between the open-circuit and closed-circuit terminal voltages is due to the voltage drop inside the cell. This is equal to the current the load draws multiplied by the internal resistance in the cell. Therefore, the discharging voltage that a lead-acid cell can supply under closed-circuit conditions is equal to the open-circuit voltage of the cell minus the *IR* drop in the cell.

To give a high discharge current and a high terminal voltage under load, a battery must have low internal resistance. This characteristic can be achieved through extensive plate area. Therefore, each cell contains several sets of plates. All the positive plates of a cell are connected by one connecting bar, and all the negative plates by another. Thus, the plates are connected in parallel, further decreasing the internal resistance of the cell. The open circuit cell voltage is not affected; it remains the same as that of a single pair of plates.

Lead-acid Battery Ratings

The voltage of a battery is determined by the number of cells connected in series to form the battery. Although the voltage of one lead-acid cell just removed from a charger is approximately 2.2 volts, a lead-acid cell is normally rated at only 2 volts, because it soon drops to that value. A battery rated at 12 volts consists of 6 lead-acid cells connected in series, and a battery rated at 24 volts is composed of 12 cells.

The capacity of a storage battery is rated in ampere-hours (amperes furnished by the battery times the amount of time current can be drawn). This rating indicates how long the battery may be used at a given rate before it becomes completely discharged.

Theoretically, a 100 ampere-hour battery will furnish 100 amperes for 1 hour, 50 amperes for 2 hours, or 20 amperes for 5 hours. Actually, the ampere-hour output of a particular battery depends on the rate at which it is discharged. Heavy discharge current heats the battery and decreases its efficiency and total ampere-hour output. For airplane batteries, a period of 5 hours has been established as the discharge time in rating battery capacity, However, this time of 5 hours is only a basis for rating and does not necessarily mean the length of time during which the battery is expected to furnish current. Under actual service conditions, the battery can be completely discharged within a few minutes, or it may never be discharged if the generator provides sufficient charge.

The ampere-hour capacity of a battery depends upon its total effective plate area. Connecting batteries in parallel increases ampere-hour capacity. Connecting batteries in series increases the total voltage but not the ampere-hour capacity. In multiengine airplanes, where more