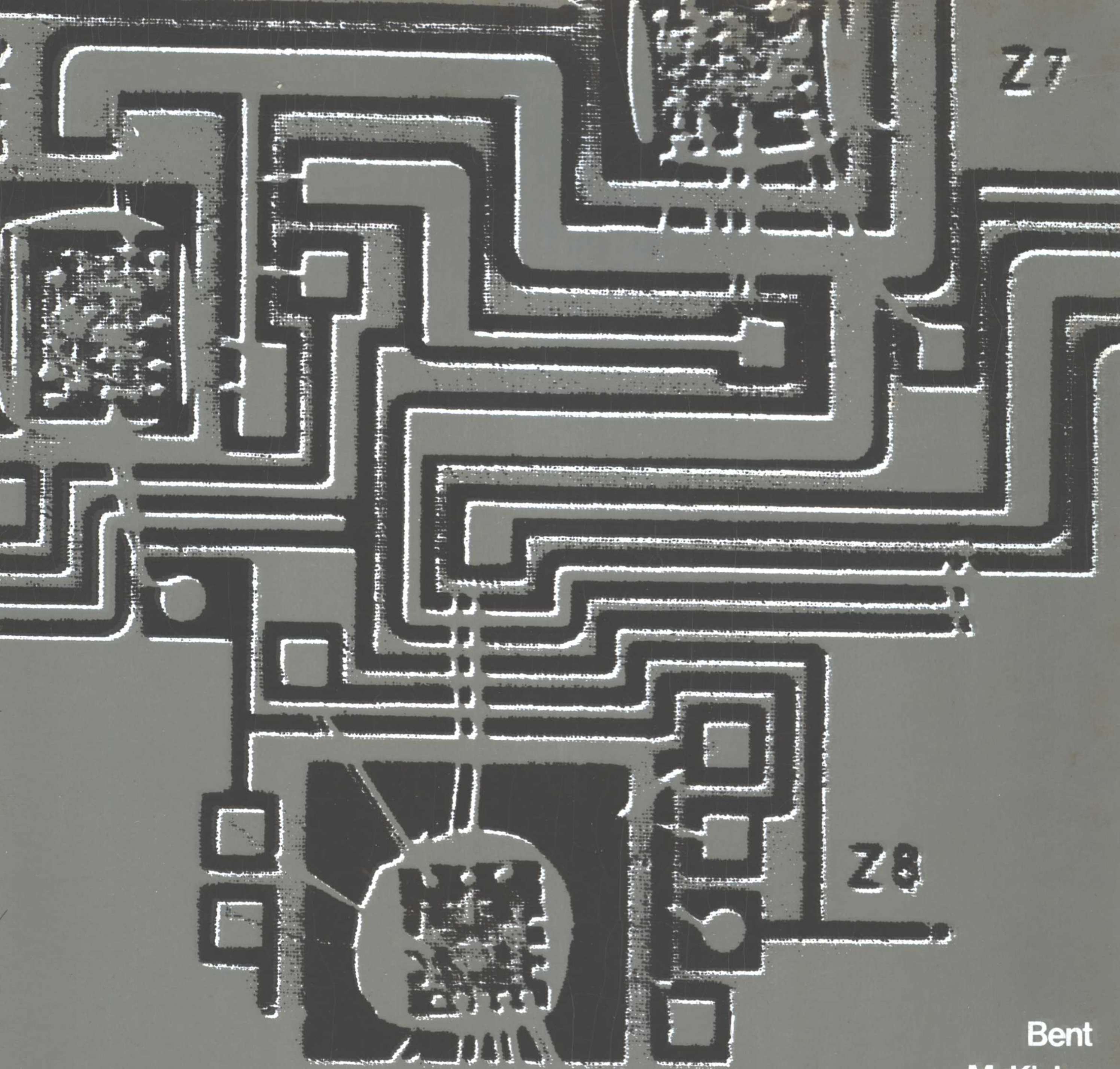

Bent
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Aircraft Electricity and Electronics

Third Edition

AIRCRAFT ELECTRICITY AND ELECTRONICS

Third Edition

Ralph D. Bent
James L. McKinley

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PREFACE

Aircraft Electricity and Electronics is one of the four texts in the Aviation Technology Series. This edition has been revised to include material which, when used in connection with classroom discussions, lectures, demonstrations, and practical application, should assist the student in attaining the proficiency levels defined in current Federal Aviation regulations.

In preparing this edition, the authors have reviewed at length *A National Study of the Aviation Mechanics Occupation* together with FAR Part 147 and FAA Advisory Circulars 65-2C and 43.23-1A. In addition, numerous suggestions and recommendations were solicited and received from aviation instructors, aircraft manufacturers, aviation operators, and maintenance specialists. Both the new material and the revised sequence of chapters reflect the composite result of all these sources.

This textbook provides thorough coverage of electrical and electronic theory at a level which may be easily understood by the student who does not have a knowledge of advanced mathematics. Following the chapters explaining fundamental theory, the applications to electrical and electronic systems are described. Although a detailed study of electronic systems and solid-state devices as applied to microelectronics is beyond the scope of this text, the last several chapters provide descriptions of these systems and devices as applied to modern aircraft needs. Electronics as applied to aircraft is usually termed *avionics* which is a contraction of *aviation electronics*.

In the earlier sections of the text, specific information is given concerning typical aircraft electrical equipment, power systems, and basic electronic circuits. A thorough study of these portions of the text will give the technician a solid foundation on which to build for more advanced work in electric and electronic technology. The later sections of the text provide general information on the application of avionics in aircraft.

For the person who is not an electrical or avionics specialist but who is assigned to work on equipment in which electrical and avionic systems are installed, the information contained in this text will provide an increased appreciation of the systems and their application to aircraft.

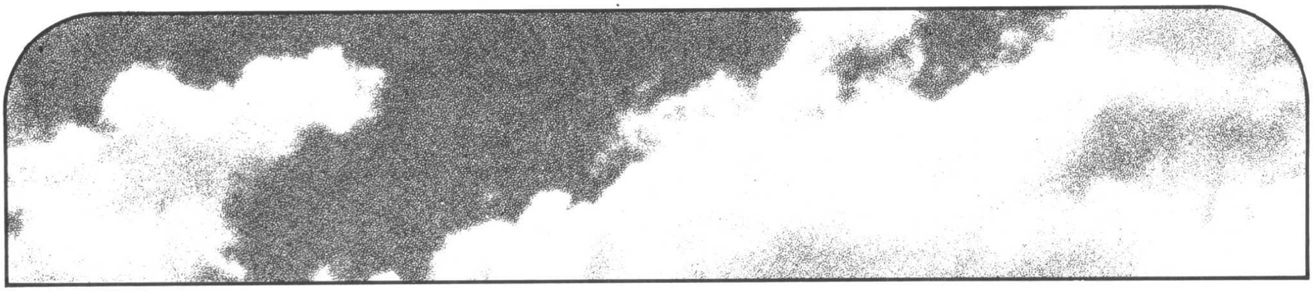
Each topic in the *Aviation Technology Series* has been explained in a logical sequence so that the student may advance step by step and build a solid foundation for increased learning. Numerous pictures, charts, and drawings should give students an enhanced understanding of the explanations and descriptions included in each text.

The subjects in the *Aviation Technology Series* have been organized to provide a wealth of classroom material for instructors in public and private technical schools, training departments of aircraft manufacturing companies, vocational schools, high schools, and technical departments of colleges. The series should also be of substantial value to those who seek self development in aviation technology.

Ralph D. Bent
James L. McKinley

CONTENTS

CHAPTER I



Fundamentals of Electricity

This present period in history may well be called *the age of electronics* because electricity and electronics have become vital in every facet of modern technology. This is particularly true in the aviation and aerospace fields because all modern aircraft and spacecraft are very largely dependent upon electronics and electricity for communications, navigation, and control. **Electronics** is merely a special application of electricity wherein precise manipulation of electrons is employed to control electric power for a vast number of functions.

Airframe and powerplant maintenance technicians are not usually required to have an extensive knowledge of electronic phenomena; however, they should understand the basic principles of electricity and electronics and be able to perform a variety of service operations involved in the installation of electric and electronic equipment on an airplane. The repair, overhaul, and testing of electronic equipment is usually performed by *avionic* specialists who have had extensive training in this type of work.

Previous to the last century, little was known concerning the nature of electricity. Its manifestation in the form of lightning was considered by many to be a demonstration of divine displeasure. During the last century, the causes of electrical phenomena have been accurately determined, and we are now able to employ electricity to perform a multitude of tasks.

Today electricity is so common that we take it for granted. Without it there would be no modern automobiles, refrigerators, electric irons, electric lights, streetcars, airplanes, missiles, spacecraft, radios, x-ray, telephones, or television. Life, in the modern sense, could not continue; we would soon revert to the horse-and-buggy era.

One function of electricity in an airplane is to ignite the fuel-air charge in the engine. Electricity for this purpose is supplied by magnetos coupled to the engine. In the case of gas-turbine engines such as turbojets or turboprops, electrical ignition is needed only at the time of starting the engines. In addition to providing engine ignition, electricity supplies light, heat, and power. For example, it operates position lights, identification lights, landing lights, cabin lights, instrument lights, heaters, retractable landing gear, wing flaps, engine cowl flaps, radio, instruments, and navigation equipment. Airliners contain many miles of electric wiring and hundreds of electric and electronic components; hence it is obvious that any person engaged in the servicing, operation, maintenance, or design of such aircraft must have a thorough understanding of electrical principles. This applies to pilots, aircraft and powerplant technicians, instrument technicians, flight engineers, design engineers, maintenance engineers, and many others interested in the technical aspects of aircraft operation and maintenance.

THE ELECTRON THEORY

Many persons who are unfamiliar with electricity believe that an understanding of the subject is extremely difficult to attain and that only a few individuals of superior intelligence can hope to learn much about it. This is not true. A few hours of study will enable almost anyone with sufficient interest to understand the basic principles. These principles are Ohm's law, magnetism, electromagnetic induction and inductance, capacitance, and the nature of direct and alternating currents. These fundamentals are not difficult to master, and almost all electrical applications and phenomena may be explained in terms of these principles.

MOLECULES AND ATOMS

Matter is defined as anything that occupies space; hence everything that we can see and feel constitutes matter. It is now universally accepted that matter is composed of molecules, which, in turn, are composed of atoms. If a quantity of a common substance, such as water, is divided in half, and the half is then divided, and the resulting quarter divided, and so on, a point will be reached where any further division will change the nature of the water and turn it into something else. The smallest particle into which any compound can be divided and still retain its identity is called a **molecule.**

If a molecule of a substance is divided, it will be found to consist of particles called **atoms.** An atom is the smallest possible particle of an element, and until recently it was considered impossible to divide or destroy an atom.

There are more than 100 recognized elements, several of which have been artificially created from various radioactive elements. An **element** is a substance that cannot be separated into different substances except by nuclear disintegration. Common elements are iron, oxygen, aluminum, hydrogen, copper, lead, gold, silver, and so on. The smallest division of any of these elements will still have the properties of that element.

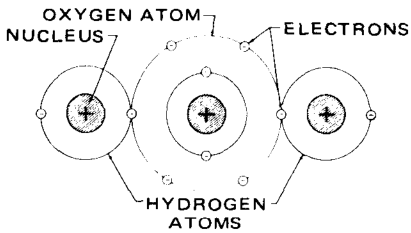


Fig. 1-1 Drawing to illustrate a water molecule.

A **compound** is a chemical combination of two or more different elements, and the smallest possible particle of a compound is a molecule. For example, a molecule of water (H_2O) consists of two atoms of hydrogen and one atom of oxygen. A diagram representing a water molecule is shown in Fig. 1-1.

ELECTRONS, PROTONS, AND NEUTRONS

Many discoveries have been made that greatly facilitate the study of electricity and provide new concepts concerning the nature of matter. One of the most important of these discoveries has dealt with the structure of the atom. It has been found that an atom consists of infinitesimal particles of energy known as electrons, protons, and neutrons. All matter consists of one or more of these basic components. The simplest atom is that of hydrogen, which has one electron and one proton as represented in the diagram of Fig. 1-2*a*. The structure of an oxygen atom is indicated in Fig. 1-2*b*. This atom has eight protons, eight neutrons, and eight electrons. The protons and neutrons form the **nucleus** of the atom; electrons revolve around the nucleus in orbits varying in shape from an ellipse to a circle and may be compared to the planets as they move around the sun. A **positive** charge is carried by each proton, **no** charge is carried by the neutrons, and a **negative** charge is carried by each electron. The charges carried by the electron and the proton are equal but opposite in nature; thus an atom which has an equal number of protons and electrons is electrically neutral. The charge carried by the electrons is balanced by the charge carried by the protons.

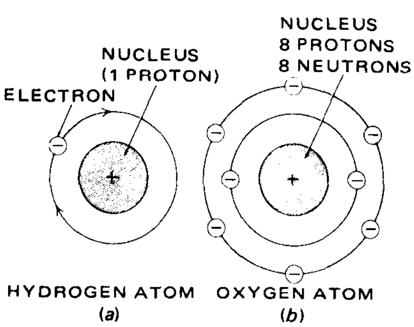


Fig. 1-2 Structure of atoms.

Through research on the weight of atomic particles, scientists have found that a proton weighs approximately 1845 times as much as an electron and that a neutron has the same weight as a proton. It is obvious, then, that the weight of an atom is determined by the number of protons and neutrons contained in the nucleus.

It has been explained that an atom carries two opposite charges: a positive charge in the nucleus and a negative charge in each electron. When the charge of the nucleus is equal to the combined charges of the electrons, the atom is neutral; but if the atom has a shortage of electrons, it will be **positively charged.** Conversely, if the atom has an excess of electrons, it will be **negatively charged.** A positively charged atom is called a **positive ion,** and a negatively charged atom is called a **negative ion.** Charged molecules are also called ions.

ATOMIC STRUCTURE AND FREE ELECTRONS

The path of an electron around the nucleus of an atom describes an imaginary sphere or shell. Hydrogen and helium atoms have only one shell, but the more complex atoms have numerous shells. When an atom has more than two electrons, it must have more than one shell, since the first shell will accommodate only two electrons. This is shown in Fig. 1-2*b*. The number of shells in an atom depends upon the total number of electrons surrounding the nucleus.

The atomic structure of a substance is of interest to the electrician because it determines how well the substance can conduct an electric current. Certain elements, chiefly metals, are known as **conductors** because an electric current will flow through them easily. The atoms of these elements give up electrons or receive electrons in the outer orbits with little difficulty. The electrons that move from one atom to another are called **free electrons.** The movement of free electrons from one atom to another is indicated by the diagram in Fig. 1-3, and it will be noted that they pass from the outer shell of one atom to the outer shell of the next. The only electrons shown in the diagram are those in the outer orbits.

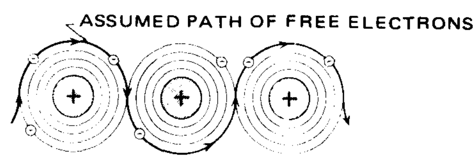


Fig. 1-3 Assumed movement of free electrons.

An element is a conductor, nonconductor (insulator), or semiconductor, depending upon the number of electrons in the outer orbit of the atom. If an atom has less than four electrons in the outer orbit, it is a conductor. If it has more than four atoms in the outer orbit, it is an **insulator.** A **semiconductor** material such as germanium or silicon has four electrons in the outer orbit of its atoms. These materials have a very high resistance to current flow when in the pure state; however, when measured amounts of other elements are added, the material can be made to carry current. The nature and use of semiconductors are discussed in a later chapter.

To cause electrons to move through a conductor, a force is required, and this force is supplied in part by the electrons themselves. When two electrons are near each other and are not acted upon by a positive charge, they repel each other with a relatively tremendous force. It is said that if two electrons could be magnified to the size of peas and were placed 100 ft apart, they would repel each other with tons of force. It is this force which is utilized to cause electrons to move through a conductor.

Electrons cluster around a nucleus because of the neutralizing positive force exerted by the protons in the nucleus and also because of an unexplained phenomenon called the **nuclear binding force.** If the binding force were suddenly removed, there would be an explosion like that of the atomic bomb. The force of the atomic-bomb explosion is the result of an almost infinite number of atoms disintegrating simultaneously.

The movement of electrons through a conductor is due, not to the disintegration of atoms, but to the repelling force which the electrons exert upon one another. When an extra electron enters the outer orbit of an atom, the repelling force immediately causes another electron to move out of the orbit of that atom and into the orbit of another. If the material is a conductor, the electrons move easily from one atom to another.

We are all familiar with the results of passing a hard rubber or plastic comb through the hair. When the hair is dry, a faint crackling sound may be heard and the hair will stand up and attempt to follow the comb. As the comb moves through the hair, some of the electrons in the hair are dislodged and picked up by the comb. The reason for the transfer is probably that the outer orbits of the atoms of the material in the comb are not filled; they therefore attract electrons from the hair. When the hair is agitated by the comb, the unbalanced condition existing between the atoms of the comb and of the hair causes the electrons to transfer. The hair now becomes positively charged because it loses electrons, and the comb becomes negatively charged because it gains electrons.

When the hair is thus charged, it will tend to stand up, and the single strands will repel one another because each has a similar charge. If the comb is then brought near the hair, the hair will be attracted by the comb because the hair and the comb have unlike charges. The attraction is the result of the electrons on the comb being attracted by the positive charge of the hair.

Static charging by friction between two or more dissimilar materials is called **triboelectric** charging. This type of charging is an important factor in the design and installation of electric and electronic equipment in aircraft or space vehicles.

A charged body, such as a comb or plastic rod, may be used to charge other bodies. For example, if two pith balls are suspended near each other on fine threads, as in Fig. 1-4*a*, and each ball is then touched with a charged plastic rod, a part of the charge is conveyed to the balls. Since the balls will now have a similar charge, they will repel each other as in Fig. 1-4*b*. If the rod is rubbed with a piece of fur, it will become negatively charged and the fur positively charged. By touching one of the balls with

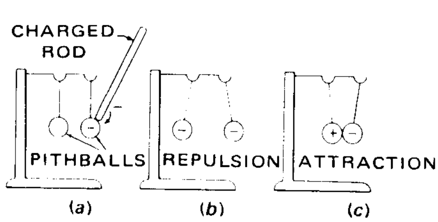


Fig. 1-4 Reaction of like and unlike charges.

the rod and the other with the fur, the balls are given opposite charges. They will then attract each other as shown in Fig. 1-4*c*.

The behavior of a charged body indicates that it is surrounded by an invisible field of force. This field is assumed to consist of lines of force extending in all directions and terminating at a point where there is an equal and opposite charge. A field of this type is called an **electrostatic field.** When two oppositely charged bodies are in close proximity, the electrostatic field is relatively strong. If the two bodies are joined by a conductor, the electrons from the negatively charged body flow along the conductor to the positively charged body, and the charges are neutralized. When the charges are neutral, there is no electrostatic field.

DIRECTION OF CURRENT FLOW

It has been shown that an electric current is the result of the movement of electrons through a conductor. Since a negatively charged body has an excess of electrons and a positively charged body a deficiency of electrons, it is obvious that the electron flow will be **from** the negatively charged body **to** the positively charged body when the two are connected by a conductor. It is therefore clear that electricity flows from negative to positive.

Until recently, however, it was assumed that electric current flowed from positive to negative. This was because the polarities of electric charges were arbitrarily assigned names without the true nature of electric current being known. The study of radio and other electronic devices has made it necessary to consider the true direction of current flow, but for all ordinary electrical applications, the direction of flow may be considered to be in either direction so long as the theory is used consistently. Even though there are still some texts which adhere to the old conventional theory that current flows from positive to negative, it is the purpose of this text to consider all current flow as moving from negative to positive. Electrical rules and diagrams are arranged to conform to this principle in order to prevent confusion and to give the student a true concept of electrical phenomena.

The student will sometimes read or hear the statement "electron flow is from negative to positive, and current flow is from positive to negative." This statement is a fallacy because current flow consists of electrons moving through a conductor, and the movement is from negative to positive as explained in this section. The student should fix this principle firmly in mind to avoid being confused when encountering an application of the old "conventional" current-flow theory.

It is expected that eventually all writers and teachers will teach the principle as it actually is; however, it often takes many years to correct a false idea, and the student is warned to exercise care in the study of electricity. Particular care must be paid to rules dealing with current flow and its effects.

STATIC ELECTRICITY

ELECTROSTATICS

The study of the behavior of static electricity is called **electrostatics.** The word **static** means stationary or at rest, and electric charges which are at rest are called **static electricity.** In the previous section it was shown that static electric charges may be produced by rubbing various dissimilar substances together and triboelectric charging takes place. The nature of the charge produced is determined by the types of substances. The following list of substances is called the **electric series,** and the list is so arranged that each substance is positive in relation to any which follow it, when the two are in contact:

1. Fur	**6.** Cotton	**11.** Metals
2. Flannel	**7.** Silk	**12.** Sealing wax
3. Ivory	**8.** Leather	**13.** Resins
4. Crystals	**9.** The body	**14.** Gutta percha
5. Glass	**10.** Wood	**15.** Guncotton

If, for example, a glass rod is rubbed with fur, the rod becomes negatively charged, but if it is rubbed with silk it becomes positively charged.

When a nonconductor is charged by rubbing it with a dissimilar material, the charge remains at the points where the friction occurs because the electrons cannot move through the material; however, when a conductor is charged, it must be insulated from other conductors or the charge will be lost.

An electric charge may be produced in a conductor by induction if the conductor is properly insulated. Imagine that the insulated metal sphere shown in Fig. 1-5 is charged negatively and brought near one end of a metal rod which is also insulated from other conductors. The

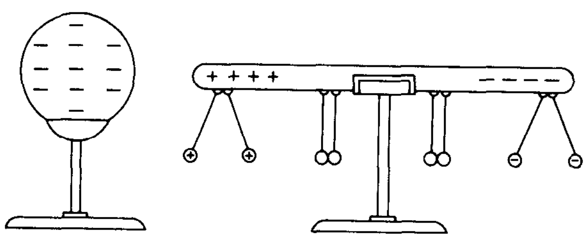


Fig. 1-5 Charging by induction.

electrons constituting the negative charge in the sphere repel the electrons in the rod and drive them to the opposite end of the rod. The rod then has a positive charge in the end nearest the charged sphere and a negative charge in the opposite end. This may be shown by suspending pith balls in pairs from the middle and ends of the rod by means of conducting threads. At the ends of the rod, the pith balls separate as the charged sphere is brought near one end; but the balls near the center do not separate because the center is neutral. As the charged sphere is moved away from the rod, the balls fall to their original positions, thus indicating that the charges in the rod have become neutralized.

LIGHTNING

The familiar flash of lightning is nothing but an enormous spark caused by the discharge of static electricity from a highly charged cloud. Clouds become charged because of friction between their many minute particles of water, air, and dust. Lightning is most commonly found in cumulus and cumulonimbus clouds. These latter are the towering, billowy clouds frequently seen in the summer; they are caused by warm moist air moving up into colder areas where condensation takes place. Such clouds have air currents moving up through their centers at speeds which are sometimes in excess of 100 miles per hour (mph) [161 kilometers per hour (km/h)]. The turbulence caused by these updrafts is largely responsible for the electric charges which cause lightning.

Although serious damage to an aircraft as the result of lightning is rare, studies have been made to establish safe procedures when lightning may be encountered. Such studies have indicated that a positive charge develops in the forward portion of the cloud, where the updrafts are more pronounced. Thus it seems that the rising air currents are removing electrons from that portion of the cloud. The negative charge develops in the rear portion of the cloud and is separated from the positive charge by a neutral area. When the difference between the charges becomes great enough, a flash of lightning occurs and the cloud becomes neutral for a time in that particular area.

The use of weather radar in modern airliners has helped pilots to avoid flying through thunderstorms where the danger of lightning would be greatest. Danger areas show up clearly on the radar **scopes** at a sufficient distance for the pilot to have adequate time to fly around them.

STATIC ELECTRICITY AND THE AIRPLANE

As mentioned previously, the effects of static electricity are of considerable importance in the design, operation, and maintenance of aircraft. This is particularly true because modern airplanes are equipped with radio and other electronic equipment. The pop and crackle of static is familiar to everyone who has listened to a radio receiver when static conditions are prevalent. An airplane in flight picks up static charges because of contact with rain, snow, clouds, dust, and other particles in the air. The charges thus produced in the aircraft structure result in **precipitation static** (p static). The charges flow about the metal structure of the airplane as they tend to equalize, and if any part of the airplane is partially insulated from another part, the static electricity causes minute sparks as it jumps across the insulated joints. Every spark causes p-static noise in the radio communication equipment and also causes disturbances in other electronic systems. For this reason, the parts of an airplane are **bonded** so that electric charges may move throughout the airplane structure without causing sparks. Bonding the parts of an airplane simply means establishing a good electrical contact between them. Movable parts, such as ailerons, flaps, and rudders, are connected to the main structure of the airplane with flexible woven-metal leads called **bonding braid.**

The **shielding** of electronic devices and wiring is also necessary to help eliminate the effects of p static on electric equipment in the airplane. Shields consist of metal coverings which intercept undesirable waves and prevent them from affecting sensitive electronic systems.

An airplane in flight often accumulates very high electric charges, not only from precipitation, but also from the high-velocity jet-engine exhaust as it flows through the tailpipe. When the airplance charge becomes sufficiently high, electrons will be discharged into the surrounding air from sharp or pointed sections of the airplane. The level at which this begins is called the **corona threshold.** Corona discharge is often visible at night, emanating from wing tips, tail sections, and other sharply pointed sections of a plane. The visible discharge is called *Saint Elmo's fire.*

Corona discharge occurs as short pulses at very high frequencies, thus producing energy fields which couple with radio antenna fields to cause severe interference. The solution to the problem is to cause the charge on the airplane to be partially dissipated in a controlled manner so that the energy level of the discharge will be reduced and the effects of the discharge will cause a minimum of interference. In the past, static-discharge **wicks** were used to reduce the charge on the airplane. See Fig. 1-6.

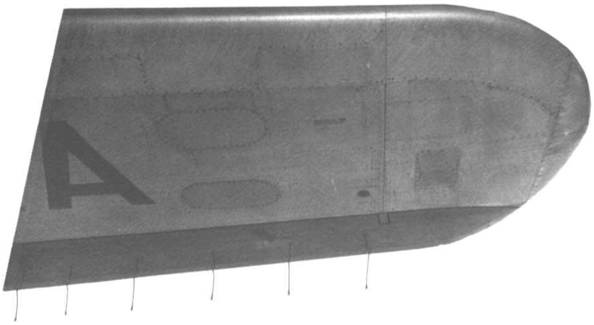


Fig. 1-6 Static discharge wicks.

Because of the high speeds of jet aircraft and the fact that they are powered by gas-turbine engines that tend to increase static charges, it became necessary to develop static-discharge devices more effective than the wicks formerly used. A type of discharger that has proved most successful is called a **null field discharger.** These dischargers are mounted at the trailing edges of outer ailerons, vertical stabilizers, and other points where high discharges tend to occur. They produce a discharge field which has minimum coupling with radio antennas. Typical installations are shown in Fig. 1-7.

Static charges must be taken into consideration when an airplane is being refueled. Gasoline or jet fuel flowing through the hose into the airplane will usually cause a static charge to develop at the nozzle of the hose unless a means is provided whereby the charge may bleed off. If the nozzle of the fuel hose should become sufficiently charged, a spark could occur and cause a disastrous fire. To prevent such an occurrence, the nozzle of the fuel hose is connected electrically to the aircraft by means of a grounding cable or other device, and the aircraft is grounded to the earth. In this way, the fuel nozzle and the aircraft are kept neutral with the earth, and no charges can develop sufficient to create a spark.

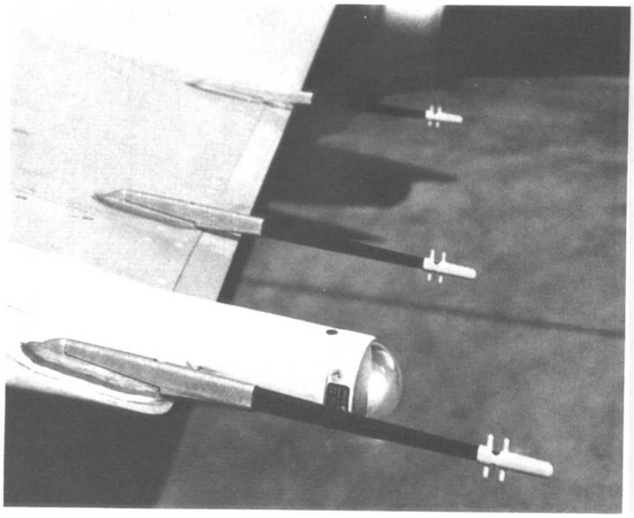


Fig. 1-7 Installation of Null Field Dischargers. (Dayton Aircraft Products Div., Dayton International)

THE ELECTRIC CURRENT

DEFINITION

An electric **current** is defined as a flow of electrons through a conductor. In an earlier part of this chapter it was shown that the free electrons of a conducting material move from atom to atom as the result of the attraction of unlike charges and the repulsion of like charges. If the terminals of a battery are connected to the ends of a wire conductor, the negative terminal forces electrons into the wire and the positive terminal takes electrons from the wire; hence as long as the battery is connected, there is a continuous flow of current through the wire until the battery becomes discharged.

It is said that an electric current travels at more than 186 000 miles per second (mps) [299 000 km/s]. Actually, it would be more correct to say that the effect, or force, of electricity travels at this speed. Individual electrons move at a comparatively slow rate from atom to atom in a conductor, but the influence of a charge is "felt" through the entire length of a conductor instantaneously. A simple illustration will explain this phenomenon. If we completely fill a tube with tennis balls, as shown in Fig. 1-8, and then push an additional ball into one end of the tube, one ball will fall out the other end. This is similar to the effect of electrons as they are forced into a conductor. When electrical pressure is applied to one end of the conductor, it is immediately effective at the other end. It must be remembered, however, that under most conditions, electrons must have a conducting path before they will leave the conductor.

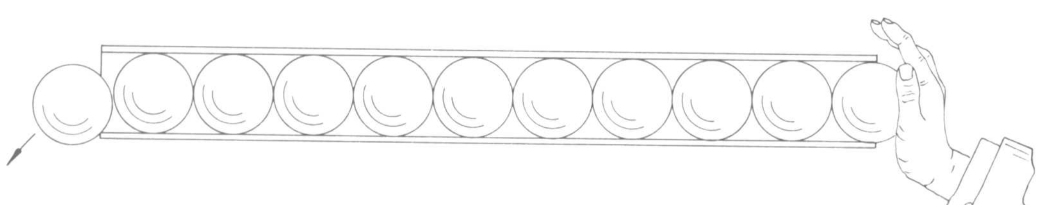


Fig. 1-8 Demonstration to illustrate current flow.

POTENTIAL DIFFERENCE AND ELECTROMOTIVE FORCE

Just as water flows in a pipe when there is a difference of pressure at the ends of the pipe, an electric current flows in a conductor because of a difference in electrical pressure at the ends of the conductor. If two tanks containing water at different levels are connected by a pipe with a valve, as shown in Fig. 1-9, water flows from the tank with the higher level to the other tank when the valve is open. The difference in water pressure is due to the higher water level in one tank.

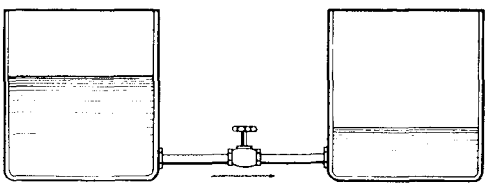


Fig. 1-9 Difference of pressure.

It may be stated that in an electric circuit, a large number of electrons at one point will cause a current to flow to another point where there is a small number of electrons if the two points are connected by a conductor. In other words, when the electron level is higher at one point than at another point, there is a *difference of potential* between the points. When the points are connected by a conductor, electrons flow from the point of high potential to the point of low potential. There are numerous simple analogies which may be used to illustrate potential difference. For example, when an automobile tire is inflated, there exists a difference of potential (pressure) between the inside of the tire and the outside. When the valve is opened, the air rushes out. If the tip of an old-fashioned light bulb is broken off, air rushes into the bulb because the inside of the bulb is at a lower pressure than the atmosphere. In this case the bulb represents a positive charge and the atmosphere a negative charge.

For all practical purposes, the earth is considered to be electrically neutral; that is, it has no charge. Therefore, if a positively charged object is connected to the earth, electrons flow from the earth to the object; and if a negatively charged object is connected, the electrons flow from the object to the earth.

The force which causes electrons to flow through a conductor is called **electromotive force,** abbreviated emf, or *electron-moving* force. The practical unit for the measurement of emf or potential difference is the **volt** (V). The word volt is derived from the name of the famous electrical experimenter, Alessandro Volta (1745-1827), of Italy, who made many contributions to the knowledge of electricity.

Electromotive force and potential difference may be considered the same for all practical purposes. When there is a potential difference, or difference of electrical pressure, between two points, it simply means that a field of force exists which tends to move electrons from one point to the other. If the points are connected by a conductor, electrons will flow as long as the potential difference exists.

With reference to Fig. 1-9, it may be stated that a difference of potential exists between the two water tanks because the weight of the water in one tank exerts a greater pressure than the weight of the water in the other tank. We may compare the difference in pressure at the ends of the connecting pipe with emf. If the water in one tank exerts a pressure of 10 pounds per square inch (psi) [68.95 kilopascals (k Pa)] at the end of the pipe, and the water in the other tank exerts a pressure of 5 psi [34.48 k Pa], there is a difference of 5 psi between the ends of the pipe. In like manner, we may say that there is an emf of 5 V between two electric terminals.

Since potential difference and emf are measured in volts, the word **voltage** is commonly used instead of longer terms. For example, we may say that the voltage of an aircraft storage battery is 24. This means that there is a potential difference of 24 V between the terminals. In simple terms, **1 volt is the emf required to cause current to flow at the rate of 1 ampere through a resistance of 1 ohm.** The terms *ampere* and *ohm* will be clarified in the study of Ohm's law.

RESISTANCE

Resistance is that property of a conductor which tends to hold back, or restrict, the flow of an electric current; it is encountered in every circuit. Resistance may be termed *electrical friction* because it affects the movement of electricity in a manner similar to the effect of friction on mechanical objects. For example, if the interior of a water pipe is very rough because of rust or some other material, a smaller stream of water will flow through the pipe at a given pressure than would flow if the interior of the pipe were clean and smooth.

The unit used in electricity to measure resistance is the **ohm.** The ohm is named for the German physicist Georg S. Ohm (1789–1854), who discovered the relationship between electrical quantities known as Ohm's law. The practical value of the ohm will be discussed in the study of this law. The symbol for ohm or ohms is the Greek letter omega (Ω).

It has been explained that materials which have a relatively large number of free electrons are conductors. When an emf is not acting on a conductor, it is assumed that the free electrons are moving at random from atom to atom and filling the gaps in outer orbits of atoms deficient in electrons. When an emf is applied to a conductor, the free electrons begin to move in a definite direction through the material, provided that there is a complete circuit through which the current can flow. The greater the emf applied to a given circuit, the greater the current flow.

The best conductors of electricity in the order of their conductivity are silver, copper, gold, and aluminum, but the use of gold or silver for conductors is limited because of the cost. The resistance of a copper wire of a given diameter and length is lower than that of an aluminum wire of the same size; but for a given weight of each material, aluminum has the lower resistance. For this reason aluminum wire may be used to advantage where the weight factor is important.

Gold is used extensively in modern electronic equipment to provide corrosion-free contacts for *plug-in* modules and other units which can be removed and replaced for service or repair. The many *black boxes* containing complex electronic circuitry can be quickly and easily repaired merely by removing a circuit module and plugging in another. The gold at the contacts provides positive electrical connections whenever a change is made.

The resistance of a standard length and cross-sectional area of a material is called its **resistivity.** For example, the resistivity of copper wire is 10.4 Ω per circular-mil-foot (cmil·ft). This means that 1 foot (ft) [30.48 centimeters (cm)] of copper wire having a cross-sectional area of 1 cmil, or 0.001 in [0.0254 millimeters (mm)], diameter will have 10.4 Ω resistance. For aluminum, the resistivity is 19.3 Ω/cmil·ft.

Insulators are materials which have relatively few free electrons. There are no perfect insulators, but many substances have such high resistance that for practical purposes they may be said to prevent the flow of current. Substances having good insulating qualities are dry air, glass, mica, porcelain, rubber, plastic, asbestos, and fiber compositions. The resistance of these substances varies to some extent, but they may all be said effectively to block the flow of current.

According to the electron theory, the atoms of an insulator do not give up electrons easily. When an emf is applied to such a substance, the outer electron orbits are distorted; but as soon as the emf is removed, the electrons return to their normal positions. If, however, the emf applied is so strong that it strains the atomic structure beyond its elastic limit, the atoms lose electrons and the material becomes a conductor. When this occurs, the material is said to be ruptured.

The resistance of a wire varies inversely with the area of the cross section. For example, if the area of the cross section of one wire is twice the cross-sectional area of another wire of the same length in material, the larger wire has one-half the resistance of the smaller wire. When the cross-sectional area of a wire remains constant, the resistance increases in proportion to length. For example, a wire 2 ft [60 cm] long has twice the resistance of a similar wire 1 ft [30 cm] long.

Temperature is another factor which affects the resistance of a wire. Usually, the resistance of a wire increases with an increase in temperature. However, some substances such as carbon, decrease in resistance as the temperature increases. The degree of resistance change due to temperature variation is not constant but depends upon the material. Some materials have a greater variation of resistance as a result of a given temperature change than other materials.

The general rule for the resistance of a conductor is as follows: **The resistance of a given conductor varies directly as its length, and inversely as the area of its cross section, when the temperature remains constant.** This may be expressed as a formula:

$$R = \frac{KL}{S}$$

K is a constant which depends upon the resistivity of the material; for example, copper has a resistivity of 10.4 Ω at 68°F [20°C]. In the formula, L is the length of the wire in feet, and S is the cross-sectional area in circular mils. To find the resistance of 300 ft [9.14 m] of copper wire having a cross-sectional area of 100 cmil [0.0507 mm^2], the formula is applied as follows:

$$R = \frac{10.4 \times 300}{100} \qquad R = 31.2\ \Omega$$

As indicated in the previous paragraph, the cross-sectional area of a wire is measured in circular mils. One mil is one-thousandth of an inch. One circular mil is the area of a circle having a diameter of 1 mil, or 0.001 in. The area of a square having sides equal to 1 mil is 1 square mil (mil^2) [0.000645 mm^2]. These areas are illustrated in Fig. 1-10.

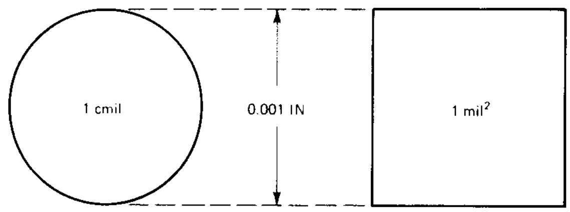


Fig. 1-10 The circular mil.

The formula for the area of a circle is

$$\frac{\pi d^2}{4} \qquad \text{or} \qquad 0.7845d^2$$

If a circle has a diameter (d) of 1 mil, the area in square mils is 0.7854×1^2, or 0.7854 mil^2. Since a circular mil is defined as the area of a circle having a diameter of 1 mil, then 1 cmil is equal to 0.7854 mil^2, and

$$1\ \text{mil}^2 = \frac{1}{0.7854}\ \text{cmil}$$

The formula, A (area) $= 0.7854d^2$, gives the area of a circle in square mils when the diameter is in mils. Since

$$1\ \text{mil}^2 = \frac{1}{0.7854}\ \text{cmil}$$

the area of a circle in circular mils may be given as

$$A\ (\text{cmil}) = \frac{0.7854d^2}{0.7854} = d^2$$

Hence, when we wish to know the area of a circle in circular mils, we merely square the diameter.

Resistance in electric circuits produces heat just as mechanical friction produces heat. This is called the **heat of resistance.** Normally the heat of resistance is dissipated as fast as it is produced, and the wire of the circuit may become only slightly warm. However, if the current flowing in the wire is so great that it generates heat faster than the heat can be carried away by the surrounding air or insulation, the wire will eventually overheat. This may lead to the burning of the insulation and a possible fire. Tables are available which give the current-carrying capacity of copper wire according to size. For continuous-duty circuits, these limits must not be ex-

TABLE 1-1 Current-carrying Capacities for AN-S-C-48 Electric Cable

AWG wire size	Continuous rating, *A* In bundles or conduit	Continuous rating, *A* Single cable in free air	Intermittent rating, *A*
20	7	10	15
18	10	15	20
16	13	20	25
14	18	30	35
12	24	40	48
10	32	55	67
8	44	70	90
6	60	95	115
4	80	125	155
2	110	170	210
1	125	190	240
1/0	150	230	300
2/0	175	260	340
3/0	190	310	410
4/0	225	375	500

ceeded. Table 1-1 gives the current-carrying capacities of commonly used sizes of aircraft electric wire.

Two sections of wire having the same resistance generate the same amount of heat when they carry equal currents; but if one wire has a greater surface, it can carry more current without damage because it can dissipate the heat faster than the other. For example, if one section of copper wire has a length of 1 in [2.54 cm] and a cross-sectional area of 10 cmil [0.00507 mm^2], and another section of copper wire is 2 in [3.08 cm] long and has a cross-sectional area of 20 cmil [0.01014 mm^2], the resistance of the two sections of wire is the same. However, the larger wire can carry more current because it can dissipate heat more rapidly.

CURRENT

When it is necessary to measure the flow of a liquid through a pipe, the rate of flow is often measured in **gallons per minute.** The gallon is a definite quantity of liquid and may be called a unit of quantity. The unit of quantity for electricity is the **coulomb** (C), named for Charles A. Coulomb (1736-1806), a French physicist who conducted many experiments with electric charges. One coulomb is the amount of electricity which, when passed through a standard silver nitrate solution, will cause 0.001118 gram (g) of silver to be deposited upon one electrode. (An electrode is a terminal, or pole, of an electric circuit.) A coulomb is also defined as 6.28×10^{18} electrons, that is, 6.28 billion billion electrons.

The rate of flow for an electric current is measured by the number of coulombs per second passing a given point in a circuit. Instead of designating the rate of flow in coulombs per second, a unit called the **ampere** (A) is used. **One ampere is the rate of flow of 1 coulomb per second.** The ampere was named in honor of the French scientist André M. Ampère (1775-1836).

The flow of electricity through a conductor is called a **current.** Hence, when current is mentioned, it indicates a flow of electricity measurable in amperes.

OHM'S LAW

In mathematical problems, emf is expressed in **volts** and the symbol E is used to indicate the emf until the actual number of volts is determined. R is the symbol for resistance in ohms, and I is the symbol for current, or amperage. The letter I may be said to represent the **intensity** of current. The letter symbols E, R, and I have an exact relationship in electricity given by Ohm's law. This law may be stated as follows: **The current in an electric circuit is directly proportional to the emf (voltage) and inversely proportional to the resistance.** Ohm's law is further expressed by the statement: **1 volt causes 1 ampere to flow through a resistance of 1 ohm.** The equation for Ohm's law is

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

which indicates that the current in a given circuit is equal to the voltage divided by the resistance.

An equation is defined as a proposition expressing equality between two values. It may take as many forms as those shown for Ohm's law in Fig. 1-11. The different

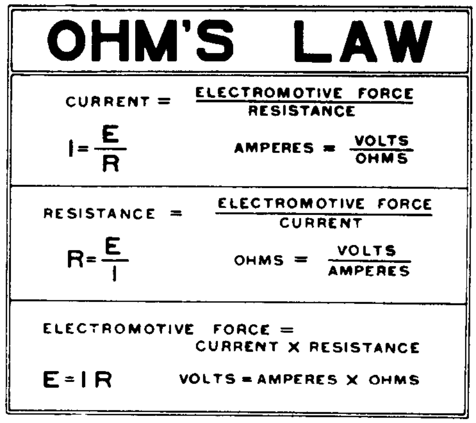


Fig. 1-11 Equations for Ohm's law.

forms for the Ohm's law equation are derived by either multiplication or division. For example,

$$R(I) = R\left(\frac{E}{R}\right) \qquad \text{becomes} \qquad RI = \frac{RE}{R}$$

Then

$$RI = E \qquad \text{or} \qquad E = IR$$

In a similar manner, if both sides of the equation $E = IR$ are divided by I, we arrive at the form

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

Thus we find it simple to determine any one of the three values if the other two are known. Ohm's law may be used to solve any common direct-current (dc) circuit problem because any such circuit, when operating, has voltage, amperage, and resistance. To solve alternating-current (ac) circuit problems, other values must be taken into consideration. These will be discussed in the section on alternating current.

From the study of Ohm's law, it has been seen that the current flowing in a circuit is directly proportional to the voltage and inversely proportional to the resistance. If the voltage applied to a given circuit is doubled, the current will double. If the resistance is doubled and the voltage remains the same, the current will be reduced by one-half (see Fig. 1-12). The circuit symbol for a battery which is the power source for these circuits and the circuit symbol for a resistor or resistance are indicated in the illustration.

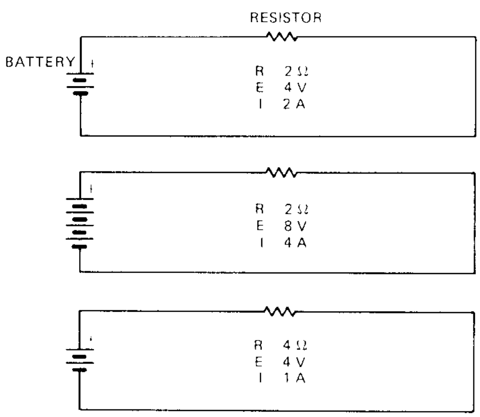


Fig. 1-12 Effects of resistance and voltage.

The equations of Ohm's law are easily remembered by using the simple diagram shown in Fig. 1-13. By covering the symbol of the unknown quantity in the diagram with the hand or a piece of paper, the known quantities are found to be in their correct mathematical arrangement.

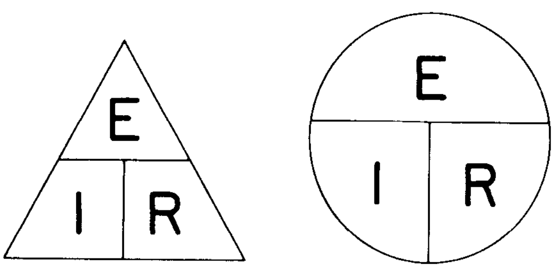


Fig. 1-13 Diagrams for Ohm's law.

For example, if it is desired to find the total resistance of a circuit in which the voltage is 10 and the amperage is 5, cover the letter R in the diagram. This leaves the letter E over the letter I; then

$$R = \frac{E}{I} = \frac{10}{5} \quad \text{or} \quad R = 2\ \Omega$$

If it is desired to find the voltage in a circuit when the resistance and the amperage are known, cover the E in the diagram. This leaves I and R adjacent to each other; they are therefore to be multiplied according to the equation form $E = IR$.

It is important for electricians or technicians who are to perform electrical work on an airplane to achieve a thorough understanding of Ohm's law, because this knowledge will enable them to determine the correct size and length of wire to be used in a circuit, the proper sizes of fuses and circuit breakers, and many other details of a circuit and its components. Further study of the use of Ohm's law is made in the next section of this chapter.

ELECTRIC POWER AND WORK

Power means the rate of doing work. One horse-power (hp) [746 watts (W)] is required to raise 550 pounds (lb) [249.5 kilograms (kg)] a distance of 1 ft [30.48 cm] in 1 s. When 1 lb [0.4536 kg] is moved through a distance of 1 ft, 1 foot-pound (ft·lb) [13.82 cm·kg] of work has been performed; hence, 1 hp is the power required to do 550 ft·lb [7601 cm·kg] of work per second. The unit of power in electricity and in the SI metric system is the **watt** (W), which is equal to 0.00134 hp. Conversely, 1 hp is equal to 746 W. In electrical terms, **1 watt is the power expended when 1 volt moves 1 coulomb per second through a conductor; that is, 1 volt at 1 ampere produces 1 watt of power.** The formula for electric power is

$$W = EI \quad \text{or} \quad \text{Watts} = \text{volts} \times \text{amperes}$$

Another unit used in connection with electrical work is the **joule** (J) named for James Prescott Joule (1818-1889), an English physicist. **The joule is a unit of work, or energy, and represents the work done by 1 watt in 1 second.** This is equal to 0.7376 ft·lb. To apply this principle, let us assume that we wish to determine how much work in joules is done when a weight of 1 ton is raised 50 ft. First we multiply 2000 by 50 and find that 100 000 ft·lb of work is done. Then, when we divide 100 000 by 0.7376, we determine that approximately 135 575 J of work, or energy, were used to raise the weight.

A joule is also defined as 10^7 ergs. An **erg** can be defined as a dyne-centimeter (dyn·cm), that is, the energy expended when a force of 1 dyne (dyn) is expended through a distance of 1 cm in the direction of the force. A **dyne** is the force required to impart an acceleration of 1 cm/s^2 to a mass of 1 g. One newton (N) is equal to 10^5 dyn, which is the force necessary to move a mass of 1 kg at an acceleration rate of 1 m/s^2. This is equal to 0.2248 lb.

It is wise for the technician to understand and have a good concept of the joule because this is the unit designated by the SI metric system for the measurement of work or energy. Other units convertible to joules are the British thermal unit (Btu), calorie (cal), foot-pound, and watthour (Wh). All these units represent a specific amount of work performed.

Electric power expended in a circuit is manifested in the form of heat or motion. In the case of electric lamps, electric irons, electric cooking ranges, etc., power is expended in the form of heat. In an electric motor or electromagnet, the power is expended in the form of motion, and work is done. An electric current flowing through a wire will always produce heat, although in many cases the rise in temperature is not noticeable. The heat generated in a given circuit is proportional to the square of the current, as shown by the following formulas:

$$W = EI \quad \text{and} \quad E = IR$$

By substitution

$$W = IR \times I \qquad \text{or} \qquad W = I^2 R$$

When energy is lost in an electric circuit in the form of heat, it is called an $I^2 R$ loss because $I^2 R$ represents the heat energy lost, measured in watts.

Since we know the relationship between power and electrical units, it is simple to calculate the approximate amperage to operate a given motor when the efficiency and operating voltage of the motor are known. For example, if it is desired to install a 3-hp [2.238 kilowatts (kW)] motor in a 24-V system and the efficiency of the motor is 75 percent, we proceed as follows:

$$1 \text{ hp} = 746 \text{ W}$$

$$W = 3 \times 746 = 2238 \text{ W}$$

$$I = \frac{2238}{24} = 93.25 \text{ A}$$

Since the motor is only 75 percent efficient, we must divide 93.25 by 0.75 to find that approximately 124.33 A is required to operate the motor at rated load. Thus, in a motor that is 75 percent efficient, 2984 W of power is required to produce 2.238 W of power at the output.

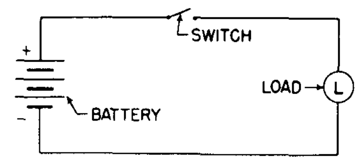


Fig. 1-14 A simple circuit.

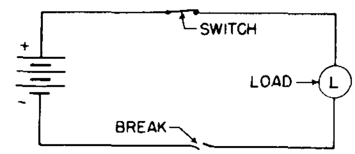


Fig. 1-15 An open circuit.

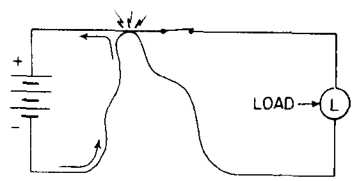


Fig. 1-16 A short circuit.

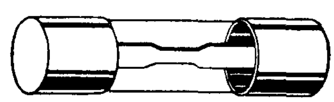


Fig. 1-17 A simple fuse.

DC CIRCUITS

TYPES OF CIRCUITS

To cause a current to flow in a conductor, a difference of potential must be maintained between the ends of the conductor. In an electric circuit this difference of potential is normally produced by a battery or a generator; so it is obvious that both ends of the conductor must be connected to the terminals of the source of emf.

Figure 1-14 shows the components of a simple circuit with a battery as the source of power. One end of the circuit is connected to the positive terminal of the battery and the other to the negative terminal. A switch is incorporated in the circuit to connect the electric power to the load unit, which may be an electric lamp, bell, relay, or any other electric device that could be operated in such a circuit. When the switch in the circuit is closed, current from the battery flows through the switch and load and then back to the battery. Remember that the direction of current flow is from the negative terminal to the positive terminal of the battery. The circuit will operate only when there is a continuous path through which the current may flow from one terminal to the other. When the switch is opened (turned off), the path for the current is broken and the operation of the circuit ceases.

One of the most common difficulties encountered in electric systems is the *open* circuit. This means simply that there is a break somewhere in the circuit and that no current can flow. An open circuit is shown in Fig. 1-15. When the circuit is complete and the current can flow, it is called a *closed* circuit. The circuit in Fig. 1-14 is a closed circuit when the switch is closed.

Another common cause of circuit failure is called a *short circuit*. A short circuit exists when an accidental contact between conductors allows the current to return to the battery through a short, low-resistance path, as shown in Fig. 1-16. This failure is prevented by making sure that all insulation on the wires is in good condition and strong enough to withstand the voltage of the power source. Furthermore, all wiring should be properly secured with insulated clamps or other devices so that it cannot rub against any structure and wear through the insulation.

The danger in a short circuit is that an excessive amount of current may flow through limited portions of the circuit, causing wires to overheat and burn off the insulation. If the short circuit is not discovered immediately, the wiring is likely to become red hot and may melt. Many fires are caused by short circuits, but the danger is largely overcome by the installation of protective devices, such as fuses or circuit breakers.

A **fuse** is a portion of a circuit composed of a metal or alloy with a low melting point. If the current in the circuit becomes too great, the fuse will melt and open the circuit. A simple fuse is shown in Fig. 1-17.

The **circuit breaker** is a mechanical device designed to open a circuit when the current flow exceeds a safe limit. Usually the circuit breaker contains an element which reacts to heat. The heat causes the metal to expand, and the expansion trips the contact points to an open position.

Heavy-duty commercial circuit breakers are usually operated by the magnetic force created by the current flow. An overload of current will give the electromagnet sufficient strength to open the circuit by means of a spring-loaded switching device. Magnetism and electromagnetism are explained in a later section of this text.

The circuit breakers employed in aircraft systems are usually of the thermal type; that is, they react to heat as explained above. Typical aircraft circuit breakers are illustrated in Fig. 1-18.

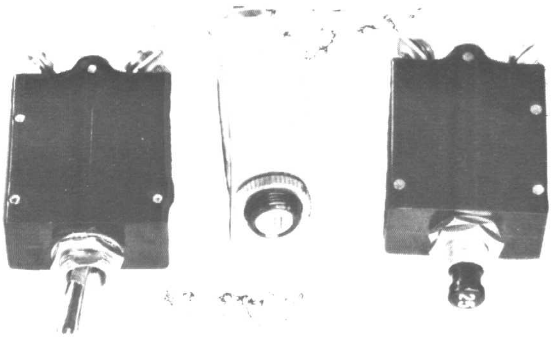


Fig. 1-18 Circuit breakers.

Since airplanes are usually constructed of metal, the airplane structure may be used as an electric conductor. In the circuit in Fig. 1-14, if one terminal of the battery and one terminal of the load are connected to the metal structure of the airplane, the circuit will operate just as well as with two wire conductors. A diagram of such a circuit is shown in Fig. 1-19. When a system of this type is used in an airplane, it is called a **grounded** or **single-wire** system. The ground circuit is that part of the complete circuit in which current passes through the airplane structure. Any unit connected electrically to the metal structure of the airplane is said to be grounded. When an airplane employs a single-wire electric system, it is important that all parts of the airplane be well bonded to provide a free and unrestricted flow of current throughout the structure. This is particularly important for aircraft in which sections are joined by adhesive bonding.

There are two general methods for connecting units in an electric system. These are illustrated in Fig. 1-20. The first diagram shows four lamps connected in **series.** In a circuit of this type, all the current flowing in the circuit must pass through each unit in the circuit. If one of the lamps should burn out, the circuit is broken and the other lamps in the circuit will stop burning. A familiar example of such a circuit is a set of series Christmas-tree lights.

In a **parallel** circuit there are two or more paths for the current, and if the path through one of the units is broken, the other units will continue to function. The units of an aircraft electric system are usually connected in parallel; hence, the failure of one unit will not impair the operation of the remainder of the units in the system. A simple parallel circuit is illustrated in the second diagram of Fig. 1-20. A circuit which has some of the units connected in series and the others connected in parallel is called a **series-parallel** circuit (see Fig. 1-21).

Ohm's law may be used to determine the electrical values in any common circuit even though it may contain a number of different load units. In order to solve such a circuit, it is necessary to know whether the units are con-

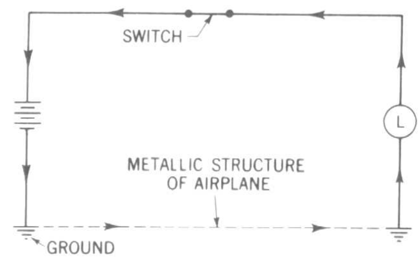


Fig. 1-19 Drawing to illustrate the single-wire system.

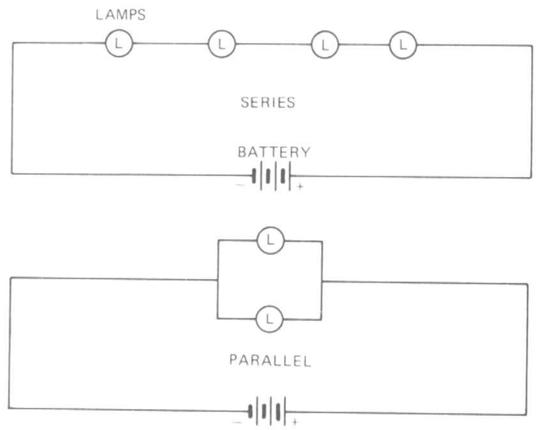


Fig. 1-20 Series and parallel circuits.

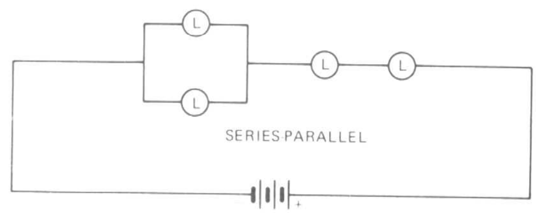


Fig. 1-21 A series-parallel circuit.

nected in series, parallel, or in a combination of the two methods. When the type of circuit is determined, the proper formula may be applied.

When a current flows through a resistance, the voltage across the resistance is equal to the product of the current and the resistance. The voltage is known as the **IR drop.** The *IR* drop in a complete circuit is equal to the voltage of the supply. This is shown in the water analogy in Fig. 1-22. Assume that the internal resistance of the battery is 0.1 Ω, the resistance of each lamp is 25 Ω, the resistance in the circuit is 100 Ω, and the battery voltage is 24 V. When load resistances are connected in series, we add them to find the total and then divide the total resistance into the voltage of the source to find the current, thus:

$$I = \frac{24}{0.1 + 25 + 25 + 100} = \frac{24}{150.1}$$
$$= 0.1599 \text{ A}$$

The voltage drop across any unit of the circuit may be found easily, because the current is the same through each unit. The voltage drop in the battery is found by