INDIAN EDITION

SIXTH EDITION

AIRCRAFT

ELECTRICITY AND ELECTRONICS

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Contents

Preface

Modern aircraft and aerospace vehicles are today more reliant on electrical and electronic systems than ever before. The "more electric airplane" is a design concept that enhances the use of electric power to replace traditional hydraulic, pneumatic, and other systems found on traditional planes. Aircraft such as the Boeing B-787 and Airbus A-380 embraced this concept in order to improve aircraft efficiencies and increase performance. The more electric airplane design concepts have also found their way into light business jets and single-engine trainer/personnel aircraft. Today, there are more electrical and electronic systems found on aircraft than ever before; for this reason all design, engineering, and technical personnel employed in the aerospace industry must have a solid understanding of the materials discussed in this text.

The integration of digital electronics and microprocessor technologies has allowed aircraft manufacturers to improve performance and safety while at the same time save weight compared to conventional systems. Electronic circuits are found in virtually every system of a modern aircraft. Large transport category aircraft are now fly-by-wire and utilize a variety of computers for navigation, flight management, and systems operation. Today, an aircraft technician must possess a thorough understanding of both basic electrical theory and advanced electronic systems. *Aircraft Electricity and Electronics* provides the reader with practical knowledge that can be used by students, engineers, and technicians alike.

In this sixth edition of *Aircraft Electricity and Electronics* several new technologies are introduced to the reader. As with modern aircraft, digital concepts are now integrated throughout the text. Digital data transfer systems, such as ARINC 664, AFDX, ARINC 429, and RS-232, are all presented in detail along with other data bus systems and concepts. Modern fly-by-wire aircraft are presented along with fiber optic technologies. New flight deck instrumentation systems, such as electronic flight bags, synthetic vision systems, and heads-up displays, are included in this edition.

The sixth edition has also improved some of the basic information necessary to build a proper foundation for understanding aircraft electrical systems. The current Federal Aviation Regulations concerning the certification of Airframe and Powerplant (A&P) Mechanics remain a vital component of this text. The text also presents information well beyond these basic requirements, thus providing the student with a thorough understanding of the theory, design, and maintenance of current aircraft electrical and electronic systems.

The book is written with the assumption that the reader possesses no prior knowledge of electricity and electronics, yet the text can also be used by experienced personnel to gain a better understanding of advanced systems. In Chaps. 1 through 5 basic electrical theory and concepts are discussed. These chapters include the fundamentals necessary for a strong understanding of the FAA's regulations as they pertain to aircraft electrical systems. Chapters 6 through 12 contain vital information on the design and maintenance of specific systems. This section begins with the basics on test equipment and electrical troubleshooting theory, and eventually presents an in-depth look at digital and microprocessor circuits as they apply to aircraft, computerized power systems, and the test equipment used for systems troubleshooting and repair. Chapters 13 through 17 introduce the reader to the advanced electronics found on modern aircraft. Integrated communication and navigation systems, autoflight and autoland systems, flat panel display systems, and fly-by-wire components are all presented to the reader in an easy-to-understand practical fashion.

The sixth edition of *Aircraft Electricity and Electronics* is the type of book you may acquire as a student and keep as a reference throughout your career.

Acknowledgments

Airbus Industrie of North America, Washington, DC, or Airbus Americas, Inc., Wichita, KS
AMP Products Corporation, Pennsylvania
Amprobe Instrument Corporation, Everett, WA
B&K Precision Corporation, Yorba Linda, CA
Beechcraft Corporation, Wichita, KS
BendixKing by Honeywell, Olathe, KS
Boeing Commercial Airplane Company, Seattle, WA
Cessna Aircraft Company, Wichita, KS
Christie Electric Corp., Gardena, CA
Clarostat Aircraft Company, Plano, TX
Concorde Battery Corporation, West Covina, CA
Daniels Manufacturing Corporation, Orlando, FL
Dayton-Granger, Inc., Fort Lauderdale, FL
Deutch Co., Banning, CA
Dynascan Technology, Inc., Irvine, CA
GC Electronics, Rockford, IL
Honeywell International, Inc., Morristown, NJ
Marathon Power Technologies, Waco, TX
Motorola Solutions, Inc., Schaumburg, IL
Piper Aircraft, Inc., Vero Beach, FL
Purdue University, Aviation Technology Department, Hanger 6 Maintenance Crew
Rockwell Collins, Rockwell International, Cedar Rapids, IA
Sundstrand Corporation, Rockford, IL
Teledyne Battery Products, Redlands, CA
Texas Instruments Inc., Dallas, TX
Thomas and Betts Corporation, Raritan, NJ
Westinghouse Electric Company, Cranberry Township, PA

Special thanks to
Nona, for her help and for her smile.

Fundamentals of Electricity 1

INTRODUCTION

This current period in history is often called the "information age" because electricity and electronic circuits can collect, store, and analyze vast quantities of information. Through the use of computer systems, electronic circuits are used to control virtually every system found on modern aircraft. **Electronics** is a special application of electricity wherein precise manipulation of electrons is employed. Today's aircraft use computers, electronics, and electrical circuits more than ever before. It is safe to say that neither state-of-the-art aircraft nor space vehicles could fly without the use of electricity/electronics.

Electrical systems serve two basic functions on modern aircraft: (1) to power systems, such as, lights and motors and (2) to collect and analyze information, such as in computer systems. The term *electricity* is used when referring to power circuits, while the term *electronics* typically refers to transistorized and computer systems. Today's technicians and engineers must possess a thorough understanding of all facets of electronics. Typically, this knowledge would be used during design, inspection, installation, and repair of the aircraft.

Before the previous century, little was known concerning the nature of electricity. However, modern theoretical concepts, mathematics, and basic physical laws have explained how electricity acts. We can now predict with extreme accuracy virtually all aspects of electricity, either through mathematics or by observation and documentation of electrical actions. The precise reasons why electricity acts as it does may be debated for quite some time; meanwhile, we will continue to make electricity a useful tool by predicting its actions.

On modern aircraft, electricity performs many functions, including the ignition of fuels in piston or turbine engines, the operation of communication and navigation systems, the movement of flight controls, and analysis of system performance. Like a modern home or office, aircraft have become computerized and onboard systems communicate using data connections similar to the Ethernet. These computerized systems make air travel more comfortable, highly efficient, and safer than ever before.

THE ELECTRON THEORY

The atomic structure of matter dictates the means for the production and transmission of electrical power. All matter contains microscopic particles made of electrons and protons. The forces that bind these particles together to create matter are the same forces that create electrical current flow and produce electrical power. Every aircraft generator, alternator, and battery, virtually all electrical components, react according to the **electron theory**. The electron theory describes specifically the internal molecular forces of matter as they pertain to electrical power. The electron theory is therefore a vital foundation upon which to build an understanding of electricity and electronics.

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. An **element** is a single substance that cannot be separated into different substances.

At the time this text was written, there were 118 known elements. Although some elements are radioactive and very unstable, there are 80 stable elements which are also known as common elements. Examples of common elements are iron, copper, lead, gold, zinc, oxygen, hydrogen, and so on. Any pure element consists of one type of atom and will have

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valence orbit of the material's atoms. The **valence orbit** of any atom is the outermost orbit (shell) of that atom. The electrons in this valence orbit are known as **valence electrons.** All atoms desire to have their valence orbit completely full of electrons, and the fewer valence electrons in an atom, the easier it will accept extra electrons. Therefore, atoms with fewer than half of their valence electrons tend to easily accept (carry) the moving electrons of an electric current flow. Such materials are called **conductors.** Materials that have more than half of their valence electrons are called **Insulators.** Insulators will not easily accept extra electrons. Materials with exactly half of their valence electrons are **semiconductors.** Semiconductors have very high resistance to current flow in their pure state; however, when exact numbers of electrons are added or removed, the material offers very low resistance to electric current flow.

Semiconductors can act like a conductor or an insulator, depending on what external charge is placed on the material. Semiconductors are the basic materials used to produce transistors and integrated circuits.

Two of the best conductors are gold and silver; their valence orbits are nearly empty, containing only one electron each. Two of the best insulators are neon and helium; their atoms contain full valence orbits. We commonly substitute other "less perfect" materials for conductors and insulators to reduce costs and increase workability. Common conductors are copper and aluminum; common insulators are air, plastic, fiberglass, and rubber Fig. 1-4. The two most common semiconductors are germanium and silicon; both of these materials have exactly four electrons in their valence orbits. As shown in Fig. 1-5 atoms with four valence electrons are semiconductors; atoms with fewer than four valence electrons are conductors; those with more than four valence electrons are insulators.

Simply being a conductor does not create electron movement. There must be an external force in addition to the molecular forces present inside the conductor's atoms. On the aircraft the external forces are usually supplied by the battery, generator, or alternator. The atoms' internal forces are caused by the repulsion of two similar charged bodies, such as two electrons or two protons, and the attraction of two dissimilar charged bodies, such as one electron and one proton.

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 that causes electrons to move through a conductor. Remember, the attraction force of the protons in their nucleus to the electrons in their orbits creates stability in an atom whenever a neutral charge is present. If an extra electron enters the atom's outer orbit, the atom becomes very unstable. It is this unstable repelling force between the orbiting electrons that

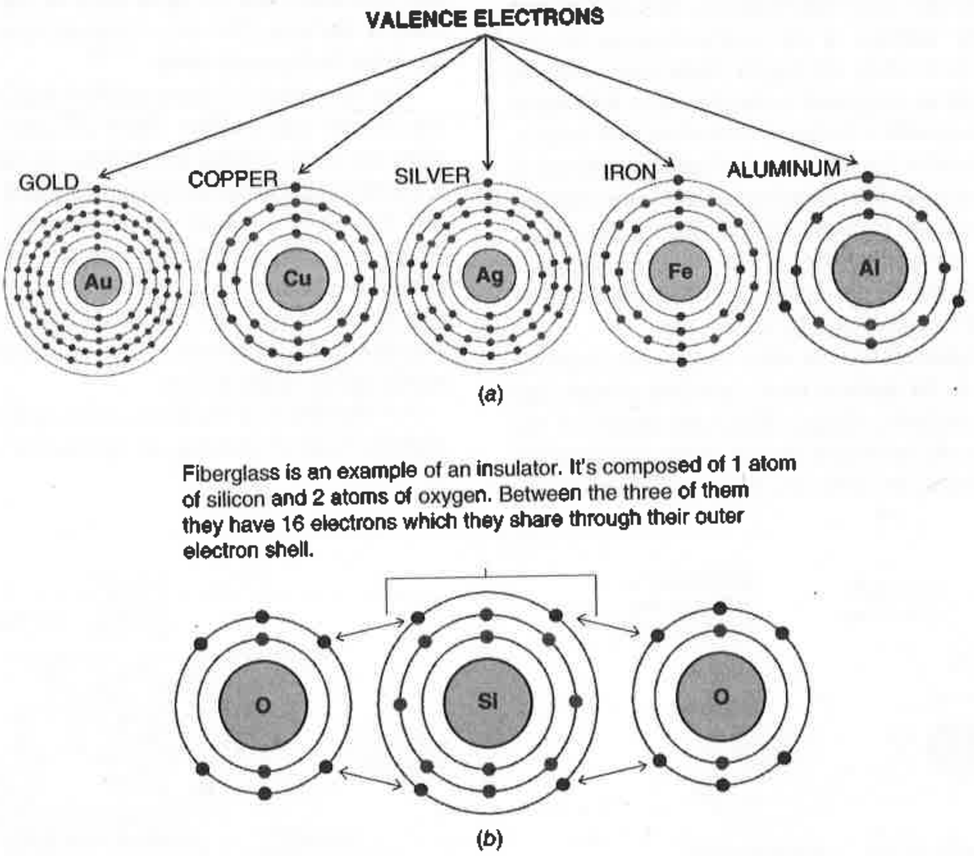


FIGURE 1-4 The number of electrons in the outer orbit of an atom determines if a material is a conductor or an insulator: (*a*) common conductors have less than 4 electrons, (*b*) insulators have more than 4 electrons.

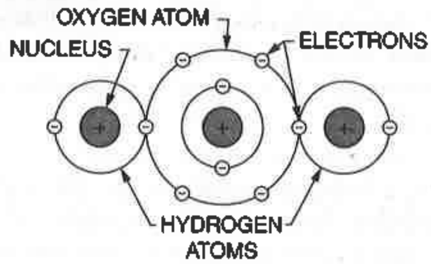


FIGURE 1-1 A water molecule.

properties of only that one element. For example, a copper element will consist of one or more atoms; each atom will have the specific properties of copper.

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

An atom consists of extremely small particles of energy known as electrons, protons, and neutrons. All matter consists of two 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 elliptical to circular 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 **negative** charge is carried by each electron. The charges carried by the electron and the proton are equal in magnitude but opposite in nature. An atom that has an equal number of protons and electrons is electrically neutral; that is, the charge carried by the electrons is balanced by the charge carried by the protons.

It has been explained that an atom carries two opposite charges: protons in the nucleus have a positive charge, and electrons have a negative charge. 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. It should be noted that protons remain within the nucleus; only electrons are added or removed from an atom, thus creating a positive or negative ion. This movement of electrons is the basis for all electrical power.

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. Figure 1-2 illustrates this concept. 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 on the total number of electrons surrounding the nucleus.

The atomic structure of a substance 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.

The movement of free electrons does not always constitute electric current flow. There are often several free electrons randomly drifting through the atoms of any conductor. It is only when these free electrons move in the same direction that electric current exists. A power supply, such as a battery, typically creates a potential difference from one end of a conductor to another (Fig. 1-3). A strong negative charge on one end of a conductor and a positive charge on the other is the means to create a useful electron flow, commonly called "current flow."

An element is a conductor, nonconductor (insulator), or semiconductor depending on the number of electrons in the

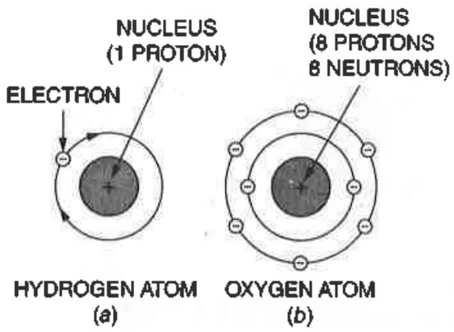


FIGURE 1-2 Structure of atoms.

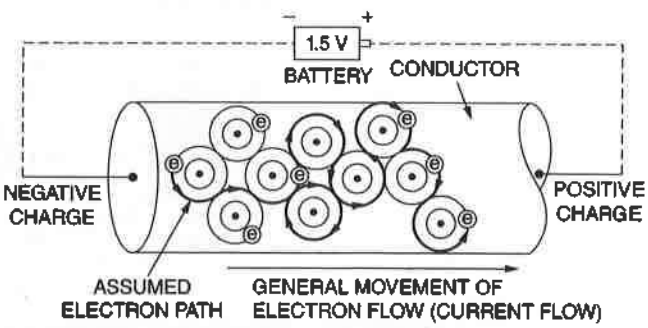


FIGURE 1-3 Electrical pressure (voltage) creates electron movement through a conductor.

The specific location of the positive and negative connections of a given circuit is called *polarity*. For example, when replacing a battery in a simple calculator one must insert the battery in the correct direction. The positive side of the battery must be placed on the positive connection and the negative side of the battery must be placed on the negative connection. This ensures the battery will be installed with the correct polarity. The calculator is said to be *polarity sensitive* and will only operate with the battery installed correctly. For most aircraft electrical installations observing the correct polarity is very important.

One of the latest theories that defines the direction of current flow states that electrons flow in one direction and holes flow in the opposite direction. A **hole** is the space created by the absence of an electron. As electrons would move from negative to positive, holes would move from positive to negative. This concept is often used when studying the internal current flow of semiconductors; however, for general applications of current flow, holes need not be considered.

It is important not to let this concept of current flow direction confuse your understanding of electricity. Simply be consistent in your approach and remember while reading this text or any FAA material, *current flows from negative to positive.*

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 that are at rest are called **static electricity.**

A material with atoms containing equal numbers of electrons and protons is electrically neutral. If the number of electrons in that material should increase or decrease, the material is left with a static charge. An excess of electrons creates a negatively charged body; a deficiency of electrons creates a positively charged body. This excess or deficiency of electrons can be caused by the friction between two dissimilar substances or by contact between a neutral body and a charged body. If friction produces the static charge, the nature of that charge 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 one that follows it, when the two are in contact.

1. Fur
2. Flannel
3. Ivory
4. Crystals
5. Glass
6. Cotton
7. Silk
8. Leather
9. The body
10. Wood
11. Metals
12. Sealing wax
13. Resins
14. Gutta percha
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 nonconductor material. When a conductor is charged, it can discharge easily since electrons travel freely through conductors.

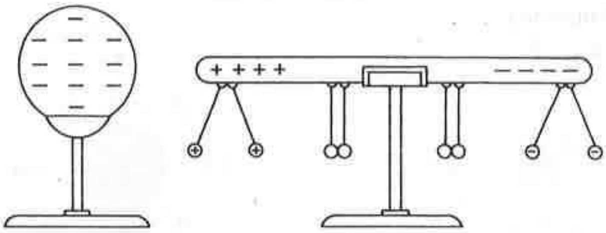


FIGURE 1-7 Charging by induction.

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. 1-7 is charged negatively and brought near one end of a metal rod that is also insulated from other conductors. The electrons constituting the negative charge in the sphere repel the electrons in the rod and drive them to the opposite site 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.

The force that is created between two charged bodies is called the **electrostatic force.** This force can be either attractive or repulsive, depending on the object's charge. Like charges repel each other. Unlike charges attract each other. The electrostatic force is similar to those forces that exist inside of an atom between electrons and protons. However, the electrostatic force is considered to be on a much larger scale, dealing with entire objects, not minute atomic particles. The amount of static charge contained within a body will determine the strength of the electrostatic field. Weak charges produce weak electrostatic fields and vice versa. Precisely, the strength of an electrostatic field between two bodies is directly proportional to the strength of the charge on those two bodies. Figure 1-8*a*

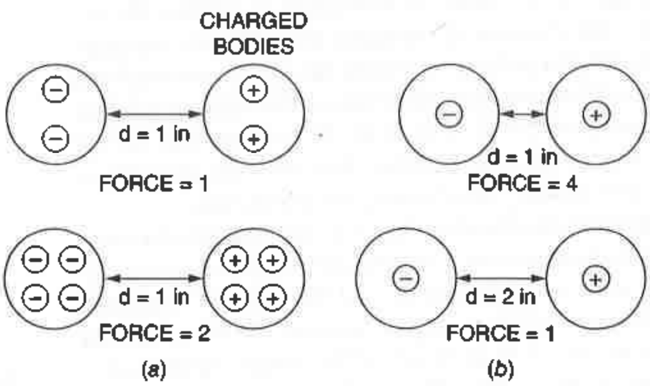


FIGURE 1-8 The strength of an electrostatic force. (*a*) Twice the static charge equals twice the static force. (*b*) Twice the distance equals one-fourth the static force.

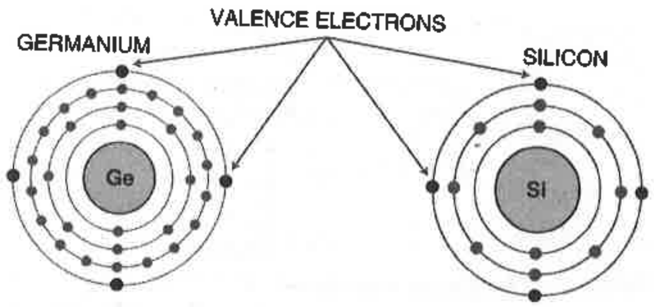


FIGURE 1-5 Semiconductors have exactly four electrons in the atom's outer orbit.

causes the movement of any extra electron through the conductor. 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.

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 can therefore be said that electricity flows from negative to positive.

In many cases it is assumed that electric current flows from positive to negative. This is often referred to as "conventional current flow." Since the polarities of electric charges were arbitrarily assigned names *(positive* and *negative),* the actual direction of current flow is difficult to distinguish without the true nature of electric current being considered. When studying the molecular nature of electricity, it is necessary to consider the true direction of electron flow, but for all ordinary electrical applications, the direction of flow can be considered to be in either direction as long as the theory is used consistently. Many texts adhere to the conventional theory that current flows from positive to negative; however, 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 Federal Aviation Administration (FAA) adheres to the concept that current flows from negative to positive; therefore, the majority of the aviation industry also follows this convention.

In most practical applications it is **not** important to know which direction current flows (negative to positive or positive to negative). If the battery and the load are connected correctly there will be a current flow and the circuit should operate, see Fig. 1-6. However, if the battery becomes disconnected from the load, the circuit will not operate. So in most cases, the technician is concerned that current flows in the circuit; not which direction current flows.

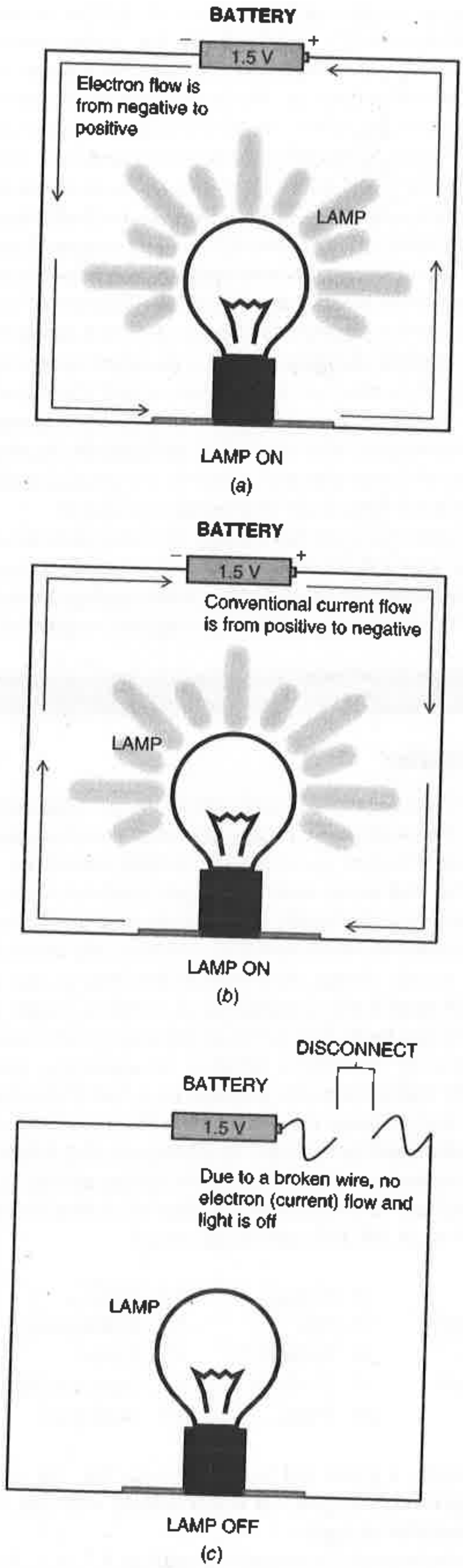


FIGURE 1-6 A complete circuit illuminates the light: *(a)* electron flow—from negative to positive, *(b)* conventional current flow—from positive to negative, *(c)* circuit disconnected—no electron/current flow.

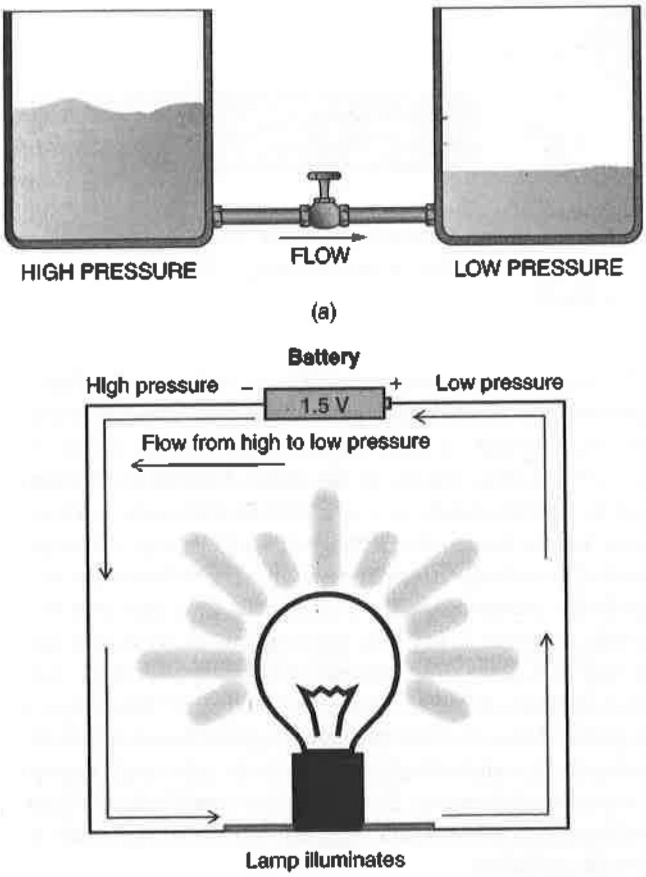


FIGURE 1-10 Pressure (force) creates movement (*a*) water flows from high to low pressure; (*b*) electrons flow from high to low pressure.

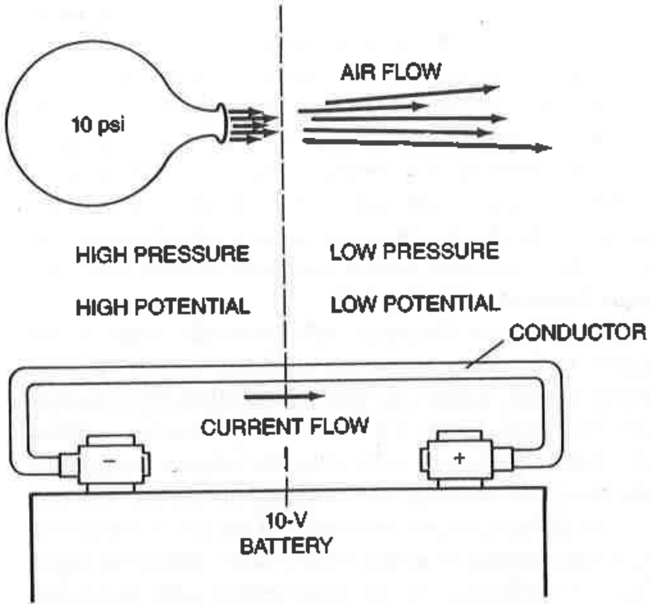


FIGURE 1-11 Comparison of voltage to air pressure.

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 (see Fig. 1-10*b*). 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 that may be used to illustrate potential difference. For example, when an automobile tire is inflated, a difference of potential (pressure) exists between the inside of the tire and the outside. When the valve is opened, the air rushes out. In this case the air inside the tire represents an excess of electrons, a high potential, or a negative charge. The air outside the tire represents a deficiency of electrons, a low potential, or a positive charge.

The force that causes electrons to flow through a conductor is called **electromotive force,** abbreviated emf. EMF can be thought of as the electron-moving force. The practical unit for the measurement of emf or potential differences 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.

One volt is the emf required to cause current to flow at the rate of 1 ampere through a resistance of 1 ohm. The term *ohm* is defined later in this chapter. 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 or force exists that 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. In practical terms, a charged battery will supply current to a circuit as long as the battery remains charged. Whenever the battery is charged, there is a voltage (electromotive force) ready to "push" electrons through a circuit.

With reference to Fig. 1-11, it can be seen that voltage, the potential difference in a battery, creates an electron flow, just as pressure inside a balloon, a potential air pressure difference, creates an air flow. Voltage (electrical pressure) causes electrons to flow through a conductor. This is no mystery. Any object, including electrons, will tend to move when pressure is applied in a certain direction.

Electromotive force, which is the force that causes electrons to move, could also be considered electrical potential or pressure. The term **voltage,** which is measured in volts, is typically substituted for emf. Voltage is symbolized by the letter **E,** and volts is symbolized by the letter **V.**

Resistance

Resistance is that property of a conductor which tends to hold, 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 electrons 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 demonstrates this concept. The strength of the electrostatic force is also affected by the distance between the two charged bodies. If the distance between the two charged substances increases, the electrostatic force decreases; conversely, if the distance decreases, the force increases. Precisely, the electrostatic force between two charged bodies is inversely proportional to the square of the distance between those two bodies. That is, as the distance becomes twice as large between the bodies, the electrostatic force is one-fourth as great. This concept is demonstrated in Fig. 1-8*b*.

Static electrical discharge will eventually occur to all charged bodies. Any unbalance of charge strives for equilibrium. Usually contact is made with another object to neutralize the static charge. If a charged body contacts a neutral body, both objects will then share the original charge. An example of this discharge occurs when a person gets shocked while touching a common door knob. If the person has generated a static charge (typically occurs while walking on carpet in dry air conditions), the discharge occurs as the individual makes contact with the metal knob. If the neutral body is large enough, such as the earth, virtually all the charge will become neutralized, or absorbed, by the large body.

Static discharge has become a major problem for modern microelectronics. The miniaturization of modern computerized systems has caused them to become extremely delicate. The discharge of static electricity can easily damage these components. Sensitive electronics are known as electrostatic discharge sensitive (ESDS) components. Anyone who designs, installs, or maintains aircraft electronics must follow proper procedures to prevent damage due to static discharge. ESDS prevention techniques will be discussed later in this text.

UNITS OF ELECTRICITY

Current

An electric **current** is defined as a flow of electrons through a conductor. Earlier in 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.

Because each electron has mass and inertia, electron flow is capable of doing work such as turning motors, lighting lamps, and warming heaters. Just as moving water can turn a primitive paddle wheel to grind wheat, moving electrons can do the same. Even at the speed of light, a single electron could not do much work; however, if enough electrons are set into motion, vast amounts of work can be done using electricity.

It is often hard to understand that moving electrons can do useful work, but remember electrons do have mass and any moving mass can perform work.

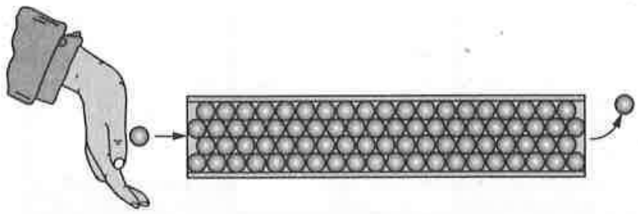


FIGURE 1-9 Demonstration of current flow. One electron into the conductor instantaneously means one electron out of the conductor.

It is said that an electric current travels at the speed of light, approximately 186000 miles per second (mps) [299000 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. 1-9, 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 complete conducting path before they will enter or leave the conductor.

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 that, 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.

For practical situations, electric current is measured in a unit called the *ampere.* **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 term **current** is symbolized by the letter **I.** Current is the measure of flow or movement of electrons. Current is measured in amperes, which is often abbreviated **amps.**

Voltage 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. 1-10(*a*), 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.

the south pole of a magnet is not known, but it is known that the force acts in a definite direction. This is indicated by the fact that a north pole will repel another north pole but will be attracted by a south pole. Like poles repel; unlike poles attract. A **permanent magnet** is one that maintains an almost constant magnetic field without the application of any magnetizing force. Most permanent magnets show practically no loss of magnetic strength over a period of several years.

A **natural magnet** is one found in nature; it is called a **lodestone,** or *leading stone.* The natural magnet received this name because it was used by early navigators to determine direction. The lodestone is composed of an oxide of iron called magnetite.

When first discovered, the lodestone was found to have peculiar properties. When it was freely suspended, one end always pointed in a northerly direction. For this reason, one end of the lodestone was called the *north-seeking* and the other the *south-seeking* end. These terms have been shortened to *north* and *south,* respectively. The reason that a freely suspended magnet assumes a north-south position is that the earth is a large magnet and the earth's magnetic field exists over the entire surface. The suspended magnet's lines of force interact with the earth's magnetic field and align the magnet accordingly. According to definition, the magnetic pole near the earth's north geographic pole is actually the earth's south magnetic pole. This can be demonstrated by suspending a magnet on a string and noting the direction in which the north pole points. The magnet's north pole points to the earth's geographic north, but by definition, north should repel north; therefore, the earth's south magnetic pole is actually nearest the earth's geographic north. This concept, is demonstrated in Fig. 1-14. To eliminate confusion, the direction in which a magnet's north pole points is called the earth's north pole. In reality it is magnetic south.

The magnetic poles of the earth are not located at the geographic poles. The magnetic pole in the northern hemisphere is located east of geographic north. The magnetic south pole is located west of geographic south, as illustrated in Fig. 1-14. The difference between the geographic and magnetic poles is called **magnetic variation.** Magnetic variation is sometimes referred to as *magnetic declination.* In general, this principle of magnetic variation does not affect electrical phenomena; however, it becomes very important when navigating aircraft using a magnetic compass.

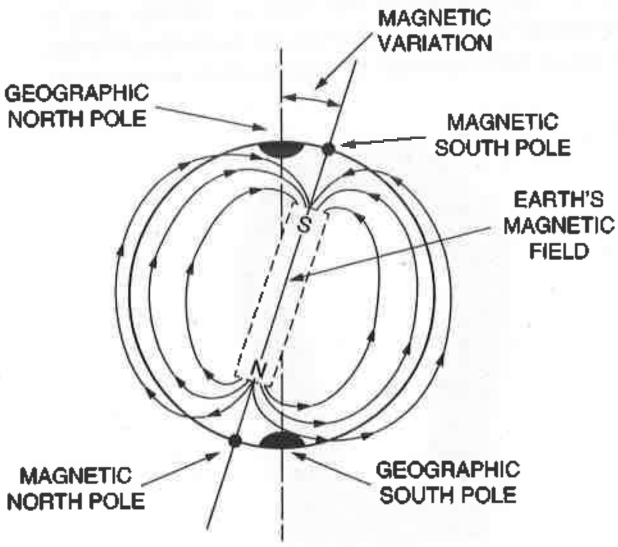


FIGURE 1-14 The earth's magnetic field.

The true nature of magnetism is not clearly understood, although its effects are well known. One theory that seems to provide a logical explanation of magnetism assumes that atoms or molecules of magnetic substances are in reality small magnets. It is reasoned that electrons moving around the nucleus of an atom create minute magnetic fields. In magnetic substances such as iron it is assumed that most of the electrons are moving in one general direction around the nuclei; hence these electrons produce a noticeable magnetic field in each atom, and each atom or molecule becomes a tiny magnet. When the substance is not magnetized, the molecules lie in all positions in the material, as shown in Fig. 1-15*a*, and their fields tend to cancel one another. When the substance is placed in a magnetic field, the molecules align themselves with the field, and the fields of the molecules add to the strength of the magnetizing field. A diagram of a magnetized substance is shown in Fig. 1-15*b*.

When a piece of soft iron is placed in a magnetic field, almost all the molecules in the iron align themselves with the field, but as soon as the magnetizing field is removed, most of the molecules return to their random positions, and the substance is no longer magnetized. Because some of the molecules tend to remain in the aligned position, every magnetic substance retains a slight amount of magnetism after having been magnetized. This retained magnetism is called **residual magnetism.**

Certain substances, such as hard steel, are more difficult to magnetize than soft iron because of the internal friction among the molecules. If such a substance is placed in a very strong magnetic field, the molecules become aligned with the field. When the substance is removed from the magnetic field, it will retain its magnetism; hence it is called a **permanent magnet.** Hard steel and certain metallic alloys—such as Alnico, an alloy containing nickel, aluminum, and cobalt—have the ability to retain magnetism. Permanent magnets retain their magnetism for the same reason that they are difficult to magnetize; that is, the molecules do not shift their positions easily. When the molecules are aligned, all the north

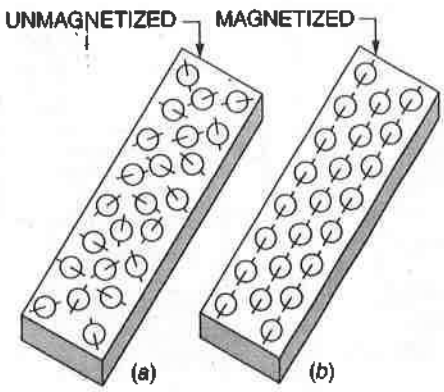


FIGURE 1-15 Theory of magnetism.

the interior of the pipe were clean and smooth. The rough pipe offers greater resistance, or friction, than the smooth pipe.

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**. Resistance is opposition to current flow and is symbolized by the letter **R**. Resistance is measured in ohms, which is symbolized by the Greek letter omega, Ω.

Earlier it was explained that materials with a small number of valence electrons, fewer than four, are conductors. Conductors have a relatively low resistance because they accept extra electrons (current flow) easily. If a voltage is applied to a conductor, an electric current will flow, assuming a complete circuit is present. As seen in Fig. 1-12*a*, if a heavy wooden crate is pushed on a highly polished floor, the crate will slide easily because the floor offers low resistance, or low opposition, to movement. If the same crate is placed on a rough concrete floor and pushed again with the same force, little or no movement will take place owing to the high resistance offered by the rough floor. Now compare the crate in Fig. 1-12*a* with the circuit in Fig. 1-12*b*. A circuit of low resistance with an applied 5 V will easily move electrons. The same 5 V applied to a circuit of high resistance—an open switch, for example—is capable of moving no electrons. It should be noted that the resistance of an open switch is so great that no current will flow. An open switch is considered infinite resistance.

Insulators are materials that have more than four valence electrons. Insulators will not accept the extra electrons of current flow easily and therefore are considered to have relatively high resistance. If a moderate voltage is applied to an insulator, no electric current will flow. 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 to block the flow of current effectively. In most cases these insulators are said to have an infinite resistance.

According to the electron theory, the atoms of an insulator do not give up electrons easily. When a voltage is applied to such a substance, the outer electron orbits are distorted, but as soon as the voltage is removed, the electrons return to their normal positions. If, however, the voltage 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. An example of this phenomenon is when a common lightning bolt travels through air during a rain storm. The lightning produces such high voltage that current is forced through the air, which is an insulator under most situations.

THEORY OF MAGNETISM

The Magnet

Almost everyone has witnessed the effects of magnetism, and many have owned simple permanent magnets such as that illustrated in Fig. 1-13. However, few people realize the importance of magnetism and its relationship to electricity. In the scientific community it is commonly thought that electricity would not exist without magnetism. A **magnet** may be defined as an object that attracts ferrous metals such as iron or steel. It produces a magnetic field external to itself that reacts with magnetic substances.

A magnetic field is assumed to consist of invisible lines of force that leave the **north** pole of a magnet and enter the **south** pole. The direction of this force is assumed only in order to establish rules and references for operation. Whether there is any actual movement of force from the north pole to

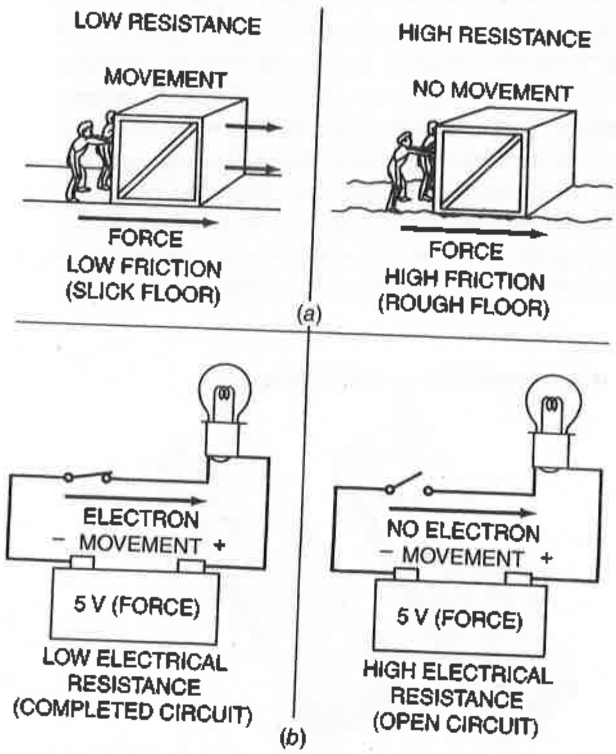


FIGURE 1-12 Comparison of resistance to friction.

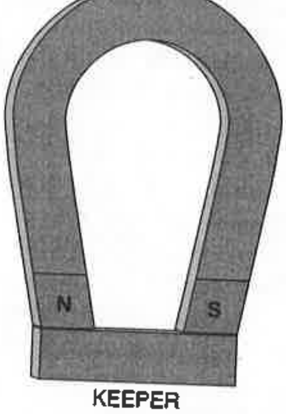


FIGURE 1-13 A permanent magnet.

MAGNETIC DEVICES

Electromagnets

Electromagnets, in various forms, are very useful items and have become commonplace on modern aircraft. **Electromagnets,** as the name implies, are produced by using an electric current to create a magnetic field. Around every conductor carrying electric current a magnetic field exists. Figure 1-19(*a*) shows a compass used to detect the magnetic field adjacent to a conductor that carries current. This magnetic field is created due to the movement of electrons through the conductor. Typically this magnetic field is so small it is unnoticed. However, if the current is very strong or the conductor is formed into a coil, the magnetic field strength increases. Most electromagnets are constructed of a wire coil with hundreds of turns to create the desired magnetic field strength.

In Fig. 1-19*b*. the shaded circle represents a cross section of a conductor with current flowing in toward the paper. The current is flowing from negative to positive. When the current flows as indicated, the magnetic field is in a counterclockwise direction. This is easily determined by the use of the left-hand rule. When a wire is grasped in the left hand with the thumb pointing from negative to positive, the magnetic field around the conductor is in the direction that the fingers are pointing.

If a current-carrying wire is bent into a loop or coil, the coil assumes the properties of a magnet; that is, one side of the loop will be a north pole, and the other side will be a south pole. Remember electromagnets are made of a wire coil, not a single wire. When a wire is made into a coil and connected to a source of power, the fields of the separate turns join and thread through the entire coil, as shown in Fig. 1-20*a*. Figure 1-20*b* shows a cross section of the same coil. Note that the lines of force produced by one turn of the coil combine with the lines of force from the other turns and thread through the coil, thus giving the coil a magnetic polarity. The polarity of the coil is easily determined by the use of the **left-hand rule for coils:** *When a coil is grasped in the left hand with the fingers pointing in the direction of current flow, that is, from negative to positive, the thumb will point toward the north pole of the coil.*

Most electromagnets wrap the wire coil around a soft iron core material. The core provides structure around which the copper wire is wrapped. And, the core helps to direct the magnetic flux fields into a given area. Of course, the wire in the coil must be insulated so that there can be no short circuit between the turns of the coil. A typical electromagnet is made by winding many turns of insulated wire on a soft-iron core that has been wrapped with an insulating material. The turns of wire are placed as close together as possible to help prevent magnetic lines of force from passing between the turns. Figure 1-21 is a cross-sectional drawing of an electromagnet.

The strength of an electromagnet is directly proportional to (1) the strength of current flowing through the electromagnetic coil, and (2) the number of turns of wire in the electromagnetic coil. That is, as either the current through the coil or the number of wire wraps around the coil increases, the electromagnet's strength also increases. Also, use of a core material of high permeability will increase an electromagnet's strength.

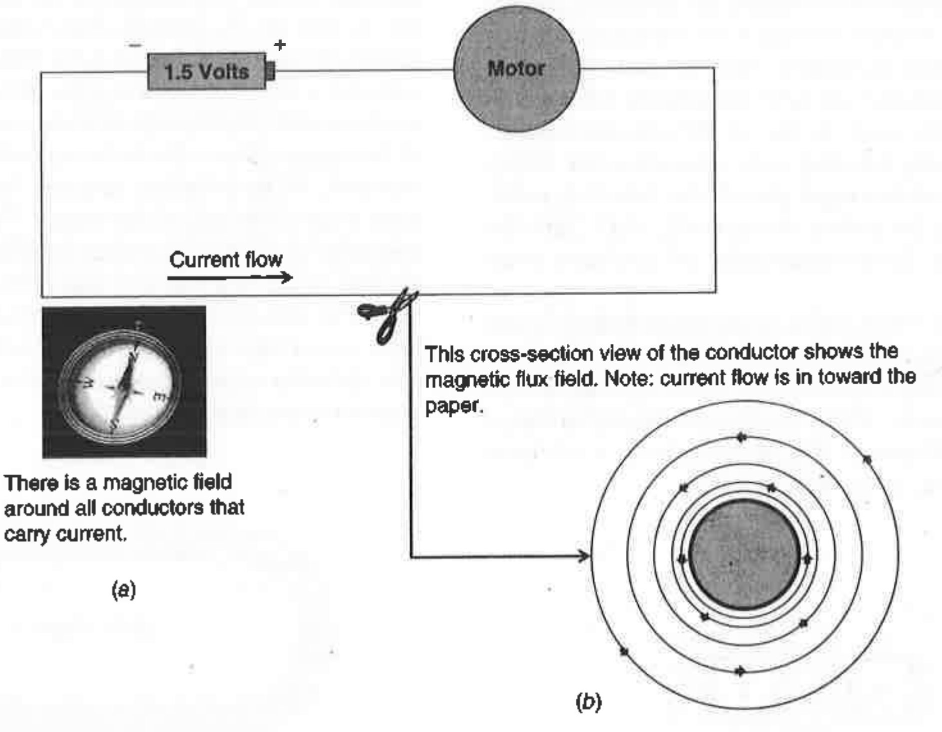


FIGURE 1-19 Electron (current) flow creates a magnetic field: (*a*) the magnetic field can be measured adjacent to a wire carrying current; (*b*) the magnetic flux field around a conductor.

poles of the molecules point in the same direction and produce the north pole of the magnet. In like manner, the south poles of the molecules produce the south pole of the magnet.

Many substances have no appreciable magnetic properties. The atoms of these substances apparently have their electron orbits in positions such that their fields cancel one another. Among these substances are copper, silver, gold, and lead.

The ability of a material to become magnetized is called **permeability.** A material with high permeability is easy to magnetize or demagnetize. A material with low permeability is hard to magnetize or demagnetize. Materials with high permeability, such as soft iron, are most useful as temporary magnets. Materials with low permeability, such as Alnico, are best suited for permanent magnets.

The most newly discovered magnetic materials are known as *rare earth elements.* These rare earth elements (or rare earth metals) are a set of 17 chemical elements which occur naturally on Earth. Despite their name, most rare earth elements are relatively plentiful in the earth's crust. However, these elements are typically widely dispersed and not often found in concentrated and economically usable forms. Whenever a rare earth element is formed into a magnet, it is often called a *rare earth magnet.* In general, most rare earth metals can be made into very strong magnets and have become popular in many modern electrical components due to their relative strength. For example, many compact, yet powerful, motors use rare earth magnets to help create a rotational force.

Properties of Magnetism

The field of force existing between the poles of a magnet is called a **magnetic field.** The pattern of this field may be seen by placing a stiff paper over a magnet and sprinkling iron filings on the paper. As shown in Fig. 1-16, the iron filings will line up with the lines of magnetic force. It will be noted that the lines directly between the poles are straight, but the lines farther from the direct path are curved. This curving is due to the repulsion of lines traveling in the same direction. If iron filings are sprinkled on a paper placed over two north poles, the field will have the pattern shown in Fig. 1-17. Here the lines of force from the two poles come out and curve away from one another.

Magnetic force, which is also called **magnetic flux**, is said to travel from north to south in invisible lines. By assuming a direction, we provide a reference by which calculations can be made and magnetic effects determined. Since iron filings in a magnetic field arrange themselves in lines, it is logical to say that magnetic force exists in lines.

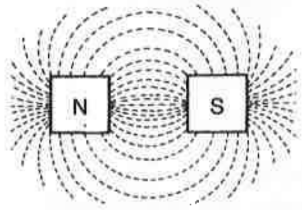


FIGURE 1-16 A magnetic field.

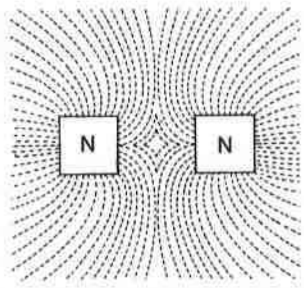


FIGURE 1-17 Magnetic field between two like magnetic poles.

The space or substance traversed by magnetic lines of force is called the **magnetic circuit**. If a soft-iron bar is placed across the poles of a magnet, almost all the magnetic lines of force (flux) go through the bar, and the external field will be very weak.

The external field of a magnet is distorted when any magnetic substance is placed in that field because it is easier for the lines of force to travel through the magnetic substance than through the air (see Fig. 1-18). The opposition of a material to magnetic flux is called **reluctance** and compares to resistance in an electric circuit. The symbol for reluctance is R and the unit is **rel.** As with electric current, the material that will completely resist magnetic flux lines is unknown. However, some materials will accept flux lines more easily than others.

In review, the properties of magnets are as follows: (1) The pole that tends to point toward the earth's geographic north is called the magnet's north pole. The opposite end is called the south pole. (2) Like magnetic poles repel each other, and unlike poles attract each other. (3) A magnetic field surrounds each magnet and contains magnetic flux lines. These flux lines are directly responsible for the magnetic properties of the material. (4) The strength of any magnet is directly proportional to the density of the flux field. That is, a stronger magnet will have a relatively larger number of flux lines concentrated in a given area. (5) Magnetic fields are strongest near the poles of the magnet. This is due to the concentration of flux lines at each pole. (6) By definition, magnetic flux lines flow from the north to the south pole of any magnet. This property becomes important when studying certain relationships of magnetism. (7) Flux lines never intersect. This is because flux lines repel each other with relatively tremendous force. (8) Magnetic flux lines always take the path of least resistance, such as when they distort in order to travel through a piece of soft iron as opposed to traveling through air.

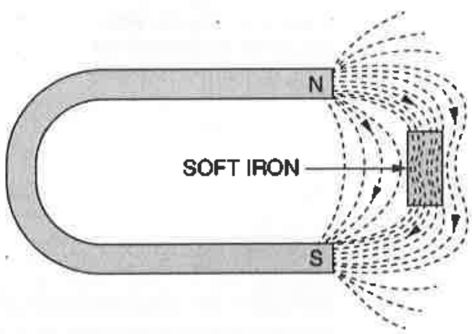


FIGURE 1-18 Field distorted by a magnetic substance.

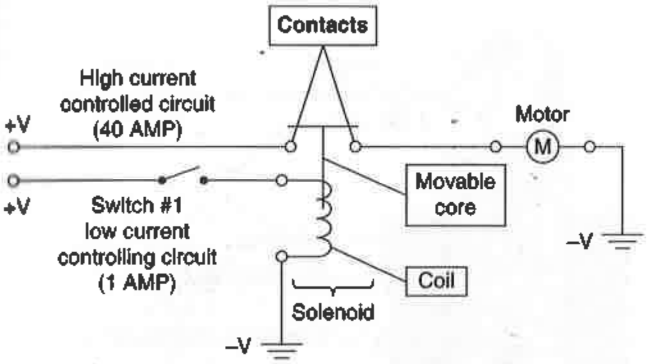


FIGURE 1-23 A solenoid has two independent circuits, a low current "controlling" circuit and a high current "controlled" circuit.

used for low-current switching applications. Figure 1-24 illustrates a typical switching relay. Note, the electromagnet core on a relay is stationary, unlike a selenoid.

The part of the relay attracted by the electromagnet to open or close the contact points is called the **armature.** There are several types of armatures in electrical work, but in every case it will be found that an armature consists, in part, of a bar or core of material that may be acted upon by a magnetic field. In a relay, the armature is attracted to the electromagnet, and the movement of the armature either closes or opens the contact points. In some cases, the electromagnet operates several sets of contact points simultaneously.

There is much confusion surrounding the terminology of relays and solenoids because of their similarities. Relays are often called solenoids and vice versa. For the purpose of this text, and as generally accepted in the aircraft industry, a *solenoid* is an electromagnet with a movable core material, and a *relay* is an electromagnet with a fixed core. These definitions hold true whether the electromagnet is used for electrical switching or other mechanical functions. Figure 1-25 shows the photos of both a relay and a solenoid. Note the differences: (1) the solenoid has a movable core, while the relay core is stationary; (2) the solenoid is used to control high-current circuits and the relay is used to control low-current circuits. Due to the immovable core, a solenoid is much stronger than a relay. This is why solenoids are typically used for operation of mechanical systems, such as a mechanical latch. Solenoids (not relays) are also used to control high-current circuits, such as starter motors. To help eliminate confusion, many aircraft manufacturers have substituted the term *contactor* or *breaker* for electrical switching solenoids or relays.

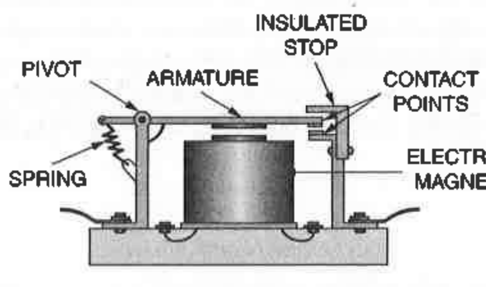


FIGURE 1-24 Electromagnetic switches: relay.

METHODS OF PRODUCING VOLTAGE

As discussed earlier, *voltage* is the force, or pressure, that creates electron movement. Voltage must be present in all circuits in order to produce current flow, but what creates voltage? Voltage is created by limited means, and only two methods produce nearly 100 percent of all electric power consumed by typical aircraft.

Friction is a method of producing voltage by simply rubbing two dissimilar materials together. This usually produces **static electricity,** which is not typically a useful form of power. In fact, most static electricity found on the aircraft becomes a nuisance to both communication and navigation systems as well as advanced electronic devices.

Pressure is another means of producing voltage. **Piezoelectricity** means electricity created by applying pressure to certain types of crystals. Since only small amounts of power are produced using piezoelectricity, applications are limited. Some microphones used for radio communications employ the piezoelectric effect to convert sound waves into electric power. Most piezoelectric devices use crystalline materials like quartz to produce voltage. When a force is applied to certain crystals, their molecular structure distorts and electrons may be emitted into a conductor. Piezoelectric crystals are also used in some navigation equipment and various systems sensors. These will be discussed later in this text.

Light is a source of energy that also can be converted into electricity. The **photoelectric effect** produces a voltage when light is emitted onto certain substances. Zinc is a typical photosensitive material. If exposed to ultraviolet rays, under the correct conditions, zinc will produce a voltage. Although photoelectric devices are limited in modern aircraft, spacecraft and satellites rely heavily on photo cells (solar cells) and the sun for a source of electric power. Some aircraft use light sensors on modern flight deck display systems. These sensors operate using the photoelectric effect. As more light reaches the sensor, more voltage is produced, see Fig. 1-26.

Heat can also be used to produce voltage. Electricity produced by subjecting two dissimilar metals to above normal temperatures is called the **thermoelectric effect.** For example, copper and zinc held firmly together will produce voltage when subjected to heat. This combination of two dissimilar metals is called a **thermocouple.** Thermocouples are used in virtually any electronic temperature sensor found on aircraft. These include exhaust gas and cylinder head temperature sensors, electronic equipment temperature monitors, and some fire detectors.

Chemical action takes place in all batteries to produce electricity for aircraft systems. A battery is found on virtually all aircraft, producing voltage because of the reaction of two or more different chemicals. When two or more of the correct chemicals come in contact, their structures are altered and voltage is produced. Most aircraft contain a battery used for engine starting and emergency procedures. Modern large aircraft contain several batteries used to power a variety of equipment.

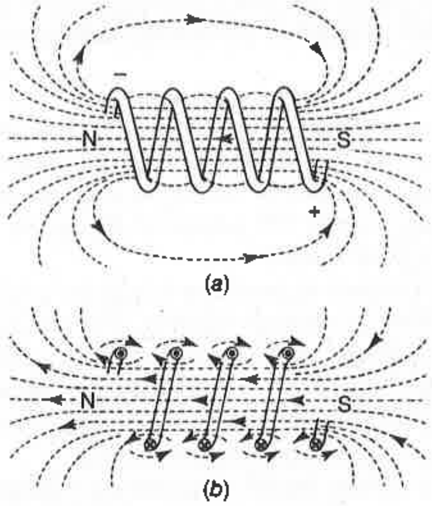


FIGURE 1-20 The magnetic field of a coil.

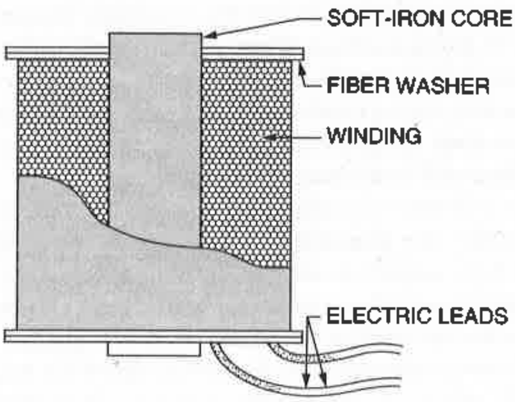


FIGURE 1-21 An electromagnet.

The same electromagnet using a core of low permeability would have a decreased magnetic strength. Other factors also affect an electromagnet's strength, although they are negligible for most general-purpose applications.

The force exerted upon a magnetic material by an electromagnet is inversely proportional to the square of the distance between the pole of the magnet and the material. For example, if a magnet exerts a pull of 1 lb [0.4536 kg] upon an iron bar when the bar is $\frac{1}{2}$ in. [1.27 cm] from the magnet, then the pull will only be $\frac{1}{4}$ lb [0.1134 kg] when the bar is 1 in. [2.54 cm] from the magnet. For this reason, the design of electric equipment using electromagnetic actuation requires careful consideration of the distance through which the magnetic force must act.

Solenoids

It has been explained that a coil of wire, when carrying a current, will have the properties of a magnet. Such coils are frequently used to actuate various types of mechanisms. If a soft-iron bar is placed in the field of a current-carrying coil, the bar will be magnetized and will be drawn toward the center of the coil, thus becoming the core of an electromagnet. By means of suitable attaching linkage, the movable core may be used to perform many mechanical functions, such as an electrically operated door lock. An electromagnet with a movable core is called a **solenoid.**

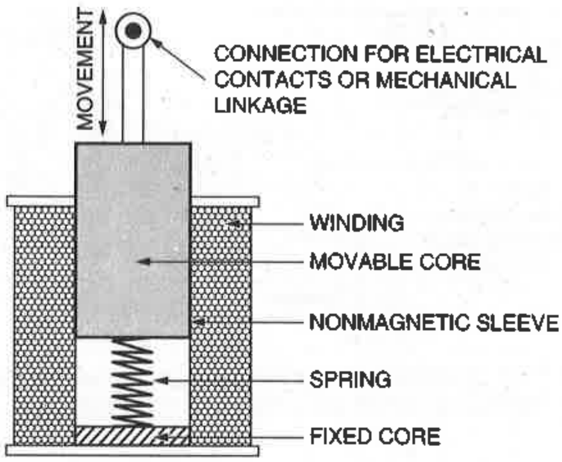


FIGURE 1-22 A solenoid.

A solenoid typically uses a split core; one part of the core is a nonmagnetic outer sleeve fixed permanently inside the coils. The other portion of the core is allowed to slide inside this fixed outer sleeve, as demonstrated in Fig. 1-22. The spring typically holds the movable core partially extended from one end of the electromagnetic coil. When the coil is energized, the electromagnet's force pulls the movable core into the hollow sleeve opposing the spring force. This imparts motion through a connecting rod to the mechanical linkage.

Solenoids are commonly used to operate electrical contacts, valves, circuit breakers, and several types of mechanical devices. The chief advantage of solenoids is that they can be placed almost anywhere in an airplane and can be controlled remotely by small switches or electronic control units. Although the use of solenoids is limited to operations where only a small amount of movement is required, they have a much greater range of movement, quicker response, and greater strength than fixed-core electromagnets.

Most solenoids found on aircraft are used to operate electrical contacts. As seen in Fig. 1-23, a low-amperage circuit is used to activate the solenoid electromagnet. When the electromagnet is energized (by closing switch #1), the core material and the electrical contacts move due to the magnetic field within the coil. In this circuit, the electrical contacts are used to close a second circuit which turns on a motor. A solenoid can be used to turn on or turn off a circuit when even the coil is energized. In most cases the solenoid contains two independent circuits: (1) the controlling circuit and (2) the controlled circuit.

Relays

Electromagnets that contain a fixed core and a pivoting mechanical linkage are called **relays.** Relays are usually

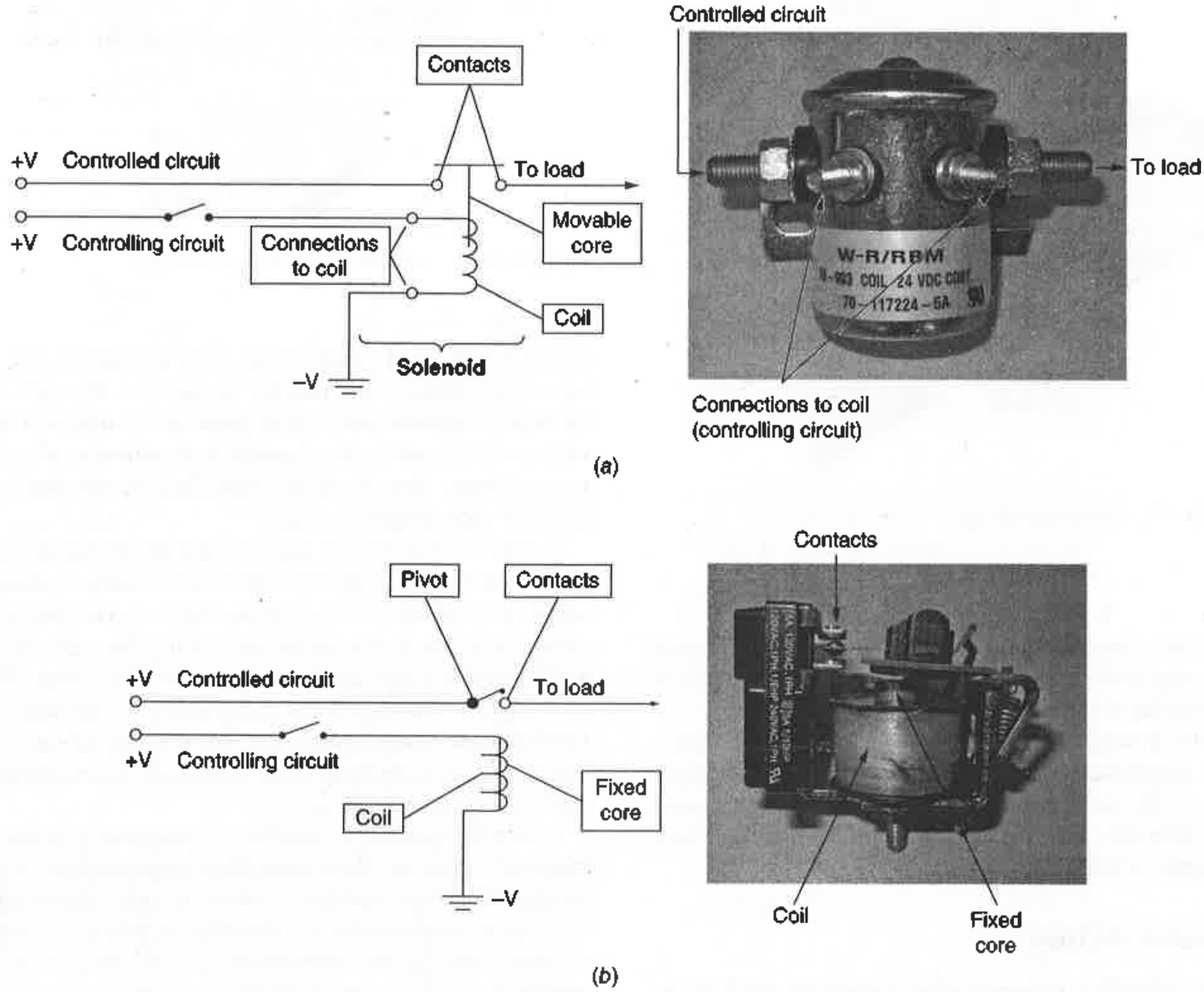


FIGURE 1-25 Comparison of a solenoid and relay: (*a*) a solenoid photo and diagram; (*b*) a relay photo and diagram.

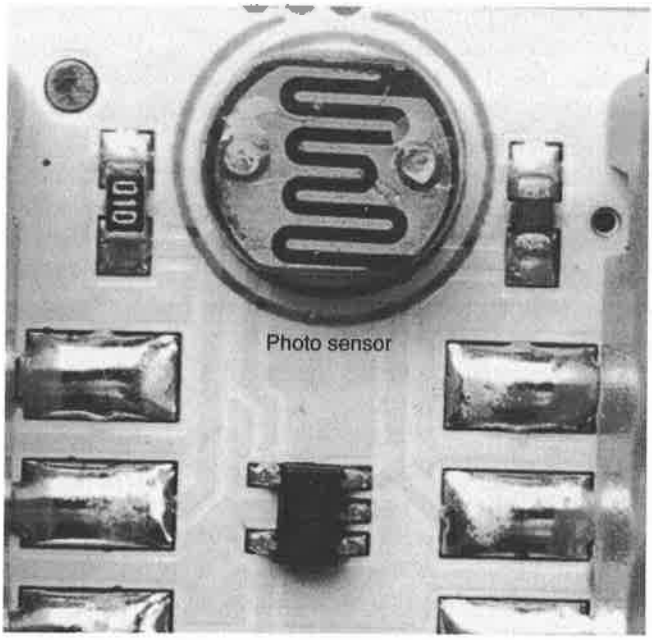


FIGURE 1-26 A typical photo sensor mounted on a circuit board.

Magnetism is used to produce the majority of all electric power. **Electromagnetic induction** is the process where voltage is produced by moving a conductor through a magnetic field.

ELECTROMAGNETIC INDUCTION

Basic Principles

The transfer of electric energy without direct electrical connections is called **induction.** When electric energy is transferred by means of a magnetic field, it is called **electromagnetic induction.** This type of induction is universally employed in the generation of electric power. Almost all electrical power is produced through electromagnetic induction using a device known as a generator or an alternator. Generators and alternators will be discussed later in this text. Electromagnetic induction is also the principle that makes possible the operation of electric transformers and the transmission of radio signals.

Electromagnetic induction occurs whenever there is a relative movement between a conductor and a magnetic field. To produce power the conductor moves across the magnetic

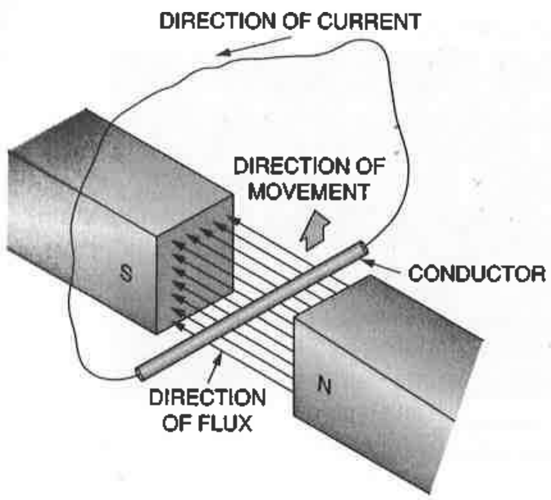


FIGURE 1-27 Generator action.

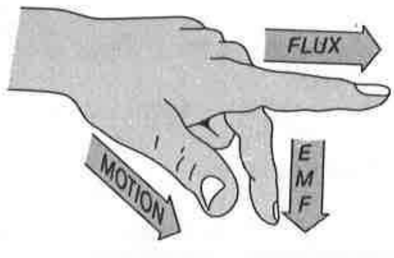


FIGURE 1-28 Left-hand rule for generators.

lines of force (not parallel to them). The relative movement may be caused by a stationary conductor and a moving field or by a moving conductor with a stationary field.

The two general classifications of electromagnetic induction are **generator action** and **transformer action.** Both actions are the same electrically, but the methods of operation are different. Transformer action will be discussed in a later chapter of this text.

Generator Action

The basic principle of generator action is shown in Fig. 1-27. As the conductor is moved through the field, a voltage is induced in it. The same action takes place if the conductor is stationary and the magnetic field is moved. The direction of the induced voltage depends on the direction of the field and may be determined by using the **left-hand rule for generators:** *Extend the thumb, forefinger, and middle finger of the left hand so that, they are at right angles to one another, as shown in Fig. 1-28. Turn the hand so that the index finger points in the direction of the magnetic field and the thumb points in the direction of conductor movement. Then the middle finger will be pointing in the direction of the induced voltage.*

Figure 1-29 illustrates another kind of generator action. Here a bar magnet is pushed into a coil of wire. A sensitive meter connected to the coil shows that a current flows in a certain direction as the magnet moves into the coil. As soon as the magnet stops moving, the current flow stops. When the magnet is withdrawn, the meter shows that the current is flowing in the opposite direction. The current induced in the coil is caused by the field of the magnet as it cuts across the turns of wire in the coil.

Generally speaking, to produce a voltage through electromagnetic induction, there must be a magnetic field, a conductor, and relative motion between the two. The magnetic field can be produced by a permanent magnet or an electromagnet. Typically, electromagnets are used because of their advantages of increased magnetic strength. The conductor used is usually wrapped in the form of a coil, which produces a greater induced voltage. The motion can be created by moving either the magnet or the conductor. Typically, this is done by rotating a coil inside a magnetic field or by rotating a magnetic field inside a wire coil.

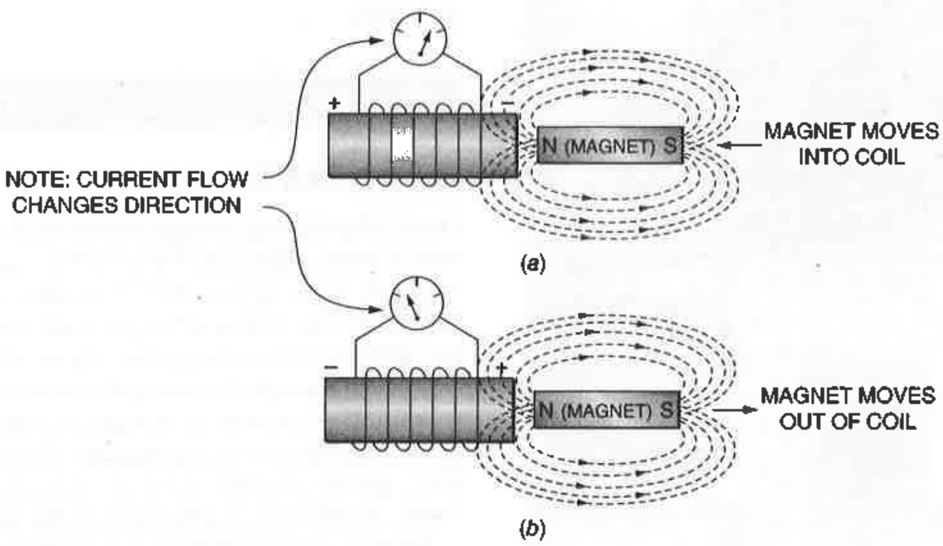


FIGURE 1-29 Induced current by a moving magnetic field: (*a*) magnet moves into coil-note meter polarity; (*b*) magnet moves out of coil-note meter polarity.

REVIEW QUESTIONS

1. Describe the properties of a permanent magnet.
2. What is the difference between substances required for permanent magnets and those used for temporary magnets?
3. Define *permeability* and *reluctance*.
4. When the direction of current flow through a coil is known, how do you determine the polarity of the coil?
5. How does the pull of a magnet on a piece of steel at 1-in. distance compare with the pull at 2-in. distance?
6. Compare a solenoid with an electromagnet.
7. Describe a relay.
8. What conditions are necessary to produce electromagnetic induction?
9. How do you determine the direction of current flow?
10. According to the FAA, what direction is current said to flow?
11. What undesirable effects are caused by static electricity during the operation of an airplane?
12. Define *molecule* and *atom*.
13. What particles are found in an atom?
14. Explain the difference between a *relay* and a *solenoid*.
15. What is another name for a charged atom?
16. What makes some substances conductors, insulators, or semiconductors?
17. What force is required to cause electrons to move through a conductor?
18. Explain the nature of static charges.
19. What is an electric current?
20. What name is given to the unit of electromotive force?
21. To what physical force may voltage be compared?
22. What is the unit of electric current flow?
23. Describe the process of *electromagnetic induction*.
24. Define *resistance* and give the unit of resistance.
25. What factors determine the resistance of a conductor?

Applications of Ohm's Law 2

INTRODUCTION

We have already studied the three fundamental elements of electricity: voltage, current, and resistance. **Ohm's law**, first presented by the German physicist Georg Simon Ohm (1787–1854), describes the relationships between these three elements. These relationships are the foundation upon which all electrical concepts are based. The mathematical relationships presented in Ohm's law explain the link between voltage, current, and resistance for virtually all direct-current (dc) electrical circuits. As you progress through this text, it should become clear how important Ohm's law is in the design and repair of aircraft electrical systems. For example, understanding Ohm's law is necessary 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. It is the purpose of this chapter to introduce the concepts of Ohm's law and present their mathematical relationships.

OHM'S LAW	
	CURRENT = $\frac{\text{ELECTROMOTIVE FORCE}}{\text{RESISTANCE}}$
$I = \frac{E}{R}$	AMPERES = $\frac{\text{VOLTS}}{\text{OHMS}}$
	RESISTANCE = $\frac{\text{ELECTROMOTIVE FORCE}}{\text{CURRENT}}$
$R = \frac{E}{I}$	OHMS = $\frac{\text{VOLTS}}{\text{AMPERES}}$
	ELECTROMOTIVE FORCE = CURRENT × RESISTANCE
$E = IR$	VOLTS = AMPERES × OHMS

FIGURE 2-1 Equation for Ohm's law.

OHM'S LAW

Definitions

In mathematical problems, emf (voltage) is expressed in volts, and the symbol used is E. R is the symbol for resistance which is measured in ohms. The symbol for current is I, which is measured in amps. 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 V causes 1 A 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.

Ohm's law can be expressed in three different equations as shown in Fig. 2-1. The different forms for the Ohm's law equation are derived by either multiplication or division, as shown below.

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

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

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

These equations make it simple to determine any one of the three values if the other two are known. Ohm's law may be used to find any unknown voltage, current, or resistance in a given circuit and to solve any common dc circuit problem because any such circuit, when operating, has voltage, current, and resistance.

From the study of Ohm's law, it has been seen that the current flowing in a circuit is directly proportional to the

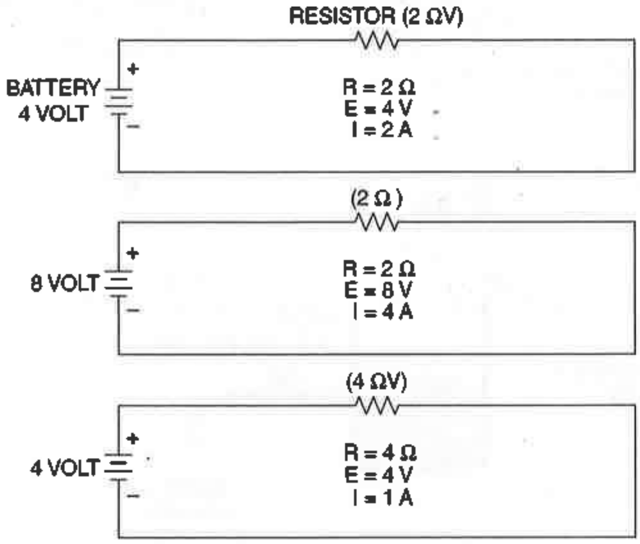


FIGURE 2-2 Effects of current and voltage.

voltage and inversely proportional to the resistance of that circuit. If the voltage applied to a given circuit is doubled, the current will double, If the resistance is doubled and the voltage remains constant, the current will be reduced by one-half (see Fig. 2-2). This circuit shows the symbols for a battery and a resistor. Electrical symbols are commonly used to explain electrical circuits and will be used throughout this text. The appendix of this text contains definitions of common electrical symbols.

The equations of Ohm's law are easily remembered by using the simple diagram shown in Fig. 2-3. 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. 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.

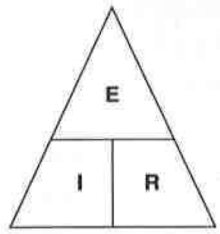


FIGURE 2-3 Diagram for Ohm's law.

This leaves *I* and *R* adjacent to each other; they are therefore to be multiplied according to the equation $E = IR$. In another 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

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

One of the simplest descriptions of the Ohm's law relationships is the water analogy. Water *pressure* and *flow*, along with the *restrictions* of a water valve, respond similar to the relationships of *voltage*, *current*, and *resistance* in an electric circuit. As illustrated in Fig. 2-4, an increase in voltage (electrical pressure) creates a proportional increase in current (electrical flow), just as an increase in water pressure creates an increase in water flow. Figure 2-5 shows the relationship between resistance and current. As the resistance of a circuit increases, the current decreases, assuming that the voltage remains constant. Water responds similarly. As the water valve is closed (increasing resistance), the water flow decreases.

The water analogy of Ohm's law is a simple comparison. Use the analogy to gain a better understanding of the relationships between voltage, current, and resistance.

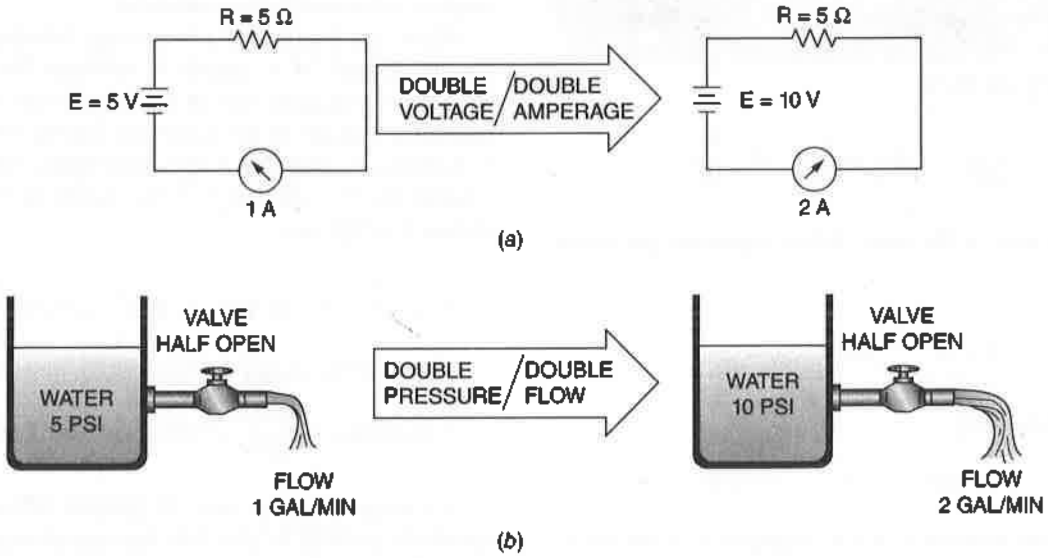


FIGURE 2-4 Water analogy of changing voltage.

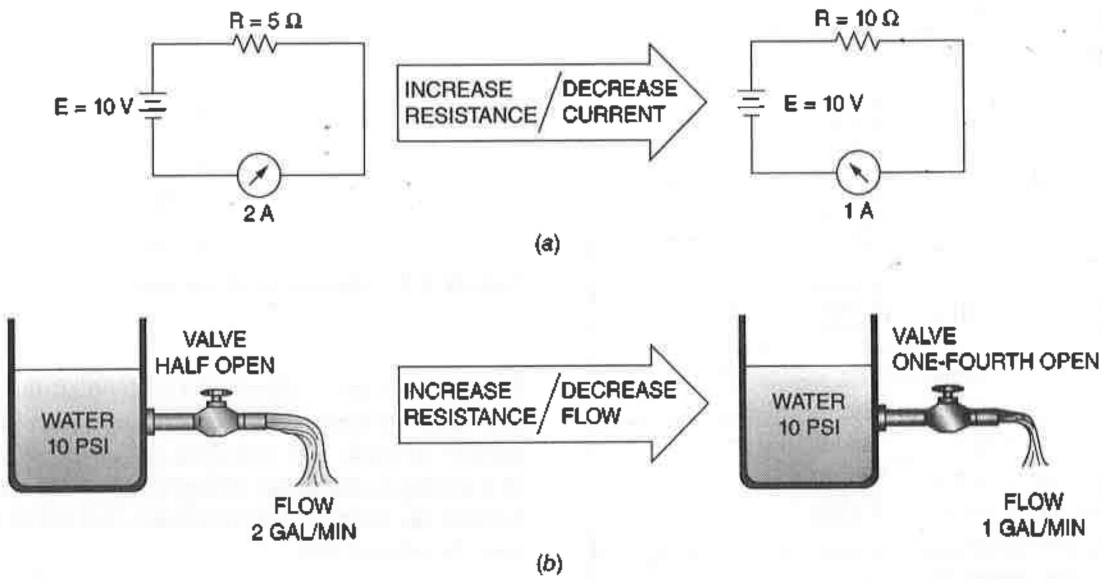


FIGURE 2-5 Water analogy of changing resistance.

Electric Power and Work

Power means the rate of doing work. One horsepower (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 is the watt (W), which is equal to 0.00134 hp. Conversely, 1 hp is equal to 746 W. In electrical terms, one watt of power is expelled when 1 V of electrical pressure moves 1 A of current through a circuit. That is, 1 V at 1 A produces 1 W of power. The formula for electric power is

$$P = EI \qquad \text{or} \qquad \text{Power} = \text{voltage} \times \text{amperage}$$

The power equation can be combined with the Ohm's law equations to allow more flexibility when determining power in a circuit. The following are the three most common varieties of the power equations:

$$P = EI \qquad P = I^2R \qquad P = \frac{E^2}{R}$$

The derivatives of the basic power equations are found as follows:

If

$$P = EI \qquad \text{and} \qquad E = IR$$

then, substituting for E,

$$P = (IR)I \qquad \text{or} \qquad P = I^2R$$

Of course, these equations can be arranged to solve for E, I, or R:

$$E^2 = PR \qquad I^2 = \frac{P}{R} \qquad \text{and} \qquad R = \frac{P}{I^2}$$

When power is lost in an electric circuit in the form of heat, it is often called the *IR loss* because the heat produced is a function of a circuit's current and resistance. The equation $P = I^2R$ best represents the heat energy loss of any dc circuit, where P equals the lost power, measured in watts.

Power in an electric circuit is always additive. That is, total power equals the sum of the powers consumed by each individual unit. The power consumed by any individual load can be found using the equation

$$P = I^2R \qquad \text{or} \qquad P = IE$$

While determining power of any portion of a circuit, be sure to apply the I, E, or R (current, voltage, or resistance) that applies to the load being calculated.

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 (2238 watts) motor in a 24-V system and the efficiency of the motor is 75 percent, we proceed as follows:

$$\text{Since 1 hp} = 746\text{ W \& I} = \text{P/E}\left[\textit{current} = \left(\frac{\textit{Power}}{\textit{voltage}}\right)\right]$$

$$\text{Power of the motor} = 3\text{ hp} \times 746\text{ W/hp} = 2238\text{ W}$$

$$I\text{ (current)} = \frac{2238\text{ W}}{24\text{ V}} = 93.25\text{ A} = 93.25\text{ A}$$

Since the motor is only 75 percent efficient, we must divide 93.25 A by 0.75 to find that approximately 124.33 A is required to operate the 3 hp motor. Thus, in a motor that is 75 percent efficient, 2984 W of input power is required to produce 2238 W (3 hp) of power at the output.

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 W in 1 second.** This is equal to approximately 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 lbs by 50 ft. and find that 100000 ft · lb of work is done. Then, when we divide 100000 ft-lbs by 0.7376 ft-lbs/jewel, we determine that approximately 135575 J of work, or energy, was used to raise the weight.

It is wise for the technician to understand and have a good concept of the joule because this is the unit designated by the 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 watt-hour (Wh). All these units represent a specific amount of work.

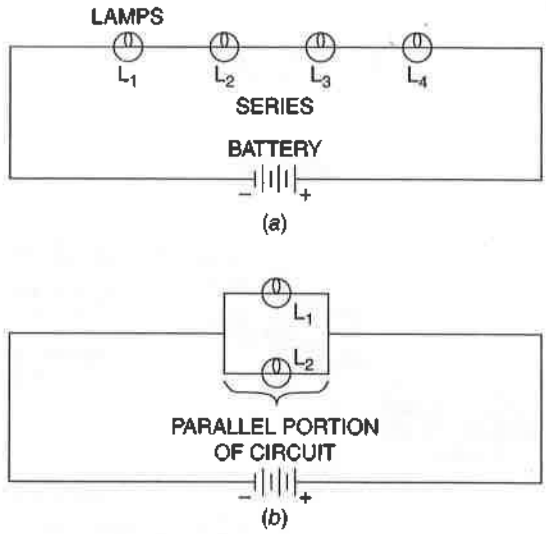


FIGURE 2-7 Two basic methods of connecting units in an electric circuit: (*a*) series—if one lamp opens, all lamps stop illuminating; (*b*) parallel—if one lamp opens, the other is unaffected.

TYPES OF CIRCUITS

To cause a current to flow through a conductor, a difference of potential (pressure) must be maintained between the ends of the conductor. In an electric circuit this difference of potential is normally produced by a battery, generator, or alternator. To simplify discussions, this text will show the battery as the typical source of electrical pressure, emf.

Figure 2-6 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, motor, radio or any other electric device that uses power. 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 of the battery to the other. When the switch is opened (turned off), the path for the current is broken, and the operation of the circuit stops.

There are two general methods for connecting units in an electric system. These are illustrated in Fig. 2-7. The first diagram shows four lamps connected in series. A **series circuit** contains only one electron path. In a series circuit or series portion of a circuit, all the current must pass through each unit of that circuit. Therefore, if one unit of a series circuit should burn out, or open, the entire circuit will no longer receive current. For example, in Fig. 2-7*a*, if lamp 1 should open, the other lamps of that circuit will also stop illuminating.

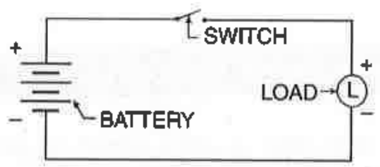


FIGURE 2-6 A simple dc circuit.

Characteristics of a series circuit are as follows:

- The current that flows through one portion of the circuit flows through all portions of the circuit.
- If one portion of a series circuit is disconnected (open), current flow will stop in the entire circuit.

In a **parallel circuit** there are two or more paths for the current to flow. In every parallel circuit, or parallel portion of a circuit, the total current flow will divide and only part of the current will travel through each path. 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 diagram of Fig. 2-7*b*.

Characteristics of a parallel circuit are as follows:

- The total current of the circuit will divide and travel independently through each leg (current path) of the circuit.
- If one portion (load) of the circuit should fail (open), the remaining portion of the circuit will continue to operate.

The automobile analogy of current flow is shown in Fig. 2-8. Imagine that automobiles are electrons traveling between two cities, say Chicago and Detroit. The cars traveling represent current flow; the road(s) represent the current path(s). If there were only one road from Chicago to Detroit, it would represent

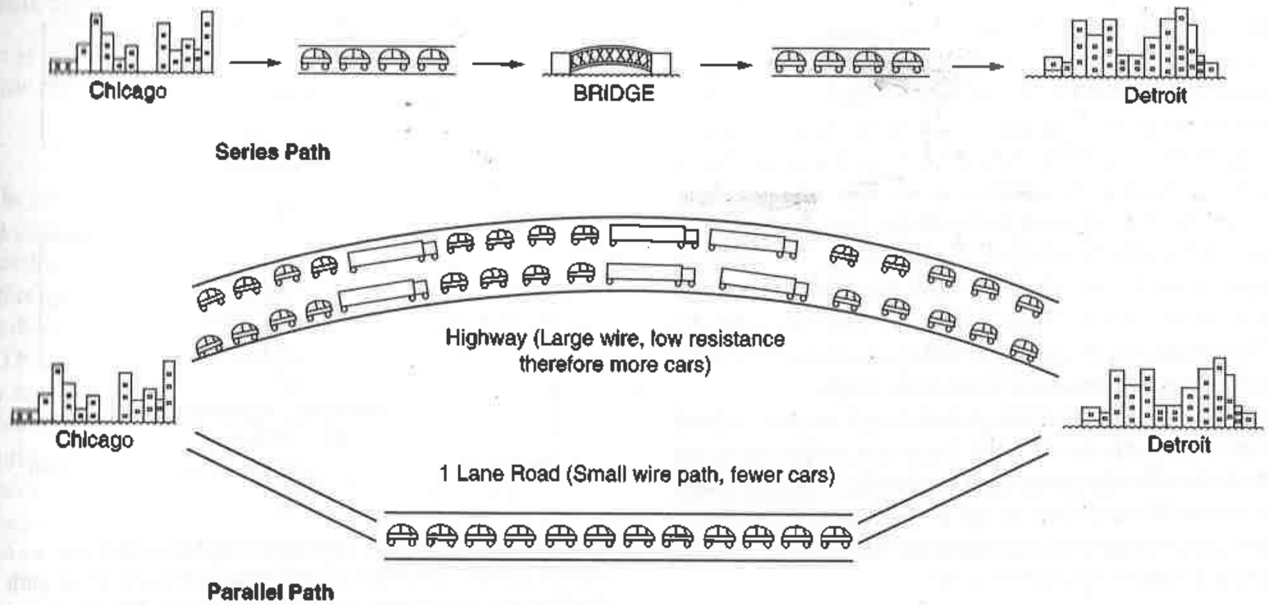


FIGURE 2-8 Characteristics of a series path and a parallel path.

a **series circuit**. In this case all the automobiles would travel on only one path. In the series circuit, if a bridge should collapse along the road, all traffic would stop and the road would no longer work; in the same way, when there is a break in a wire, all current stops and the circuit no longer works.

Now imagine there are two roads between Chicago and Detroit. This represents a **parallel circuit**. All the cars leave Chicago, and then divide and a portion of the cars take each road. Most of the cars will take the highway because it offers lower opposition (resistance) to travel. A smaller portion of the drivers will take the scenic road or a smaller one-lane road, and all cars eventually reach Detroit. In this parallel example, it is easy to see that if a bridge is out on the one-lane road, the other road will still be operational; similarly, if one light opens on the aircraft instrument panel the other light will still function. See Fig. 2-8

A circuit that contains electrical units in both parallel and series is called a **series-parallel circuit** (see Fig. 2-9.) Most complex electrical systems, such as communication radios, flight computers, and navigational equipment, consist of several combinations of series-parallel circuits. Ohm's law can 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 connected in series, in parallel, or in a combination of the two methods. When the type of circuit is determined, the proper formula may be applied.

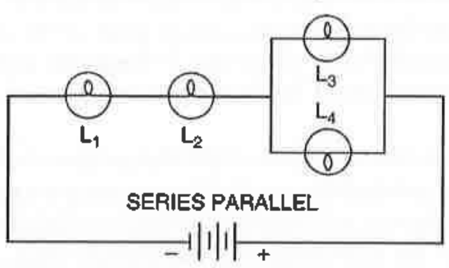


FIGURE 2-9 A series-parallel circuit diagram.

Voltage Drop

When a current flows through a resistance, a voltage or pressure drop is created. This loss of voltage, known as a **voltage drop** (V_x), is equal to the product of current and resistance. An individual voltage drop is expressed as $V_x = IR$, where V_x is measured in volts, I in amps, and R in ohms. *Note:* The subscript (x) is used here to represent a number that applies to a specific voltage drop, such as voltage drop #1 (V_1) or voltage drop #2 (V_2). In a series circuit, the sum of the individual voltage drops is equal to the applied voltage. This may be expressed as

$$E_t = V_1 + V_2 + V_3$$

for a circuit containing three resistors.

Figure 2-10 shows this concept using the water analogy. Notice that with either the water or electrical circuit, the total pressure rise is equal to the total pressure drop; that is, the electrical pressure increase created by the battery is equal to the total pressure drop across both lamps and the resistor. This can be expressed mathematically as

$$E_t = V_{L_1} + V_{L_2} + V_R$$

SOLVING SERIES CIRCUITS

As explained previously, a series circuit consists of only one current path. When two or more units are connected in series, the entire quantity of moving electrons (current) must

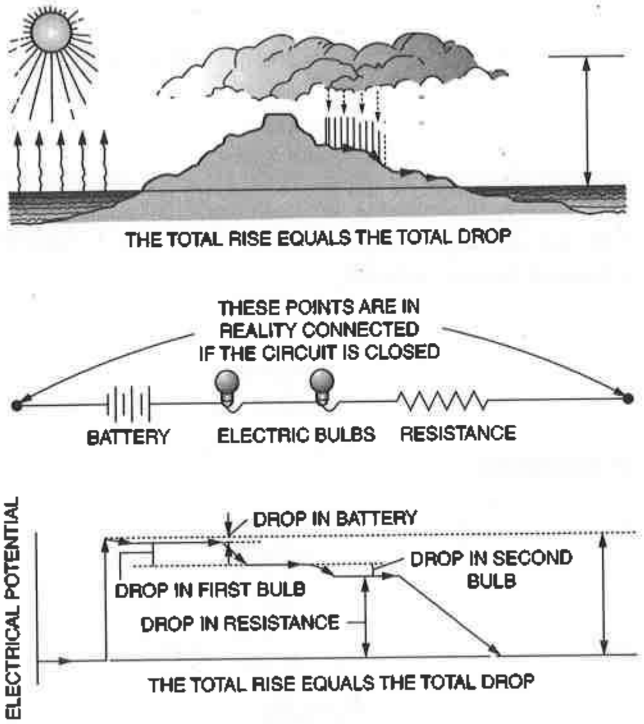


FIGURE 2-10 Water analogy of voltage drops.

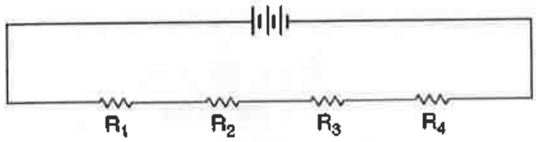


FIGURE 2-11 A series circuit with four separate loads.

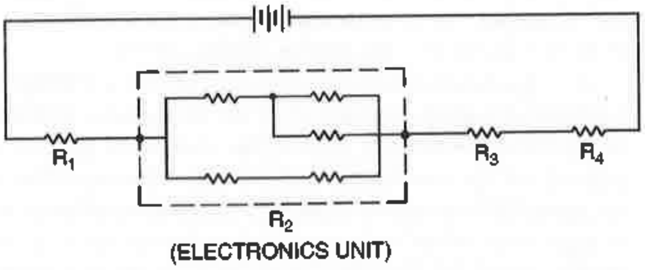


FIGURE 2-12 A series circuit containing a series-parallel load.

pass through each unit to complete the circuit. Therefore, each unit of a series circuit receives the same current flow, even though their individual voltage drops may vary.

Two or more units do not have to be adjacent to each other in a circuit to be in series. In the circuit of Fig. 2-11, it can be seen that the current flow through each unit in the circuit must be the same, regardless of the direction of current flow. If we replace the load resistor R_2 with an electronic unit (often called an LRU) as shown in Fig. 2-12, the current flow in each resistor will still be the same, provided that the total resistance of the electronics unit is the same as it was for R_2. In this case, we regard the electronics unit as a single unit rather than concern ourselves with the separate components

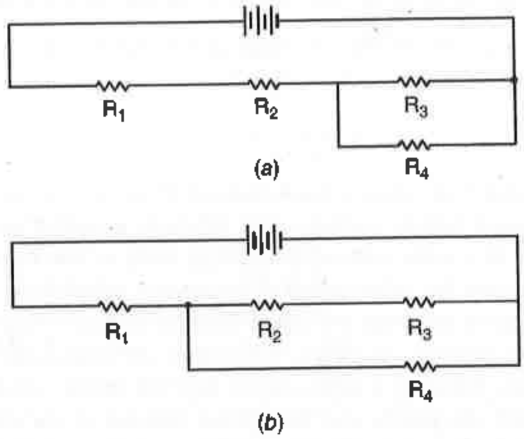


FIGURE 2-13 A circuit diagram showing load units connected in both series and parallel.

within that unit. Thus we see that there is only one path for current flow in a series circuit; however, an individual load unit may consist of more than one component within itself. Note that the electronics unit in Fig. 2-12 is shown with several resistances connected in a network within the box. In the series circuit under consideration, we are only concerned with the total resistance of the electronics unit.

The load units adjacent to each other in a circuit are connected in series if there are no electrical junctions (dividing points) between the two units. This is illustrated in Fig. 2-13. In circuit *a*, R_1 and R_2 are connected in series because there is no electrical junction between them to take a part of the current, and all the current flowing through R_1 must also pass through R_2. In circuit *b*, R_1 and R_2 are not connected in series because the current that flows through R_1 is divided between R_2 and R_4. Note, however, that R_2 and R_3 are in series and the same current must pass through both.

Examine the circuit of Fig. 2-14 in which R_1, R_2, and R_3 are connected in series, not only to each other but also to the power source. The electrons flow from negative to positive in the circuit and from positive to negative in the power source. The same flow, however, exists in every part of the circuit, because there is only one path for current flow. Since the current is the same in all parts of the circuit.

$$I_t = I_1 = I_2 = I_3$$

That is, the total current is equal to the current through R_1, R_2, or R_3.

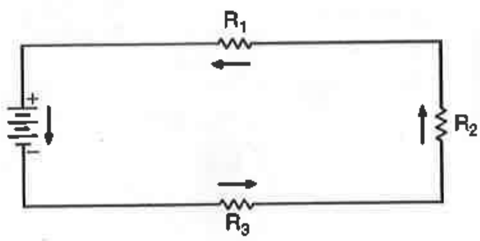


FIGURE 2-14 Current flow in a series circuit. Each load receives equal current.

Resistance and Voltage in a Series Circuit

In a series circuit, the total resistance is equal to the sum of all the resistances in the circuit; hence,

$$R_t = R_1 + R_2 + R_3 + \cdots$$

In practical terms, a resistance can be any load connected to a power supply (voltage). For example, a resistor may be placed in a series with a light bulb in order to dim the light. In this case the voltage drop of the resistor added to the voltage drop of the lamp will equal the total applied voltage.

The voltage (potential difference) measured between any two points in a series circuit depends on the resistance between the points and the current flowing in the circuit. Figure 2-15 shows a circuit with three resistances connected in series. The difference in potential supplied by the battery between the ends of the circuit is 24 V.

As previously explained in the discussion of Ohm's law, the voltage between any two points in a circuit can be determined by the equation

$$E = IR$$

That is, the voltage is equal to the current multiplied by the resistance. In the circuit of Figure 2-15, we have given a value of 1 Ω to R_1, 3 Ω to R_2, and 8 Ω to R_3. According to our previous discussion, the total resistance of the circuit is expressed by

$$R_t = R_1 + R_2 + R_3$$

or

$$R_t = 1 + 3 + 8$$
$$= 12\ \Omega$$

Since the total voltage E_t for the circuit is given as 24, we can determine the current in the circuit by Ohm's law, using the form

$$I_t = \frac{E_t}{R_t}$$

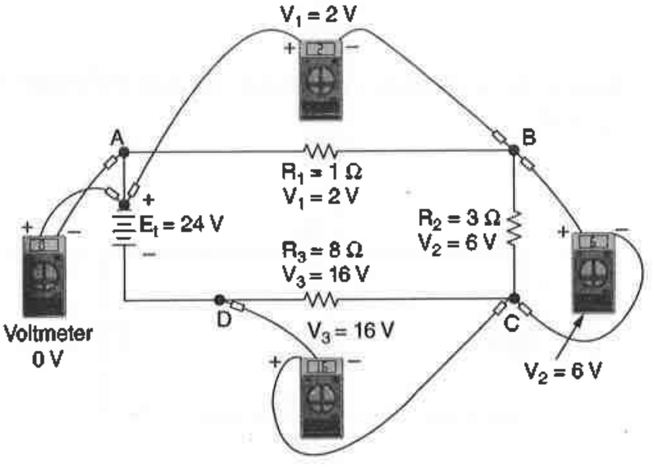


FIGURE 2-15 The summation of voltage drops.

Then

$$I_t = \frac{24\ V}{12\ \Omega}$$
$$= 2\ \text{A}$$

Since we know that the current in the circuit is 2 A, it is easy to determine the voltage across each load resistor. Since R_1 = 1 Ω, we can substitute this value in Ohm's law to find the voltage difference across R_1.

$$V_1 = I_1 R_1$$
$$= 2 \times 1$$
$$= 2\ \text{V}$$

In like manner,

$$V_2 = I_2 R_2$$
$$= 2 \times 3$$
$$= 6\ \text{V}$$

and

$$V_3 = I_3 R_3$$
$$= 2 \times 8$$
$$= 16\ \text{V}$$

When we add the voltages in the circuit, we find

$$E_t = V_1 + V_2 + V_3$$
$$V_t = 2 + 6 + 16$$
$$= 24\ \text{V}$$

We have determined by Ohm's law that the sum of the voltages (voltage drops) across units in a series circuit is equal to the voltage applied by the power source, in this case R_1(2 V) + R_2(6 V) + R_3(16 V) = the battery voltage (24 V).

In a practical experiment, we can connect a **voltmeter** (voltage-measuring instrument) from the positive terminal of the battery in a circuit such as that shown in Fig. 2-15 to point *A*, and the reading will be zero. This is because there is no appreciable resistance between these points and hence no voltage drop. When we connect the voltmeter between the positive terminal of the battery and point *B*, the instrument will give a reading of 2 V (the voltage drop of R_1). By similar use of the voltmeter, we measure between points *B* and *C* and obtain a reading of 6 V (the voltage drop of R_2), and between points *C* and *D* for a reading of 16 V (the voltage drop of R_3). In a circuit such as that shown, we can assume that the resistance of the wires connecting the resistors is negligible. If the wires were quite long or extremely small diameter, it would be necessary to consider their resistances in analyzing the circuit.

As we have shown, in a series circuit, the voltage drop across each resistor (or any electrical load unit) is directly proportional to the value of the resistor. Since the current through each unit of the circuit is the same, it is obvious that it will take a higher electrical pressure (voltage) to push the current through a higher resistance, and it will require a lower pressure to push the same current through a lower resistance.

The voltage across a load resistor is a measure of the work required to move a unit charge (given quantity of current) through the resistor. Electric energy is consumed as current flows through a resistor, and the electric energy is converted to heat energy. (In a lamp the electrical energy would be converted to light; in a motor it would be converted to rotary motion.) As long as the power source produces electric energy as rapidly as it is consumed, the voltage across a given resistor will remain constant.

Most load units in a typical aircraft are not simple resistors. For example, a practical load could be a lamp, motor, or radio. In each case, the concepts of Ohm's law apply to that unit just as they apply to a simple resistor. Students who have mastered Ohms's law and the three fundamental formulas for series circuits can apply their knowledge to the solution of any series circuit where sufficient information is given. The following examples are shown to illustrate the techniques for solution:

Example A: Refer to Fig. 2-16 during the following explanation:

$$E_t = 12\text{ V}$$
$$I_1 = 3\text{ A}$$
$$R_2 = 2\ \Omega$$
$$R_3 = 1\ \Omega$$

To solve for the unknown values of the circuit, proceed as follows:
Since I_1 is given as 3 A, it follows that I_t, I_2, and I_3 are also equal to 3 A, because current is constant in a series circuit.

Then the total resistance of the circuit can be determined.

$$R_t = \frac{E_t}{I_t}$$
$$= \frac{12}{3}$$
$$= 4\ \Omega$$

To determine the resistance R_t

$R_t = R_1 + R_2 + R_3$ (R_2 and R_3 are given; R_t was previously calculated.)

Or

$$R_1 = R_t - R_2 - R_3$$
$$R_1 = 4 - 2 - 1$$
$$R_1 = 1\text{ ohms}$$

To determine the voltage drags over each resistance, use the following:

$$V_1 = I_1 \times 2$$
$$V_1 = 3 \times 1$$
$$V_1 = 3\text{ V}$$

$V_2 = I_2 \times R_2$ (*Note:* Current is consistent in a series circuit; in this case, 3 A.)

$$V_2 = 3 \times 2$$
$$V_2 = 6\text{ V}$$

$$V_3 = I_3 \times R_3$$
$$V_3 = 3 \times 1$$
$$V_3 = 3\text{ V}$$

$$V_2 = 2 \times 3 = 6\text{ V}$$
$$V_3 = 1 \times 3 = 3\text{ V}$$

The solved problem may then be expressed as follows:

$E_t = 12\text{ V}$	$I_t = 3\text{ A}$	$R_t = 4\ \Omega$
$V_1 = 3\text{ V}$	$I_1 = 3\text{ A}$	$R_1 = 1\ \Omega$
$V_2 = 6\text{ V}$	$I_2 = 3\text{ A}$	$R_2 = 2\ \Omega$
$V_3 = 3\text{ V}$	$I_3 = 3\text{ A}$	$R_3 = 1\ \Omega$

Example B: Refer to Fig. 2-17 during the following explanation:

$$E_t = 24\text{ V}$$
$$R_1 = 30\ \Omega$$
$$R_2 = 10\ \Omega$$
$$R_3 = 8\ \Omega$$

Then

$$R_t = R_1 + R_2 + R_3$$
$$R_t = 30 + 10 + 8$$
$$= 48\ \Omega$$

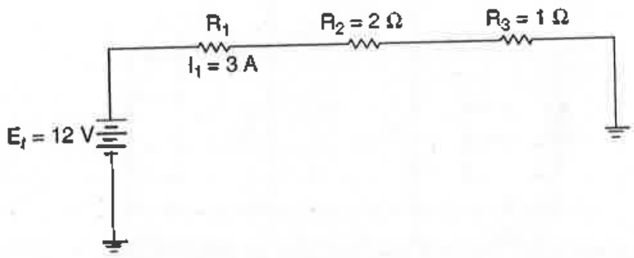


FIGURE 2-16 Series circuit for Example A.

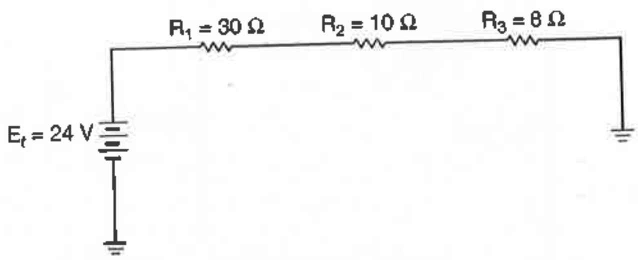


FIGURE 2-17 Series circuit for Example B.

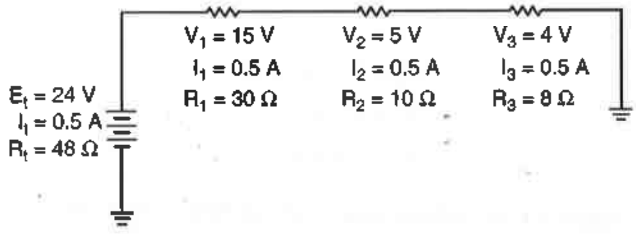


FIGURE 2-18 Simplified circuit for Example B.

$$I_t = \frac{E_t}{R_t}$$
$$= \frac{24}{48}$$
$$= 0.5\text{ A}$$

V_1, V_2 and V_3 are determined by multiplying each resistance value by 0.5 A, the current value of the circuit. The solved circuit is shown in Fig. 2-18.

Example C: Refer to Fig. 2-19 during the following discussion. This circuit present the case where current and resistance are known, and it is required to find the individual and total voltages. The known circuit values are as follows:

$$I_t = 3\text{ A}$$
$$R_1 = 9\ \Omega$$
$$R_2 = 3\ \Omega$$
$$R_3 = 4\ \Omega$$

From the values given, we can easily determine that the total resistance is 16 Ω ($R_1 + R_2 + R_3 = R_t$). The voltages can then be determined by Ohm's law:

$$E = IR$$
$$E_t = I_t \times R_t$$
$$= 3 \times 16$$
$$= 48\text{ V}$$

The values of the solved circuit are then as shown below:

$E_t = 48$ V	$I_t = 3$ A	$R_t = 16\ \Omega$
$V_1 = 27$ V	$I_1 = 3$ A	$R_1 = 9\ \Omega$
$V_2 = 9$ V	$I_2 = 3$ A	$R_2 = 3\ \Omega$
$V_3 = 12$ V	$I_3 = 3$ A	$R_3 = 4\ \Omega$

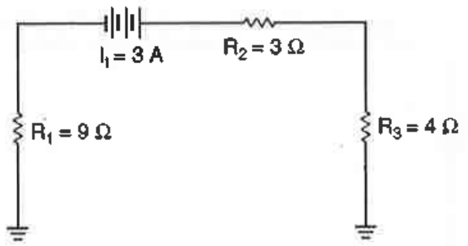


FIGURE 2-19 Series circuit for Example C.

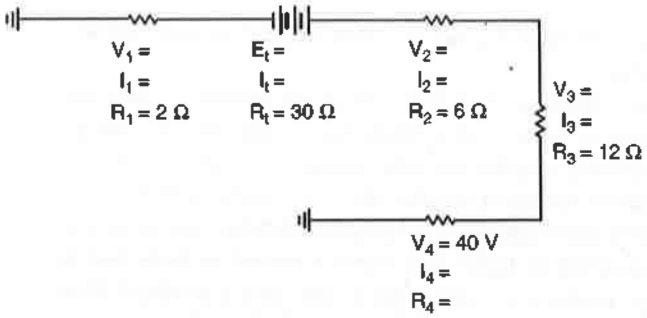


FIGURE 2-20 Series circuit for Example D.

It will be noted in all the circuits presented thus tar that the values are always in accordance with Ohm's law formulas. It is recommended that the student check the problems given to verify the results.

Example D: Figure 2-20. Certain values for the circuit shown are indicated in the illustration. It is left up to the student to work out the solution. Follow the steps as previously described to find all unknown values.

SOLVING PARALLEL CIRCUITS

A parallel circuit always contains two or more electric current paths. When two or more units are connected in parallel, each unit will receive a portion of the circuit's total current flow. That is, the circuit's total current divides at one or more points, and a portion travels through each resistance of the circuit (see Fig. 2-21.)

Typically, when we analyze a circuit of this type, we assume that the resistance of a wire is negligible and the power source has no internal resistance. A parallel circuit always contains more than one path for current to flow; therefore, the current can "choose" which load unit to travel through. Current always tries to take the path of least resistance and will divide proportionally through a parallel circuit containing load units of different resistances. In a parallel circuit, each load unit will receive a portion of the total current flow. The unit with the highest resistance will receive

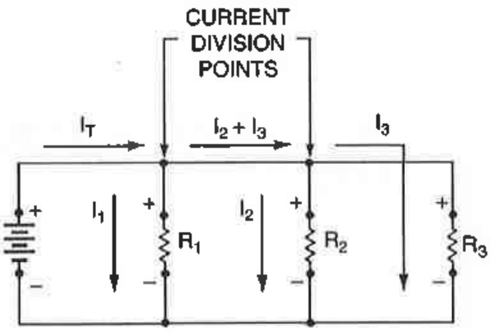


FIGURE 2-21 Current flow through a parallel circuit.

the least current flow. The unit with the lowest resistance will receive the highest current flow. Equal resistors receive equal current flows.

Think of current flow (electron movement) through a wire as cars traveling down a road. All the electrons desire to travel from the negative connection of the battery to the positive connection of the battery. Just as cars traveling may choose a different route from Chicago to Detroit, in a parallel circuit, some electrons will take one path and others will take another path. Due to the nature of physics (and Ohm's law) more electrons will take the path of lower resistance and fewer electrons will take the path of higher resistance. So in a parallel circuit, any path of higher resistance naturally receives less current flow and low-resistance circuits will receive greater current flow.

Typically, load such as lamps, radios, or motors, are arranged in parallel with respect to the power source and to each other. This is done to allow a different current path through each unit; therefore, the resistance of each unit will determine the current flow through that unit. An example is a flap motor using 30 A, a navigation light using 2 A, and the landing light, with the switch turned off, using 0 A. This type of current flexibility is a necessity for almost every electrical system.

The resistors (load units) do not need to be arranged as in Fig. 2-21 to be connected in parallel. The three circuits of Fig. 2-22 show loads connected in parallel. Circuits *a* and *b* are identical to the circuit of Fig. 2-21, and circuit *c* has an additional load unit connected in parallel. A careful examination of the circuits will reveal that the connections are in common for each side of the power source. There is a direct connection (current path) without resistance from any one negative terminal of a load unit to the negative terminal of any other load unit and to the negative terminal of the power source. The same condition is true with respect to all positive terminals.

There may be some junctions between two or more resistors connected in parallel, but these junctions do not change the fact that the resistances are still connected in parallel.

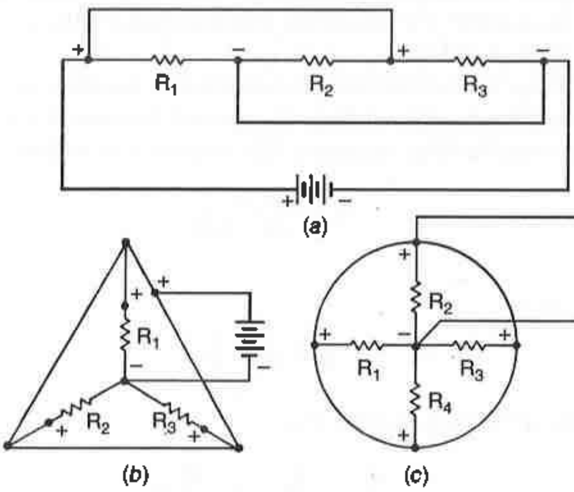


FIGURE 2-22 Different arrangements of parallel circuits.

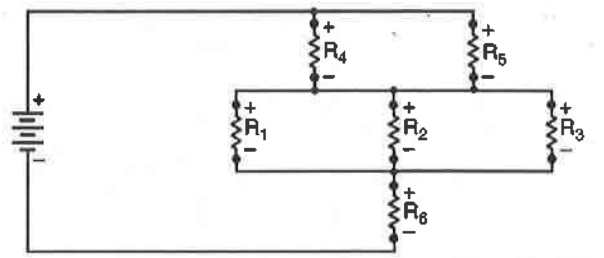


FIGURE 2-23 Parallel grouping of resistors.

It will be noted in Fig. 2-23 that three of the resistances, R_1, R_2, and R_3, have common terminals with one another, even though there are other resistances connected between their common terminals and the power source. It will further be noted that R_4 and R_5 are connected in parallel because they have positive terminals connected together and negative terminals connected together. The resistance R_6 is in series, not with any other single resistance, but with the parallel groups.

The circuit shown in Fig. 2-23 would be called a series-parallel, and will be discussed shortly. The voltage across any resistance in a parallel group is equal to the voltage across any other resistance in the group. Note in Fig. 2-24 that the voltage of the source is 12 V. Since the terminals of the power source are connected directly to the terminals of the resistances, the difference in potential across each resistance is the same as that of the battery. By testing with a voltmeter, it would be found that the potential difference across each resistance in the circuit would be 12 V. The formula for voltage in a parallel circuit is

$$E_t = V_1 = V_2 = V_3 = V_4 \cdots$$

This formula states that the same voltage will be applied to each unit of a parallel circuit. The ability to apply an equal voltage to all power users is another important reason that the entire aircraft electrical system (not necessarily individual electrical components) is wired in parallel. As described earlier, the current in a parallel circuit divides proportionately among each resistance (load unit).

In the circuit of Fig. 2-25, the current through R_1 is given as 4 A, the current through R_2 is 2 A, and the current through R_3 is 6 A. To supply this current flow through the three resistances, the power source must supply 4 + 2 + 6, or a total of 12 A to the circuit. It must be remembered that the power source does not actually manufacture electrons, but it does apply the pressure to move them. All the electrons that leave the battery to flow through the circuit must return to the battery. The power source for a circuit can be compared to a pump that moves

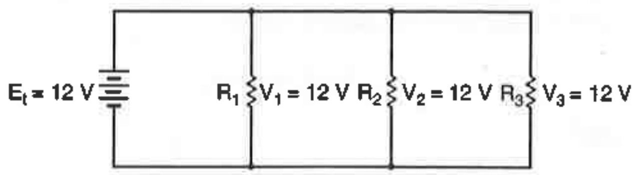


FIGURE 2-24 Voltages in a parallel circuit.

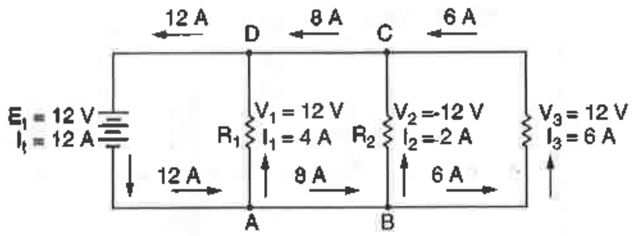


FIGURE 2-25 Current flow in a parallel circuit.

water through a pipe. Eventually water must return to the pump so it can be "pushed" through the pipe in a continuous loop. The pump does not create the water; it creates the pressure to move the water.

An examination of the circuit in Fig. 2-25 reveals that a flow of 12 A comes from the negative terminal of the battery, and at point *A* the flow divides to supply 4 A for R_1 and 8 A for the other two resistors. At point *B* the 8 A divides to provide 2 A for R_2 and 6 A for R_3. On the positive side of the circuit, 6 A joins 2 A at point *C*, and the resulting 8 A joins 4 A at point *D* before returning to the battery. The formula for current in a parallel circuit is then seen to be

$$I_t = I_1 + I_2 + I_3 + \cdots$$

Since the current flow and voltage are given for each resistor in Fig. 2-25, it is easy to determine the value of each resistance by means of Ohm's law; that is,

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

Then

$$R_1 = \frac{E_1}{I_1} = \frac{12}{4} = 3\,\Omega$$

$$R_2 = \frac{E_2}{I_2} = \frac{12}{2} = 6\,\Omega$$

$$R_3 = \frac{E_3}{I_3} = \frac{12}{6} = 2\,\Omega$$

$$R_t = \frac{E_t}{I_t} = \frac{12}{12} = 1\,\Omega$$

Remember when solving for R_1 to be sure to use the voltage drop for resistor 1 and current through resistor 1 (V_1 and I_1). However, E_t can be substituted for V_1 because voltage is constant in a parallel circuit.

The formula for the total resistance in a parallel circuit can be derived by use of Ohm's law and the formulas for total voltage and total current. Since

$$I_t = I_1 + I_2 + I_3$$

and

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

we can replace all the values in the preceding formula for total current with their equivalent values in terms of voltage and resistance. Thus we arrive at the equation

$$\frac{E_t}{R_t} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

In a parallel circuit, $E_t = V_1 = V_2 = V_3$. Therefore, we can divide all the terms in the previous equation by E_t and arrive at the formula

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Solving for R_t, the equation becomes

$$R_t = \frac{1}{1/R_1 + 1/R_2 + 1/R_3}$$

This equation can be used to find the resistance total for all parallel circuits and is expressed verbally as follows: *The total resistance in a parallel circuit is equal to the reciprocal of the sum of the reciprocals of the resistances.*

The **reciprocal** of a number is the quantity 1 divided by that number. For example, the reciprocal of 3 is $\frac{1}{3}$.

If the formula for total resistance in a parallel circuit is applied to the circuit problem of Fig. 2-25, we find

$$R_t = \frac{1}{1/R_1 + 1/R_2 + 1/R_3}$$

$$R_t = \frac{1}{1/3 + 1/6 + 1/2}$$

$$= \frac{1}{0.33 + 0.167 + 0.5}$$

$$= \frac{1}{1}$$

$$= 1\,\Omega$$

If some or all of the resistances in a parallel circuit are of the same value, the resistance value of one can be divided by the number of equal-value resistances to obtain the total resistance value. For example, if a circuit has four 12-Ω resistors connected in parallel, the value 12 can be divided by the number 4 to obtain the total resistance value of 3 Ω for the four resistances.

When two resistances are connected in parallel, we can use a formula derived from the general formula for R_t to determine the total resistance. The formula is as follows:

$$R_t = \frac{1}{1/R_1 + 1/R_2}$$

Inverting,

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

Using a common denominator,

$$\frac{1}{R_t} = \frac{R_2}{R_1 \times R_2} + \frac{R_1}{R_1 \times R_2}$$

Combining,

$$\frac{1}{R_t}=\frac{R_1+R_2}{R_1\times R_2}$$

Inverting,

$$R_t=\frac{R_1\times R_2}{R_1+R_2}$$

From the foregoing formula, we find that when two resistors are connected in parallel, the total resistance is equal to the product of the two resistance values divided by their sum. If a 5-Ω resistance is connected in parallel with a 6-Ω resistance, we apply the formula thus:

$$R_t=\frac{5\times 6}{5+6}$$

$$=\frac{30}{11}$$

$$=2.73\,\Omega$$

Another fact of parallel resistor groups is that the total resistance of the group is always less than the smallest resistance of that group. For example, if $R_1 = 3\ \Omega$, $R_2 = 6\ \Omega$, and $R_3 = 2\ \Omega$, then R_t will be less than 2 Ω. As previously stated,

$$R_t=\frac{1}{1/R_1+1/R_2+1/R_3}$$

or

$$R_t=\frac{1}{1/3+1/6+1/2}$$

$$=\frac{1}{0.33+0.167+0.5}$$

$$=\frac{1}{1}$$

$$=1\,\Omega$$

The R_t of 1 Ω is indeed less than 2 Ω, the smallest resistance of the group.

The rules to determine voltage, current, and resistance for parallel circuits have numerous applications. For example, a parallel circuit having some resistance values unknown, but at least one current value given with a known resistance value, can be solved through the use of Ohm's law and the formula for total resistance. See Fig. 2-26.

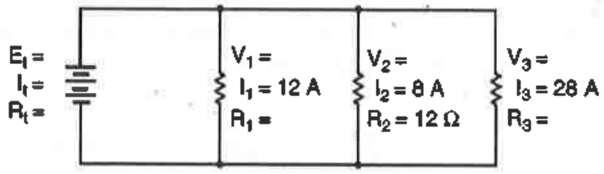


FIGURE 2-26 Diagram of a parallel circuit.

An examination of this circuit reveals that $I_2 = 8$ A and $R_2 = 12\ \Omega$. With these values it is apparent that the voltage across R_2 is equal to 96 V. That is,

$$V_2=I_2\times R_2$$

$$=8\times 12$$

$$=96\text{ V}$$

Since the same voltage exists across all the load resistors in a parallel circuit, we know that E_t, V_1, and V_3 are all equal to 96 V. We can then proceed to find that $R_1 = \frac{96}{12}$ or 8 Ω and $R_3 = \frac{96}{28}$ or 3.43 Ω. Since total current is equal to the sum of the current values, $I_t = 12 + 8 + 28$ or 48 A. The total resistance is then $\frac{96}{48} = 2\ \Omega$, since $R_t = E_t/I_t$

In any circuit where a number of load units are connected in parallel or in series, it is usually possible to simplify the circuit in steps and derive an equivalent circuit. A sample parallel circuit and its simplified equivalent are illustrated in Fig. 2-27.

The first step used to solve this parallel problem is to combine all individual resistors using the formula

$$R_t=\frac{1}{1/R_1+1/R_2+1/R_3+1/R_4}$$

or

$$R_t=\frac{1}{1/5+1/5+1/10+1/18}$$

or

$$R_t = 1.8\ \Omega$$

The second step is to solve for I_t.

$$I_t=\frac{E_t}{R_t}$$

$$=\frac{9\,V}{1.8\,\Omega}$$

$$=5\text{ A}$$

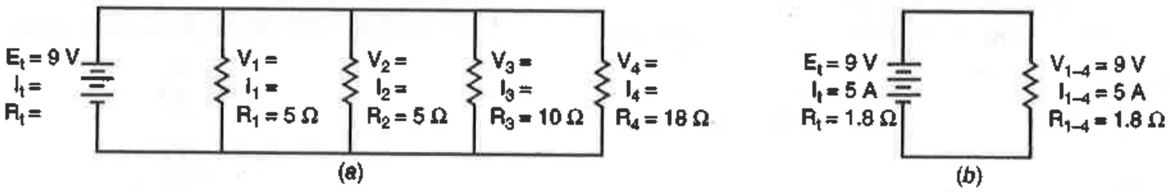


FIGURE 2-27 A parallel circuit and its simplified equivalent: (*a*) complete circuit showing all resistors, 1–4; (*b*) the simplified circuit showing effective resistor 1–4.

The third step is to find the individual current flows through each resistor. Since voltage is constant in a parallel circuit, E_t can be substituted for each individual voltage drop.

$$I_1 = \frac{E_1}{R_1} \quad I_1 = \frac{9\,V}{5\,\Omega} \quad I_1 = 1.8\text{ A}$$

$$I_2 = \frac{E_2}{R_2} \quad I_2 = \frac{9\,V}{5\,\Omega} \quad I_2 = 1.8\text{ A}$$

$$I_3 = \frac{E_3}{R_3} \quad I_3 = \frac{9\,V}{10\,\Omega} \quad I_3 = 0.9\text{ A}$$

$$I_4 = \frac{E_4}{R_4} \quad I_4 = \frac{9\,V}{18\,\Omega} \quad I_4 = 0.5\text{ A}$$

The fourth step should be to check the calculations. In a parallel circuit, current is additive to find total current. Therefore, if the sum of the individual current flows equals the total current, the calculations were done correctly. The check would be as follows:

$$\begin{aligned} I_t &= I_1 + I_2 + I_3 + I_4 \\ &= 1.8 + 1.8 + 0.9 + 0.5 \\ &= 5.0\text{ A} \end{aligned}$$

Since 5 A is the calculated total current flow, one can assume that the calculations are correct.

Another quick check can be done by comparing the calculated total resistance with the smallest resistance value of the parallel group. As stated earlier, the total resistance of a parallel group must always be less than the lowest-value resistor. If this is not true for your calculations, it must be assumed that a mistake was made.

SERIES-PARALLEL CIRCUITS

As the name implies, a series-parallel circuit is one in which some load units are connected in series and some are connected in parallel. Such a circuit is shown in Fig. 2-28. In this circuit it is quickly apparent that the resistances R_1 and R_2 are connected in series and the resistances R_3 and R_4 are connected in parallel. When the two parallel resistances are combined according to the parallel formula, one resistance, $R_{3,4}$, is found, and this value is in series with R_1 and R_2 as shown in Fig. 2-29. The total resistance R_t is then equal to the sum of R_1, R_2, and $R_{3,4}$.

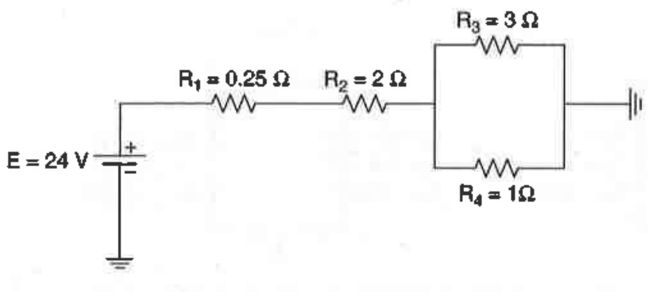


FIGURE 2-28 A simple series-parallel circuit.

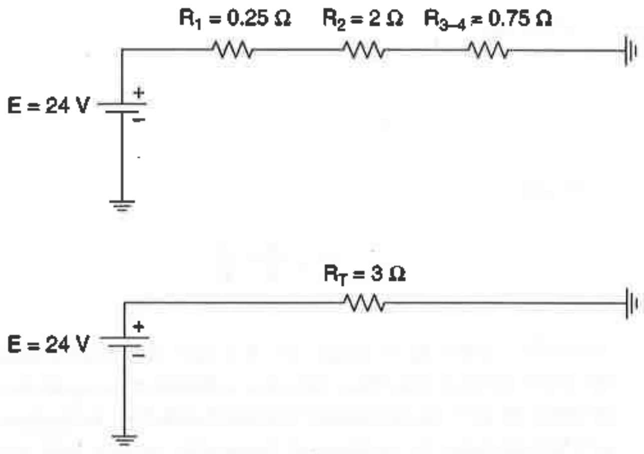


FIGURE 2-29 A series equivalent of the series-parallel circuit of Figure 2-27.

If certain values are assigned to some of the load units in the circuit of Fig. 2-27, we can solve for the unknown values and arrive at a complete solution for the circuit. For the purposes of this problem, the following are known:

$$\begin{aligned} E_t &= 24\text{ V} \\ R_1 &= 0.25\,\Omega \\ R_2 &= 2\,\Omega \\ R_3 &= 3\,\Omega \\ R_4 &= 1\,\Omega \end{aligned}$$

To solve for the unknown values, the following steps must be taken.

The first step is to combine all parallel resistors, such as in Fig. 2-29. To combine the parallel resistors R_3, and R_4, use the formula

$$\begin{aligned} R_{3,4} &= \frac{1}{1/R_3 + 1/R_4} \\ &= \frac{1}{1/3 + 1/1} \\ &= 0.75\,\Omega \end{aligned}$$

Second, combine all series resistors using the formula

$$\begin{aligned} R_t &= R_1 + R_2 + R_{3,4} \\ &= 0.25 + 2 + 0.75 \\ &= 3\,\Omega \end{aligned}$$

In this case, the resistance total was found by using only two steps. More complex circuits may require that these steps be performed in opposite order and/or several times to determine the value of R_t.

Third, compute total current using the formula

$$\begin{aligned} I_t &= \frac{E_t}{R_t} \\ &= \frac{24}{3} \\ &= 8\text{ A} \end{aligned}$$

Fourth, compute the voltage drop across the series resistors. The formula $V_x = IR$ will be used twice in this case, once for R_1 and once for R_2 *Note:* Because I_1 and I_2 have not yet been calculated. I_t must be substituted for their values. This is possible because both R_1 and R_2 are in series.

$$\begin{aligned} V_1 &= I_1 R_1 \\ &= 8 \times 0.25 \\ &= 2\text{ V} \\ V_2 &= I_2 R_2 \\ &= 8 \times 2 \\ &= 16\text{ V} \end{aligned}$$

Fifth, calculate the voltage drop across the parallel resistors using the formula $V_x = IR$. This can only be done for the entire group of parallel resistors ($R_{3,4}$) because the current flow through the individual resistors is yet unknown. *Note:* I_t was substituted for the unknown value $I_{3,4}$ because the effective resistor $R_{3,4}$ is in series (see Fig. 2-29).

$$\begin{aligned} V_{3,4} &= I_{3,4} R_{3,4} \\ &= 8 \times 0.75 \\ &= 6\text{ V} \end{aligned}$$

Since voltage is constant in parallel, the voltage drop across $R_{3,4}$ is equal to the voltage drop across R_3 and R_4 individually.

$$V_3 = 6\text{ V} \qquad \text{and} \qquad V_4 = 6\text{ V}$$

Sixth, calculate current flow through the parallel resistors using $I = V/R$.

$$\begin{aligned} I_3 &= \frac{V_3}{R_3} \\ &= \frac{6}{3} \\ &= 2\text{ A} \\ I_4 &= \frac{V_4}{R_4} \\ &= \frac{6}{1} \\ &= 6\text{ A} \end{aligned}$$

The entire circuit has now been analyzed using the basic elements of Ohm's law. The completed solution is shown in Fig. 2-30 and listed below.

$E_t = 24$ V	$I_t = 8$ A	$R_t = 3\ \Omega$
$V_1 = 2$ V	$I_1 = 8$ A	$R_1 = 0.25\ \Omega$
$V_2 = 16$ V	$I_2 = 8$ A	$R_2 = 2\ \Omega$
$V_3 = 6$ V	$I_3 = 2$ A	$R_3 = 3\ \Omega$
$V_4 = 6$ V	$I_4 = 6$ A	$R_4 = 1\ \Omega$

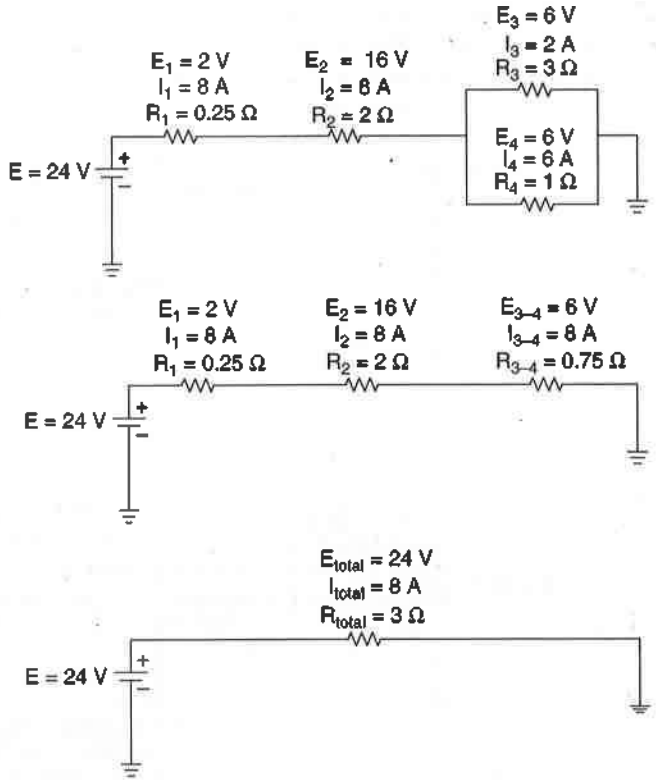


FIGURE 2-30 Solution to series parallel circuit.

It should be considered that the previous series-parallel circuit was relatively simple and therefore easy to solve. In many cases where several groups of series and parallel resistances are combined, the calculations above must be repeated and/or performed in different order.

The solution of a series-parallel circuit such as that shown in Fig. 2-31 is not difficult provided that the load-unit (resistance) values are kept in their correct relationships. To determine all the values for the circuit shown, we must start with R_8, R_9, and R_{10} (Fig. 2-31*b*). Since these resistances are connected in series with each other, their total value is 2 + 4 + 6 = 12 Ω. We shall call this total R_{8-10}; that is, $R_{8-10} = 12\ \Omega$. The circuit can then be drawn as in Fig. 2-32, which is the equivalent of the original circuit.

In the circuit of Fig. 2-32 it can be seen that R_7 and R_{8-10} are connected in parallel. The formula for two parallel resistances can be used to determine the resistance of the combination. We shall call this combination R_{7-10}. Then

$$\begin{aligned} R_{7-10} &= \frac{R_7 \times R_{8-10}}{R_7 + R_{8-10}} \\ &= \frac{12 \times 12}{12 + 12} \\ &= \frac{144}{24} \\ &= 6\ \Omega \end{aligned}$$

Now an equivalent circuit can be drawn as in Fig. 2-33 to further simplify the solution. In this circuit we combine the two series resistances, R_{7-10} and R_6, to obtain a value of

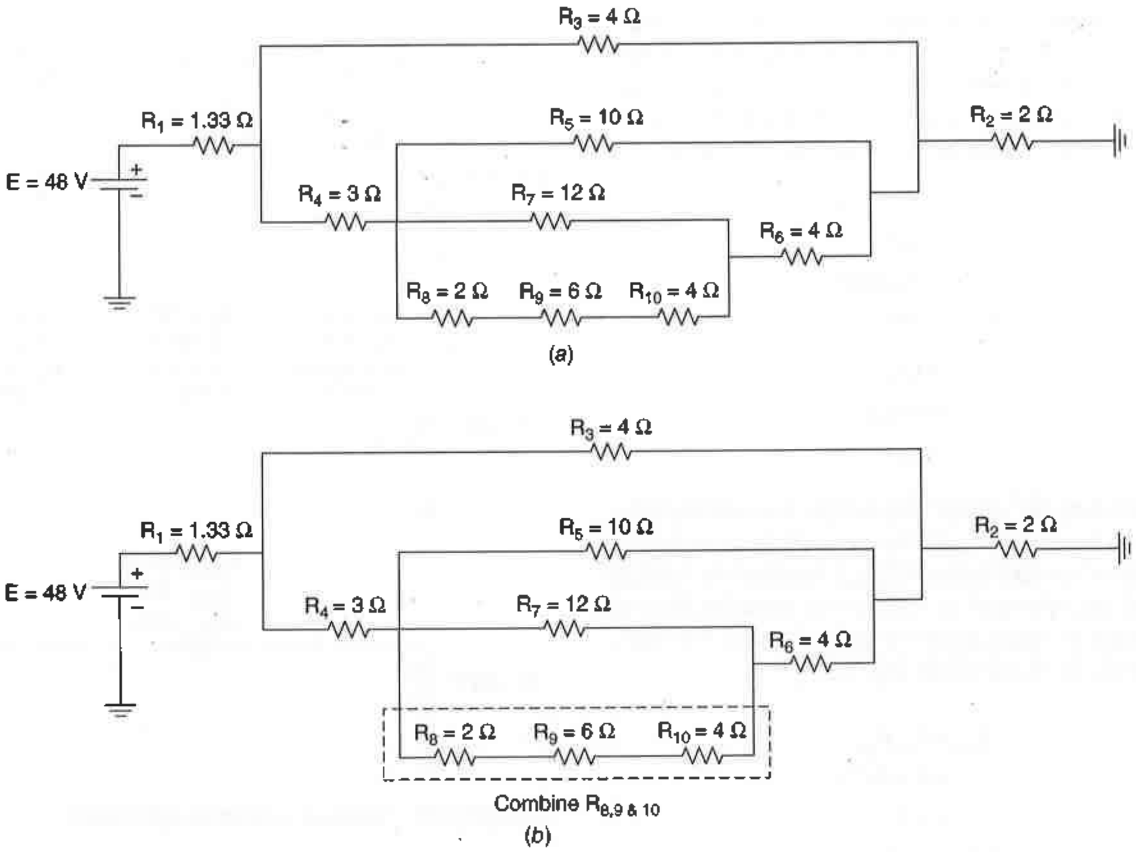


FIGURE 2-31 Series-parallel circuit: (*a*) original circuit; (*b*) first step combine series resistors.

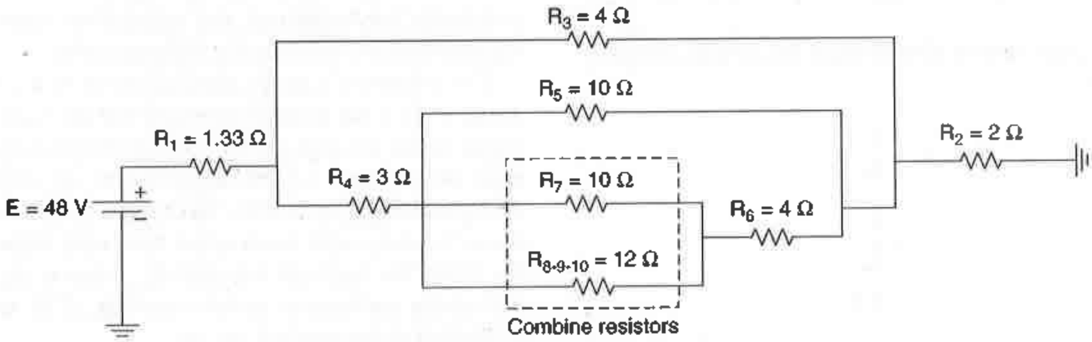


FIGURE 2-32 First simplification step.

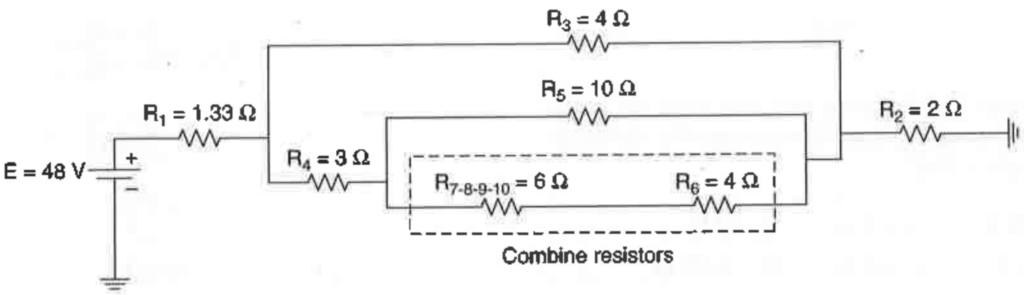


FIGURE 2-33 Second simplification step.

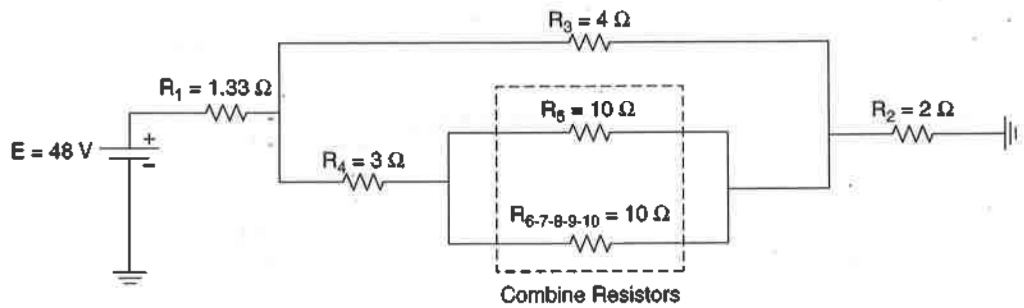


FIGURE 2-34 Third simplification step.

10 Ω for $R_{6\text{–}10}$. The equivalent circuit is then drawn as in Fig. 2-34.

Since the new equivalent circuit shows that R_5 and $R_{6\text{–}10}$ are connected in parallel and that each has a value of 10 Ω, we know that the combined value is 5 Ω. We designate this new value as $R_{5\text{–}10}$ and draw the circuit as in Fig. 2-35. $R_{5\text{–}10}$ is connected in series with R_4; hence, the total of the two resistances is 8 Ω. This is designated as $R_{4\text{–}10}$ for the equivalent circuit of Fig. 2-36. In this circuit we solve the parallel combination of R_3 and $R_{4\text{–}10}$ to obtain the value of 2.67 Ω for $R_{3\text{–}10}$. The final equivalent circuit is shown in Fig. 2-37 with R_1 $R_{3\text{–}10}$, and R_2 connected in series. These resistance values are added to find the total resistance for the circuit.

$$R_t = 1.33 + 2.67 + 2 = 6\ \Omega$$

With the total resistance known and E_t given as 48 V, it is apparent that $I_t = 8$ A ($I_t = E_t/R_t$). The values for the entire circuit can be computed using Ohm's law and proceeding in a reverse sequence from that used in determining total resistance.

First, since $I_t = 8$ A, I_1, $I_{3\text{-}10}$, and I_2, must each be 8 A because the resistances are shown to be connected in series in Fig. 2-35. By Ohm's law ($E = IR$) we find that $V_1 = 10.64$ V, $V_{3\text{-}10} = 21.36$ V, and $V_2 = 16$ V. Referring to Fig. 2-36, it can be seen that 21.36 V exists across R_3 and $R_{4\text{–}10}$. This makes it possible to determine that $I_3 = 5.33$ A and $I_{4\text{–}10} = 2.67$ A. In Fig. 2-35 we note that I_4 and $I_{5\text{-}10}$ must both be 2.67 A because the two resistances are connected in series. Then $V_4 = 8$ *V* and $V_{5\text{–}10} = 13.35$ V. Since $V_{5\text{–}10}$ is the voltage across R_5 and $R_{6\text{–}10}$ in the circuit of Fig. 2-34, it is easily found that $I_5 = 1.33$ A and $I_{6\text{–}10} = 1.33$ A. In the circuit of Fig. 2-33 it is apparent that 1.33 A must flow through both $R_{7\text{–}10}$ and R_6 because they are connected in series and we have already noted that $I_{6\text{–}10} = 1.33$ A. Then $V_{7\text{–}10} = 8$ V and $V_5 = 13.35$ V.

Since $V_{7\text{–}10} = 8$ V, we can apply this voltage to the circuits as shown in Figs. 2-31 and 2-32 and note that both V_7 and $V_{8\text{–}10}$ are 8 V. Then $I_7 = 0.67$ A and $I_{8\text{–}10} = 0.67$ A. Since R_8,

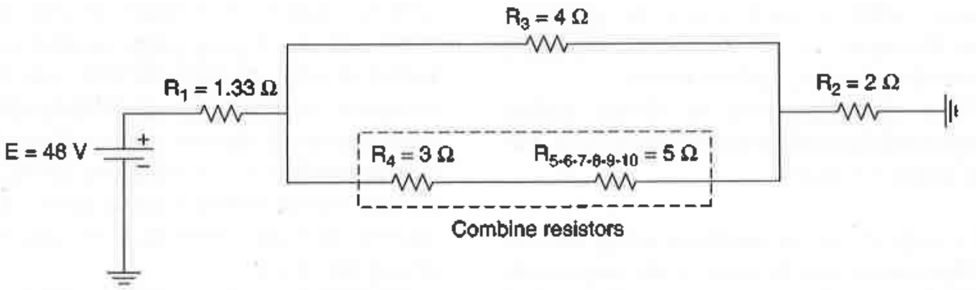


FIGURE 2-35 Fourth simplification step.

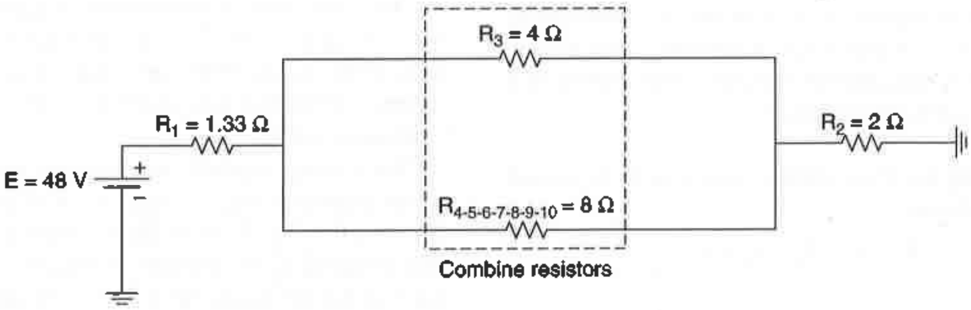


FIGURE 2-36 Fifth simplification step.

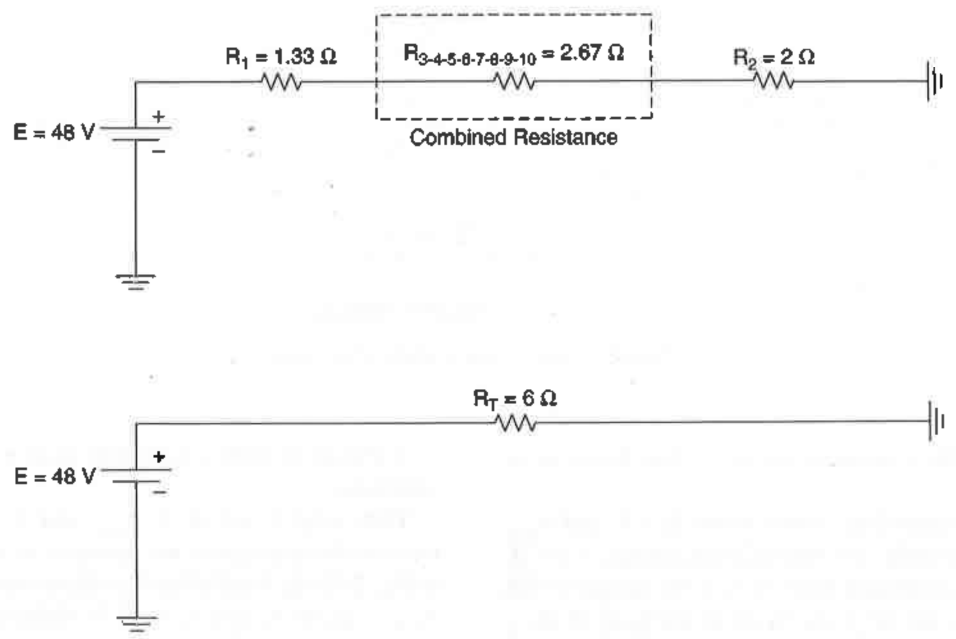


FIGURE 2-37 Final simplified version of Figure 2–31.

R_9, and R_{10} are connected in series and the same current, 0.67 A, flows through each. $V_8 = 1.33$ V, $V_9 = 4$ V, and $V_{10} = 2.67$ V.

The completely solved circuit is shown in Fig. 2-38. A check of all the values given will reveal that they comply with the requirements of Ohm's law. *Note:* Some minor error may exist due to rounding of the numbers during calculation.

KIRCHHOFF'S LAWS

The circuits in this chapter are all solvable by means of Ohm's law as demonstrated. There are, however many circuits that are more complex, which cannot be solved by Ohm's law alone. For these circuits, Kirchhoff's laws may provide the necessary techniques and procedures.

Kirchhoff's laws were discovered by Gustav Robert Kirchhoff, a German physicist of the nineteenth century. The two laws may be stated as follows:

Law No. 1. *In a series circuit, the algebraic sum of the voltage drops in that circuit must be equal to the source voltage.* Kirchhoff's law of voltage drops may also be applied to any portion of a circuit that is connected in series.

Law No. 2. *In a parallel circuit, the algebraic sum of the currents entering a point is equal to the algebraic sum of the currents leaving that point.* Kirchhoff's parallel law of current flows may also be applied to any portion of a circuit that is connected in parallel.

Kirchhoff's law for series voltage drops can be expressed algebraically as follows:

$$E_t - V_1 - V_2 - V_3 = 0$$

or

$$E_t = V_1 + V_2 + V_3$$

Figure 2-39 shows a circuit to illustrate the principle of Kirchhoff's second law. In this circuit, it can be noted that I_t the current flowing to point *A*, is equal to $I_1 + I_2 + I_3$, the current flowing away from point *A*. Kirchhoff's law of parallel current flows can be expressed by the following equations:

$$I_t - I_1 - I_2 - I_3 = 0$$

or

$$I_t = I_1 + I_2 + I_3$$

Both of Kirchhoff's laws become very useful tools in finding solutions to complex electric circuits. In general, when you are solving series-parallel circuits and you are forced to solve an equation with more than one unknown, remember the following: (1) In series circuits or series portions of a circuit, the sum of the voltage drops is equal to the voltage applied across the entire group of series resistors. (2) The current How through a series circuit is constant and equal to the total current flow through the entire series portion of the circuit.

In parallel circuits or parallel portions of a circuit: (1) The voltage applied to each resistance is constant and equal to the voltage applied to the entire parallel portion of the circuit. (2) The sum of the current flows through each parallel resistance is equal to the total current entering that parallel portion of the circuit. With these four basic principles and the correct substitution procedures there should be no circuit too difficult to solve.

Since most airplanes are constructed of metal, the airplane structure may be used as an electric conductor. In the circuit in Fig. 2-40(*a*), 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

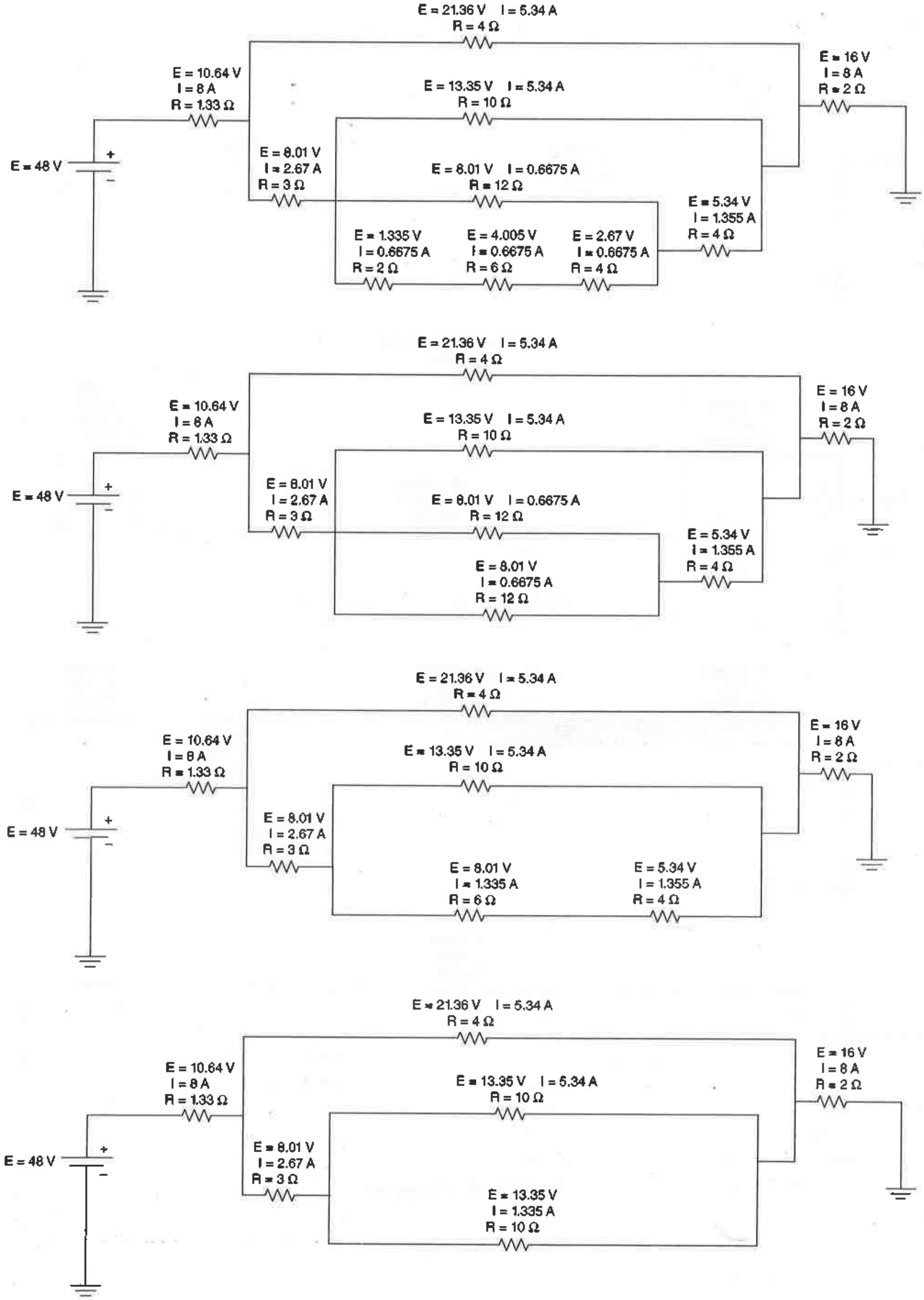


FIGURE 2-38 The completely solved version of Figure 2-29.

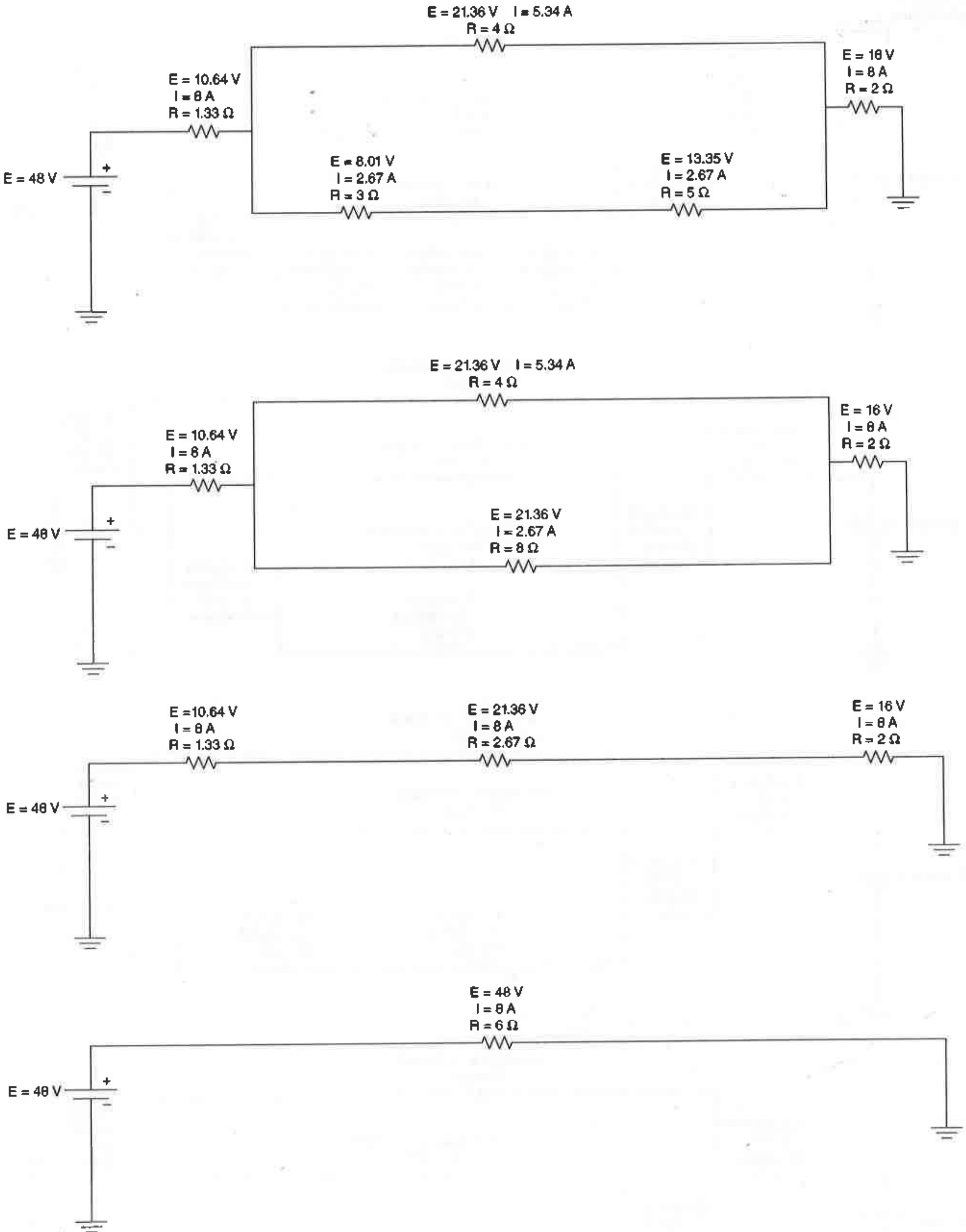


FIGURE 2-38 *(Continued)*

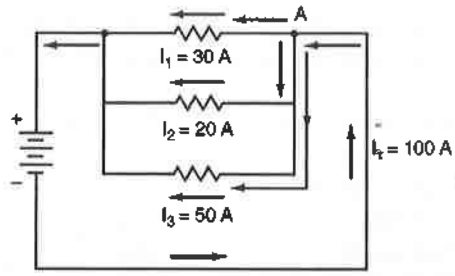


FIGURE 2-39 Diagram to illustrate Kirchhoff's second law. The current to a point is equal to the current from that point.

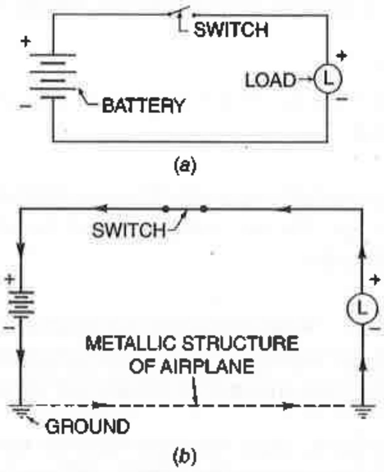


FIGURE 2-40 A simple electrical circuit: (a) a two wire system, (b) a single-wire system.

is shown in Fig. 2-40(*b*). 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.

SOLUTION OF A RESISTANCE BRIDGE CIRCUIT

When resistances are connected in a bridge circuit as shown in Fig. 2-41*a*, it will be noted that two Δ (delta) circuits are formed. These circuits share the resistance R_5. Because of this, it is not possible to solve the circuit by the methods we have explained previously. A mathematical method has been devised whereby the circuit can be solved by converting one of the Δ circuits to an equivalent Y circuit.

Figure 2-41*b* represents an equivalent circuit where the Δ circuit *ABD* of Fig. 2-41*a* has been converted to the equivalent Y circuit *ABD* in Fig. 2-41*b*. This conversion is accomplished with formulas as follows:

$$R_a = \frac{R_1 \times R_5}{R_1 + R_4 + R_5}$$

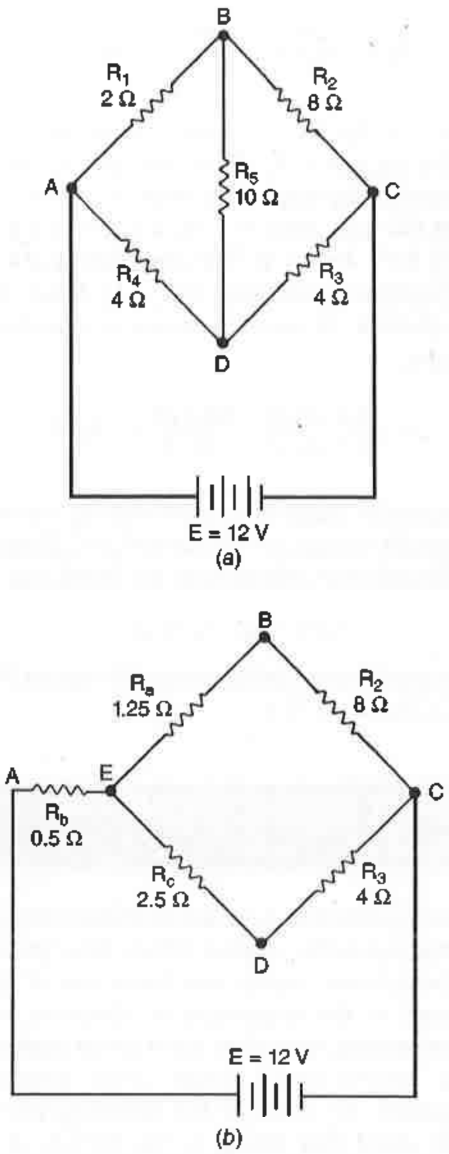


FIGURE 2-41 Circuit to illustrate the conversion of a delta circuit to an equivalent Y circuit and the solution of a resistance bridge circuit.

$$R_b = \frac{R_1 \times R_4}{R_1 + R_4 + R_5}$$

$$R_c = \frac{R_4 \times R_5}{R_1 + R_4 + R_5}$$

The circuit of Fig. 2-41*b* is a simple series-parallel type and can be solved as we have explained previously.

For an example of how the circuit of Fig. 2-41 can be solved, we shall first assign resistance values to the resistors in Fig. 2-41*a*. $R_1 = 2\ \Omega$, $R_2 = 8\ \Omega$, $R_3 = 4\ \Omega$, $R_4 = 4\ \Omega$, and $R_5 = 10\ \Omega$. Then

$$R_a = \frac{2 \times 10}{2+4+10} = \frac{20}{16} = 1.25\ \Omega$$

$$R_b = \frac{2 \times 4}{2+4+10} = \frac{8}{16} = 0.5\ \Omega$$

$$R_t = \frac{4\times10}{2+4+10} = \frac{40}{16} = 2.5\,\Omega$$

In the circuit of Fig. 2-41*b*, R_a and R_2, are in series, and R_c is connected in series with R_3. Since series circuit values are added to determine the value of the total, we add the series resistances in this case. Then $R_a + R_2 = 1.25 + 8 = 9.25\ \Omega$, and $R_c + R_3 = 2.5 + 4 = 6.5\ \Omega$. The combination of $R_a + R_2$ is in parallel with the combination of $R_c + R_3$; hence, we use the parallel formula for two resistances to determine the equivalent value.

$$R_t = \frac{6.5\times9.25}{6.5+9.25} = \frac{60.125}{15.75} = 3.82\,\Omega$$

Since the parallel circuit is in series with R_b, we add the total of the parallel resistances (3.82 Ω) to R_B (0.5 Ω) to obtain the combined equivalent resistance for the circuit; that is,

$$0.5 + 3.82 = 4.32\,\Omega$$

Since 12 V is applied to the bridge circuit, the current through the circuit is 12/4.32 = 2.78 A.

PRACTICAL APPLICATIONS OF OHM'S LAW

For an aircraft technician, there are countless uses for the material contained in this chapter. Ohm's law can be used during the installation, repair, and inspection of various electrical units; in the acquisition of electrical components; in determining wire sizes for a given application; and in basic electric circuit design. Some examples of these applications are stated in the following problems. It should be noted that owing to the brevity of these examples, they may not fully illustrate the complexity of a given situation that might be encountered during actual aircraft maintenance.

Problem No. 1. During an annual inspection it was noticed that the bus bar (the main electrical distribution connection) had been replaced by the previous aircraft owner. One way for the technician to verify the airworthiness of this bus bar is to determine its actual load-carrying capability and compare it with the aircraft's actual total load. It was determined from the part number of the bus bar that the maximum amperage allowable to enter this part was 60 amps. Is the bus bar within its amperage limit?

Solution. By applying Kirchhoffs law for parallel circuits, it was determined that the current flowing from the bus bar was also the current flowing through the bus bar. The maximum allowable current through the bus is 60 amps; therefore, the total aircraft load could not exceed this value. Since all aircraft circuits are connected in parallel to the bus, the total current was determined using

$$I_t = I_1 + I_2 + I_3 + I_4 + I_5 + I_6 + I_7$$

If the loads on the aircraft are as follows, it is a simple process to determine, if the bus bar is electrically overloaded.

Navigation lights	10 A
Navigation radio	4 A
Communication radio	3 A
Pitot heat	12 A
Flap motor	8 A
Hydraulic pump motor	16 A
Fuel pump motor	6 A

Simply sum the individual current flows to find the total current flow.

$$I_t = 10\text{ A} + 4\text{ A} + 3\text{ A} + 12\text{ A} + 8\text{ A} + 16\text{ A} + 6\text{ A} = 59\text{ A}$$

Since the aircraft's total load is only 59 amps and the bus bar can handle 60 amps, the bus installation can be considered within its current limit.

Problem No. 2. What size generator must be placed on the aircraft used in Problem 1? The approved generators for that particular airplane are rated at 30, 60, and 90 A.

Solution. Once again, since we know that the current to a point is equal to the current from that point, we can determine that the 59 A "pulled" from the aircraft's bus bar must be "pushed" into the bus bar by the generator. Therefore, the 60-A generator would be required as a minimum. However, the 59 A calculated earlier does not include the current needed to charge the battery after starting the aircraft engine. (*Note:* On this aircraft, the battery current does not feed through the bus; it is received directly from the generator.) Since battery charging current can often exceed 20 A for short periods, the 90-A generator should he installed.

Problem No. 3. While a new electric fuel pump is installed on an antique aircraft, the fuel flow adjustment must be made by changing the voltage to the pump motor. This change in voltage changes the rpm of the pump motor, hence, changing the fuel flow through the pump. To accomplish this voltage change, the aircraft system contains an adjustable resistor in series with the fuel pump motor. If the aircraft manual calls for 8 V, to be applied to the pump motor and the aircraft system voltage is 14 V, at what resistance must the variable resistor be set?

Solution. Since voltage drops are additive in a series circuit, the voltage drop of the resistor plus the voltage drop of the fuel pump must equal 14 V (system voltage); or, 14 V – 8 V = resistor voltage drop. The voltage drop of the resistor is therefore 6 V. The equation $R = E/I$ can be used to determine the resistor's value. According to the data plate of the fuel pump, the motor draws 2 A at 8 V. Since the motor and resistor are in series, 2 A must also flow through the variable resistor. Using

$$R_r = \frac{V_r}{I_r}$$

where R_r = resistance of the resistor in ohms
V_r = the voltage drop over the resistor (6 V)
I_r = the current flow through the resistor (2 A)

$$R_r = \frac{6\,V}{2\,A}$$

$$= 3\,\Omega$$

The variable resistor should be set for 3 Ω in order to produce the correct fuel flow.

REVIEW QUESTIONS

1. Define Ohm's law.
2. What letter is used to represent electric current?
3. What name is given to the unit of electromotive force?
4. How is emf expressed during calculations of Ohm's law?
5. What is the mathematical relationship between *E*, *R*, and *I*?
6. What is the basic equation for Ohm's law?
7. What simple analogy can be used to help understand the concepts of Ohm's law?
8. Water pressure can be compared to what element of Ohm's law?
9. Explain the difference between series circuits and parallel circuits.
10. Give the three forms for the formula of Ohm's law.
11. Define *watt.*
12. Compare watts with horsepower.
13. What horsepower is expended in a circuit in which the voltage is 110 V and the current is 204 A?
14. What amperage is required to drive a 5-hp motor in a 110-V circuit when the motor has an efficiency of 60 percent?
15. Explain how current flows in a *series* circuit.
16. Define *voltage drop.*
17. Explain the relationship of voltage drops in a series circuit.
18. Explain how current flows in a *parallel* circuit.
19. Explain how voltage is applied to various components in a parallel circuit.
20. What is the total resistance of a circuit that contains the following resistors connected in parallel: R_1 = 24 ohms, R_2 = 24 ohms, R_3 = 10 ohms, and R_4 = 5 ohms.
21. Explain Kirchhoff's law of voltage drops.
22. Explain Kirchhoff's law of parallel current flows.
23. Give the equation to find total resistance in a parallel group of resistors.
24. Give the equation to find total resistance in a series group of resistors.
25. In a parallel circuit, total resistance is always less than what value?

Aircraft Storage Batteries 3

INTRODUCTION

There are literally hundreds of types and sizes of batteries and cells currently in use. An increase in the various forms of electronic devices has created a demand for a variety of cells/batteries. The aircraft technician may find several types of batteries used to power monitoring or test equipment; however, there are currently two types of batteries used on nearly all aircraft, the nickel-cadmium and lead-acid battery.

All battery cells produce dc voltage. The actual voltage level is a function of the chemicals used to form the cell. Typically, a "cell" is thought of as the simplest form of a battery; and batteries are constructed by combining several cells into one vessel. The direct current supplied by a battery is a function of the chemicals used to produce the cells and the size and number of cells forming the battery. These concepts must be considered when designing a circuit and choosing the power source for that circuit. This chapter will examine the theory and construction of several types of batteries and their cells.

DRY CELLS AND BATTERIES

Voltaic Cells

In an earlier portion of this text, it was explained that various dissimilar substances have opposite polarities with respect to one another and that when two such substances are rubbed together, one will have a positive charge and the other a negative charge. Dissimilar metals also have this property, and when two such metals are placed in contact with each other, there will be a momentary flow of electrons from the one having a negative characteristic to the one having a positive characteristic. If two plates of dissimilar metals are placed in a chemical solution called an *electrolyte*, opposite electric charges will be established on the two plates.

In simple terms, an **electrolyte** is a solution of water and chemical compound that will conduct an electric current within a cell. The electrolyte in a typical aircraft storage battery consists of sulfuric acid and water. Other solutions, such as salt water can also act as an electrolyte.

An electrolyte will conduct an electric current because it contains positive and negative ions. When a chemical compound is dissolved in water, it separates into its component parts. Some of these parts carry a positive charge, and others carry a negative charge.

The action of an electrolyte will be clear if a specific case is considered. When a rod of carbon and a plate of zinc are placed in a solution of ammonium chloride, the result is an elementary voltaic cell (see Fig. 3-1). The carbon and zinc elements are called **electrodes**. The carbon, which is the positively charged electrode, is called the **anode**, and the zinc plate is called the **cathode**. The combination of two electrodes surrounded by an electrolyte will form a **cell**.

As soon as the zinc (Zn) plate is placed in the electrolyte, zinc atoms begin to go into solution as ions, each leaving two electrons at the plate. An **ion** is an atom or molecule that is either positively or negatively charged. A positively charged ion has a deficiency of electrons, and a negatively charged ion has an excess of electrons. The zinc atoms going into solution as positive ions cause the zinc plate to become negatively charged. The zinc ions in the solution are positive because each one lacks the two electrons left at the plate. This positive charge causes the zinc ions to remain near the zinc plate because the plate has become negative. The effect

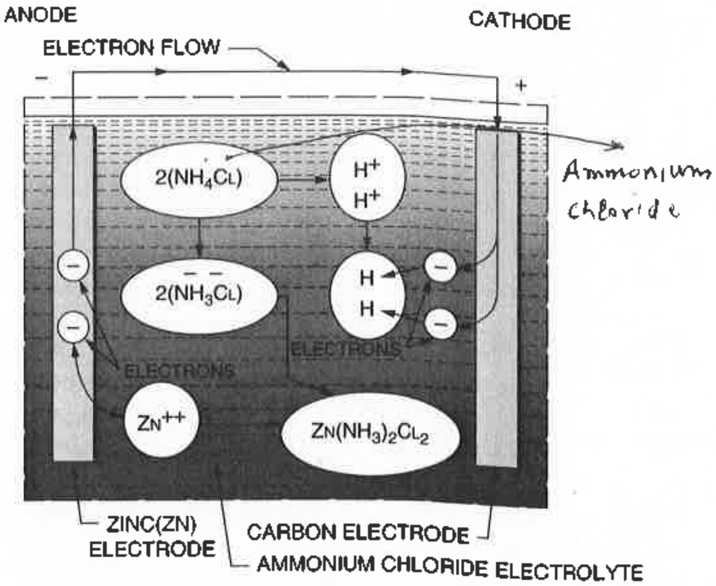


FIGURE 3-1 Chemical action in a voltaic cell.

Silver Nickel Aluminum

of the zinc ions gathered near the plate is to stop the decomposition of the zinc plate for as long as the negative charge of the plate is balanced by the positive charge of the zinc ions in solution.

The ammonium chloride in solution in the electrolyte apparently separates into positive hydrogen ions and a combination of ammonium and chlorine that is negatively charged. When the two electrodes are connected by an external conductor, the free electrons from the zinc plate flow to the carbon rod; and the hydrogen ions move to the carbon rod, where each ion picks up one electron and becomes a neutral hydrogen atom. The positive zinc ions combine with the negative ammonium chloride to take the place of the hydrogen ions released into solution. The effect of these chemical actions is to remove electrons from the carbon rod and to liberate free electrons at the zinc plate. This results in a continuous supply of electrons available at the negative (zinc) electrode. When the two electrodes are connected, the electrons will flow to the carbon rod. where the hydrogen ions become hydrogen atoms as the result of their neutralization by the electrons. Eventually, hydrogen gas bubbles form on the carbon rod and insulate it from the solution. This is called **polarization** and will cause the current flow to stop until the hydrogen is removed.

The standard carbon-zinc **dry cell** used in flashlights and for other purposes employs a compound called manganese dioxide (MnO_2) to prevent the accumulation of hydrogen at the positive electrode in the cell. Figure 3-2 is a drawing of this type of cell. A dry cell is so called because the electrolyte is in the form of a paste; the cell may therefore be handled without the danger of spillage. The zinc can is the negative electrode, and the paste electrolyte is held in close contact with the zinc by means of a porous liner. The space between the carbon rod and the zinc can is filled with manganese dioxide saturated with electrolyte. Graphite is mixed with the manganese dioxide to reduce the internal resistance of the cell. The top of the cell is sealed with non-conductive material to prevent leaking and drying of the electrolyte. Many cells are encased in a tin-plated steel can to make them more durable; a layer of insulating material is then placed between the inner zinc can and the outer can to prevent short circuiting.

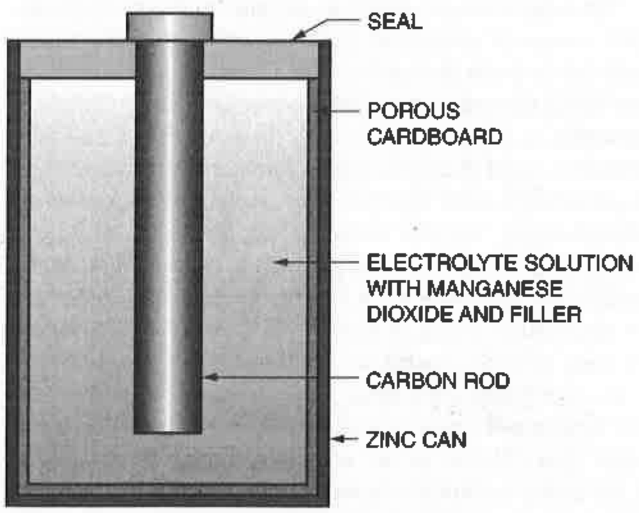


FIGURE 3-2 Construction of a simple dry cell.

The voltage developed by a zinc-carbon cell is approximately 1.5 V. The voltage of any cell depends on the materials used as the electrodes. A lead-acid secondary cell, such as those employed in storage batteries, develops a voltage of 2.1 V. The electrodes (plates) are composed of lead for the negative and lead peroxide for the positive. As previously stated, dissimilar metals always have a definite polarity with respect to one another. For example, if nickel and aluminum are placed in an electrolyte, the nickel will be positive and the aluminum negative. However, if nickel and silver are acted upon by the same electrolyte, the nickel will be negative and the silver positive. The more active a metal is chemically, the greater its negative characteristic.

A cell that cannot be recharged satisfactorily is called a **primary cell**. The elementary voltaic cell described previously in this section is a primary cell. Some of the elements deteriorate as the cell produces current; hence, the cell cannot be restored to its original condition by charging. The common flashlight cell is a familiar example of a primary cell. The negative plate of a primary cell deteriorates because the material goes into solution with the electrolyte. In the secondary cell, the material of the plates does not go into solution but remains in the plates, where it undergoes a chemical change during operation.

In a **secondary cell**, the chemical action that produces the electric current can be reversed; in other words, secondary cells can be recharged. This is accomplished by applying a voltage higher than that produced by the cell to the cell terminals; this causes a current to flow through the cell in a direction opposite to that in which the current normally flows. The positive terminal of the charging source is connected to the positive terminal of the cell, and the negative terminal of the charging source is connected to the negative terminal of the cell. Since the voltage of the charger is higher than that of the cell, electrons flow into the negative plate and out of the positive plate. This causes a chemical action to take place that is the reverse of the one that occurs during operation of the cell; the elements of the cell return to their original composition. At this time, the cell is said to be *charged*. Secondary cells can be charged and discharged many times before they deteriorate to the point at which they must be discarded.

The standard symbols for a battery and a single cell are shown in Fig. 3-3. As shown here, a battery can be made up of a single cell or several cells connected together. It should also be noted that the symbol has a given polarity, that is,

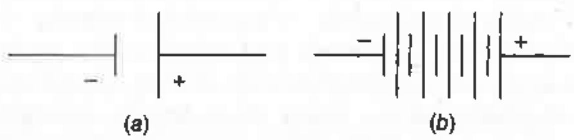


FIGURE 3-3 The electrical symbol for a cell and battery: (*a*) a single cell, (*b*) a battery consisting of five cells. NOTE: the location of the positive and negative connections.

the positive and negative connections are always shown as given in this diagram. In some cases it is important to recognize battery polarity, and the electrical symbol can be used to identify the locations for both the positive and negative connections.

Alkaline and Mercury Cells

Batteries utilizing an alkaline electrolyte are usually termed **alkaline cells**.

Specialty Batteries

In a quest for alternative energy sources, there has been a heavy interest in the development and use of high-energy batteries. These batteries are typically designed for a specific use and are found in a variety of common electronic devices. Laptop computers, cell phones, power tools, automobiles, and even electric aircraft are all made possible through the development of modern batteries. In most cases, these batteries are constructed of several secondary cells connected in series and/or parallel to create a powerful rechargeable battery. Some of these specialty batteries are also found in various aircraft electronic devices, often used for emergency or backup power.

The basic design of specialty batteries is very similar to other conventional cells; however, the chemical structure is altered to increase battery capacity and service life. Chemicals commonly used include lithium-ion (Li^+), lithium-manganese dioxide ($LiMnO_2$), nickel oxyhydroxide (NiOOH), and silver oxide (S). Wherever specialty batteries are used, take extra caution to ensure proper installation and servicing. In many cases, service or installation of the incorrect battery can cause serious damage to electronic systems. Always consult the aircraft technical information prior to battery replacement, charging, or service.

The electrolyte consists primarily of a potassium hydroxide solution. Potassium hydroxide (KOH) is a powerful caustic similar to household lye and can cause severe burns if it comes into contact with the skin. The electrodes of alkaline cells can be of several different types of materials, such as manganese dioxide and zinc, silver oxide and zinc, silver oxide and cadmium, mercuric oxide and zinc, or nickel and cadmium. These various electrode materials will determine if the alkaline cell is a rechargeable secondary cell or a nonrechargeable primary cell. The different electrodes will also determine the cell's voltage output. Most common alkaline cells produce approximately 1.5 V without a load applied to the cell. Figure 3-4 shows a variety of cells used in various electronic devices.

Mercury cells are another common type of dry cell used for a variety of applications. A mercury cell consists of a positive electrode of mercuric oxide mixed with a conductive material and a negative electrode of finely divided zinc. The electrodes and the caustic electrolyte are assembled in sealed steel cans. Some electrodes are pressed into flat circular shapes, and others are formed into hollow cylindrical shapes, depending on the type of cell for which they are made.

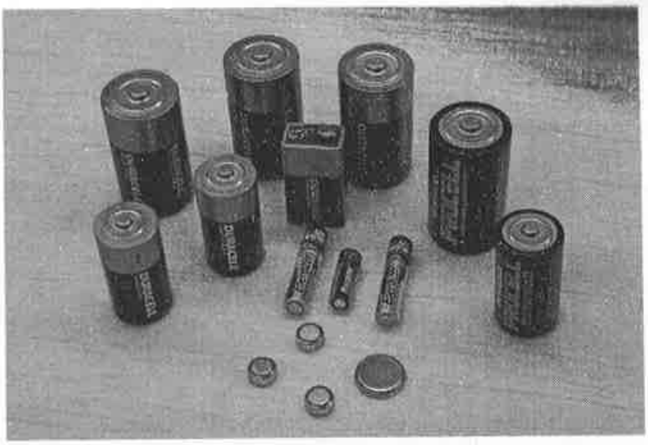


FIGURE 3-4 Dry cell batteries.

The electrolyte is immobilized in an absorbent material between the electrodes. Mercury cells are often used for small *button* batteries found in miniature equipment, such as watches and calculators.

Nickel-Cadmium Cells

Nickel-cadmium electric cells and batteries have been developed to a high degree of efficiency and dependability. They are used in small devices that formerly used carbon-zinc dry cells and in other devices where carbon-zinc cells cannot meet the load requirements. They are also being manufactured in large sizes for use in aircraft where large load requirements are present. The service and maintenance of nickel-cadmium aircraft batteries are discussed later in this chapter.

Nickel-cadmium cells are made with various electrode designs, but the active elements remain the same. In a charged state, the negative electrode consists of metallic cadmium (Cd), and the positive electrode is nickel oxyhydroxide (NiOOH). During discharge the electrodes alter chemical composition. The negative electrode becomes cadmium hydroxide (CdOH), and the positive electrode becomes nickel hydroxide [$Ni(OH)_2$].

The most common electrode designs for nickel-cadmium cells consist of perforated steel pockets to hold the active materials or perforated nickel plates or woven nickel screens into which the active materials are impregnated by sintering. **Sintering** is a process of heating finely divided metal particles in a mold to approximately melting temperature. The metal particles weld together where they are in contact with other particles, and this results in a porous material. In the case of nickel-cadmium electrodes, the sintered material is nickel or nickel carbonyl for the positive plates and cadmium for the negative plates. A nickel-cadmium cell that has been cut away to show construction is illustrated in Fig. 3-5.

As mentioned previously, a secondary cell is one that can be charged and discharged repeatedly without appreciable deterioration of the active elements. An advantage of the nickel-cadmium secondary cell is that it can stand in a discharged condition indefinitely at normal temperatures

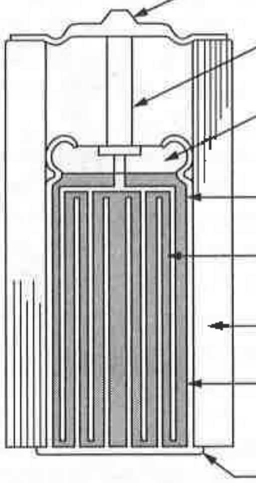


FIGURE 3-5 Ni-cad cutaways to show construction.

without deterioration. If a lead-acid battery is left in the discharged condition for a substantial period of time, sulfation of the plates occurs, and the cells lose much of their capacity.

During the discharge of a nickel-cadmium cell, electrons are released in the negative material as chemical change takes place. These electrons flow through the outer electric circuit and return to the positive electrode. Positive ions in the electrolyte remove the electrons from the positive electrode. During charge, the reverse action takes place, and the negative electrode is restored to a metallic cadmium state.

Nickel-cadmium cells generate gas during the latter part of a charge cycle and during overcharge. Hydrogen is formed at the negative electrode, and oxygen is formed at the positive electrode. In vented-type batteries, the hydrogen and oxygen generated during overcharge are released to the atmosphere together with some electrolyte fumes. In a sealed dry cell, it is necessary to provide a means for absorbing the gases. This is accomplished by designing the cadmium electrode with excess capacity. This makes it possible for the positive electrode to become fully charged before the negative electrode. When this occurs, oxygen is released at the positive electrode, while hydrogen cannot yet be generated because the negative electrode is not fully charged. The cell is so designed that the oxygen can travel to the negative electrode, where it reacts to form chemical equivalents of cadmium oxide. Thus, when a cell is subject to overcharge, the cadmium electrode is oxidized at a rate just sufficient to offset input energy, and the cell is kept at equilibrium at full charge.

If a cell is charged at the recommended rate, overcharging can occur for as long as 200 or 300 charge cycles without damage to the cell. If the charge rate is too high, the oxygen pressure in the cell can become so great that it will rupture the seal. For this reason, charge rates must be carefully controlled.

Battery Hazards

Batteries should always be treated as a potential hazard. A charged battery will contain high levels of energy, which can cause a serious danger if mishandled. Even discharged batteries can leak chemicals which may be harmful to electronic systems, people, or the environment. Always read and adhere to current warnings, cautions, and procedures when handling batteries. Common handling procedures include wearing eye protection and rubber gloves. Other personal protections may also be recommended for certain batteries.

A battery explosion may occur by the misuse or malfunction of a battery. If one tries to charge a primary cell (nonrechargeable) or if a battery is discharged too quickly (due to a circuit malfunction), the battery may overheat or explode. Lead-acid batteries (discussed later in this chapter) emit hydrogen gas when charged. This gas is very explosive and precautions must be taken during charging lead-acid batteries. Overcharging or charging too rapidly is also very dangerous; both create excess heat and potentially explosive gas.

Many battery chemicals are corrosive, poisonous, or both. Use extreme caution if a battery leak occurs. Batteries with a liquid electrolyte can accidentally spill or leak from a defective battery case. Dry cell batteries may also leak chemicals through the case due to age, improper care, or battery malfunction or damage. The chemical leakage can damage equipment and is typically harmful to humans. Many electronic device manufacturers recommend removing the batteries from devices that will not be used for extended periods of time to prevent any potential damage from leaking batteries.

Environmental Concerns

All commercially made batteries employ toxic chemicals that create environmental concerns. Used batteries contribute to electronic waste; accidental battery damage; and chemical spills may harm local soils and the water supply. The manufacturing of batteries is also environmentally hazardous and extreme precautions are necessary during battery assembly. In most cases, potential problems can be avoided with proper care and recycling procedures. Always treat batteries as a potential chemical hazard, always recycle used batteries, and always use proper cleanup procedures if a chemical spill occurs.

Open- and Closed-Circuit Voltages

There are two different ways to measure the voltage of a battery or cell. Voltage measured when there is no load applied to the battery is called the **open-circuit voltage** (OCV). The voltage measured while a load is applied to the battery is called the **closed-circuit voltage** (CCV). The OCV is always higher than the CCV because a battery can maintain a higher pressure (voltage) when there is no current flow leaving the battery. The OCV of a fully charged aircraft battery may reach 13.2 V; however, when even a small load is applied, the CCV will measure near 12 V. This battery would typically be referred to as a 12-V battery. The CCV of a battery is usually a function of the load applied and the state of charge of that battery. If a battery is connected to a heavy load, the CCV will be lower than if that battery was connected to

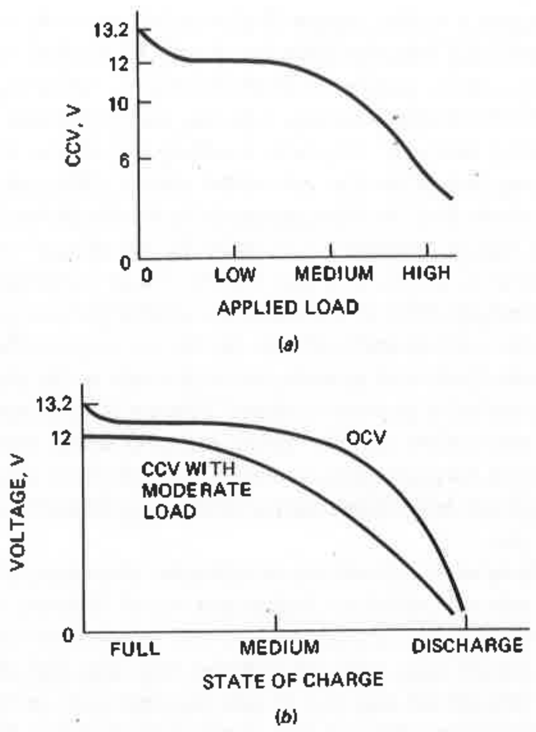


FIGURE 3-6 (a) Closed-circuit voltage versus applied load; (*b*) open- and closed-circuit voltage versus a battery's state of charge.

a light load. If a battery is near total discharge, the CCV will be lower than if that same buttery was fully charged. The OCV of a battery is typically affected very little by its state of charge until the battery reaches near complete discharge. Figure 3-6 illustrates the relationships between OCV and CCV for various loads and battery states of charge.

Internal Resistance

The resistance present inside of a battery while connected to a load is called **internal resistance** (IR). IR restricts the movement of current inside of any power source, including batteries. In the case of a battery, the IR is determined by the load applied and the battery's state of charge.

A battery's IR is equal to the difference between the OCV and the CCV, divided by the applied load. That is, IR = (OCV – CCV)/load amperage. This equation is derived from Ohm's law, $R = E/I$. A battery's internal resistance can be determined as follows: If the OCV = 14 V and the CCV = 12 V with a 100-A load applied, the IR is 0.02 Ω. The calculation is

$$\begin{aligned} IR &= \frac{OCV - CCV}{I \text{ load}} \\ &= \frac{14\text{ V} - 12\text{ V}}{100\text{ A}} \\ &= \frac{2\text{ V}}{100\text{ A}} \\ &= 0.02\,\Omega \end{aligned}$$

A battery's internal resistance always becomes greater as the battery becomes discharged. This is due to the lowering of a battery's CCV as the battery becomes weaker. The OCV remains nearly constant while the CCV drops; therefore, the difference between these two voltages increases. Hence, IR increases.

The IR of a battery becomes very significant when a power source is chosen or a delicate circuit is designed. However, for general-purpose applications, a battery's internal resistance will not adversely affect an aircraft electrical system until that battery becomes over 75 percent discharged. When the battery reaches this low state of charge, its internal resistance becomes too high and the CCV lowers. This low CCV obviously affects circuit performance.

A common example of this battery misconnection often occurs when using an extra battery to "jump-start" an automobile. Often when a car will not start due to a discharged battery, the operator will use a second car battery to jump-start the first. During this process it is important to connect the positive connection of one battery to the positive of the other battery; and the negative to the negative. This is known as observing polarity. If the polarity is not observed, a very large current flow could damages the system. Typically sparks will fly and the jumper cables will overheat the battery. If you have ever experienced this mistake, it becomes easy to see the power and inherent danger of a storage battery and why it is very important to connect batteries correctly.

LEAD-ACID STORAGE BATTERIES

The term **storage battery** has been used for many years as the name for a battery of secondary cells and particularly for lead-acid and nickel-cadmium batteries.

Two types of **lead-acid** batteries currently being used in aviation are (1) the **vented cell** and (2) the **sealed** battery (Fig. 3-7). The modern sealed-cell lead-acid batteries are more powerful and require less maintenance than the older vented lead-acid aircraft batteries. For this reason, lead-acid batteries are being used to replace the more expensive nickel-cadmium battery in some turbine-powered aircraft. On turbine-powered aircraft, however, the installation of lead-acid batteries typically requires that external power be readily available for engine starting, and the lead-acid batteries require more frequent replacement. Despite the great strides made to improve lead-acid batteries, they are still unable to deliver the current generated by nickel-cadmium batteries; therefore, nickel-cadmium batteries will remain a practical power source for most larger aircraft. Nickel-cadmium batteries are discussed later in this chapter.

Lead-acid secondary cells consist of lead-compound plates immersed in a solution of sulfuric acid and water, which is the **electrolyte**. Each cell has an OCV of approximately 2.1 V when fully charged. When connected to a substantial load, the voltage is approximately 2 V. Aircraft storage batteries of the lead-acid type are generally rated at 12 or 24 V; that is, they have either 6 or 12 cells connected in series (see Fig. 3-8).

FIGURE 3-7 A sealed lead-acid aircraft battery. (*Concord Battery Corporation.*)

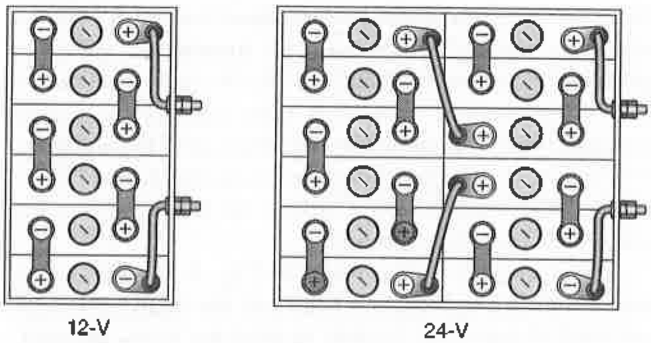


FIGURE 3-8 Arrangement of cells in a lead-acid storage battery.

Actually, the voltage of a 12-V battery is near 12.6 V (6 cells × 2.1 V/cell) when the battery is fully charged. A 24-V battery actually provides 25.2 V (12 cells × 2.1 V/cell). Figure 3-8 illustrates how the individual cells of a battery can be connected by external connector plates. On modern lead-acid batteries, cell connectors are actually housed inside the battery, therefore limiting the possibility of accidental cell shorting.

Schematic diagrams of cells connected in series and parallel are shown in Fig. 3-9. In the series diagram, six 2-V cells are connected in series to produce 12 V. If the same six cells are connected in parallel, as shown in Fig. 3-9*b*, the total voltage is the same as that of one cell; however, the capacity of a group, in amperes, is six times the capacity of a single cell. To increase both the voltage and the amperage by combining single cells, the cells are connected in a series-parallel circuit like that shown in Fig. 3-10. When 24 cells are connected in this manner, the voltage is six times as great as that of a single cell, and the current capacity of the combined cells is four times as great as that of a single cell.

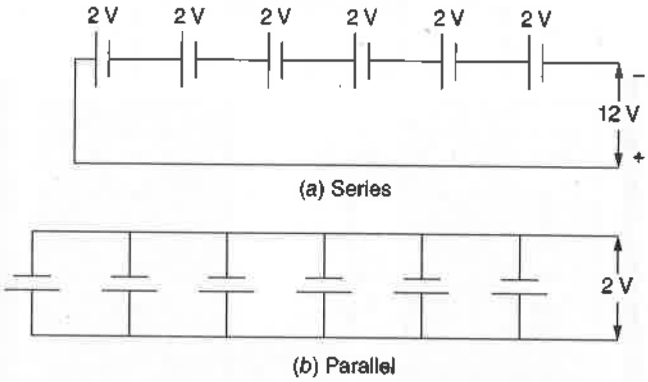


FIGURE 3-9 Series and parallel cell connections.

When batteries or cells are connected incorrectly, they may be damaged. For example, if a technician intends to connect three batteries in parallel and accidently connects one of them incorrectly, there will be a short circuit. This will either burn out the wiring or discharge the batteries and possibly damage them beyond repair. An explosion could also result due to the rapid discharge of the center battery. It is essential that the technician understand well the characteristics of battery circuits and the proper methods for connecting batteries and cells.

Storage batteries are convenient for aircraft use because their weight is not excessive for the power developed, and they can be kept in a nearly fully charged state by means of an engine-driven dc alternator. It must be remembered that the aircraft storage battery is used only when other sources of electric power are not available.

On light aircraft, the battery is used during initial engine starting, for intermittent loads that exceed alternator output, and in emergency situations (alternator failure). Large turbine-powered aircraft typically use the storage battery only for emergency power; any current required for starting the engines is supplied by a separate ground power unit. The storage battery on most commercial jets would supply approximately 30 minutes of emergency power in the case of a complete alternator system failure.

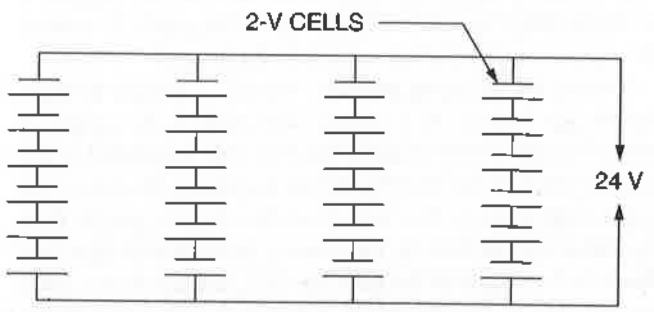


FIGURE 3-10 Series-parallel cell connections.

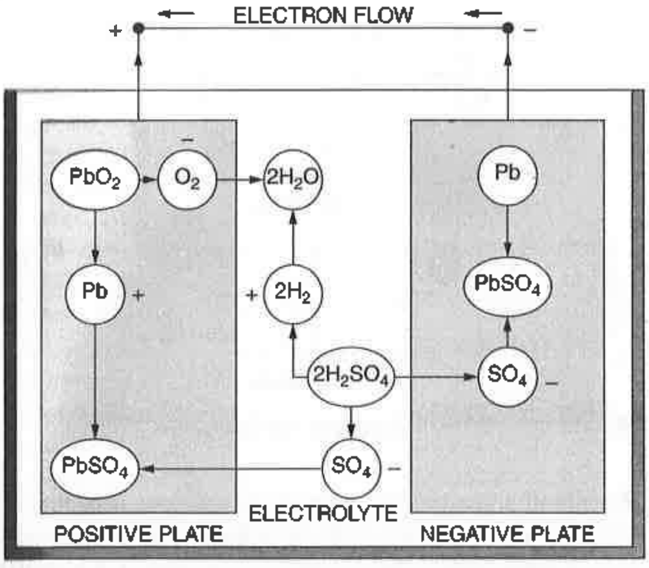


FIGURE 3-11 Chemical action in a lead-acid secondary cell.

Theory of the Lead-Acid Cell

The lead-acid secondary cell used in a storage battery consists of positive plates filled with lead peroxide (PbO_2); negative plates filled with pure spongy lead (Pb); and an electrolyte consisting of a mixture of 30 percent sulfuric acid and 70 percent water, by volume (H_2SO_4).

A chemical action takes place when a battery is delivering current as shown in Fig. 3-11. The sulfuric acid in the electrolyte breaks up into hydrogen ions (H_2) carrying a positive charge and sulfate ions (SO_4) carrying a negative charge. The SO_4 ions combine with the lead plate and form lead sulfate ($PbSO_4$). At the same time, they give up their negative charge, thus creating an excess of electrons on the negative plate.

The H_2 ions go to the positive plate and combine with the oxygen of the lead peroxide (PbO_2), forming water (H_2O), and during the process they take electrons from the positive plate. The lead of the lead peroxide combines with some of the SO_4 ions to form lead sulfate on the positive plate. The result of this action is that the positive plate has a deficiency of electrons and the negative plate has an excess of electrons.

When the plates are connected together externally by a conductor, the electrons from the negative plate flow to the positive plate. This process will continue until both plates are coated with lead sulfate and no further chemical action is possible; the battery is then said to be discharged. The lead sulfate is highly resistant to the flow of current, and it is chiefly this formation of lead sulfate that gradually lowers the capacity of the battery until it is discharged.

During the charging process, current is passed through the storage battery in a reverse direction. A dc supply is applied to the battery with the positive pole connected to the positive plate of the battery and the negative pole connected to the negative plate. The voltage of the source is greater than the voltage of the battery. This causes the current to flow in a direction to charge the battery. The SO_4 ions are driven back into solution in the electrolyte, where they combine with the H_2, ions of the water, thus forming sulfuric acid. The plates then return to their original composition of lead peroxide and spongy lead. When this process is complete, the battery is charged.

Figure 3-12 shows the chemical changes that occur to a lead-acid battery during charge and discharge.

	CHARGED STATE	CHEMICAL CHARGE	DISCHARGE
POSITIVE PLATE	PbO_2	LOOSES O_2 GAINS SO_4	$PbSO_4$
NEGATIVE PLATE	Pb	GAINS SO_4	$PbSO_4$
ELECTROLYTE	H_2SO_4	LOOSES SO_4 GAINS O_2	H_2O

FIGURE 3-12 Chemical changes of a lead-acid battery during charge and discharge.

Lead-Acid Battery Construction

A storage battery consists of a group of lead-acid cells connected in series and arranged somewhat as shown in Fig. 3-8. Under moderate load the closed circuit voltage (CCV) of the 6-cell battery is approximately 12 V, and that of a 12-cell battery is about 24 V. As stated earlier, CCV is the voltage of the battery when connected to a load.

Each cell of a storage battery has positive and negative plates arranged alternately and insulated from each other by separators. Each plate consists of a framework, called the **grid,** and the **active material** held in the grid. A traditional formula for the grid material is approximately 90 percent lead and 10 percent antimony. The purpose of the antimony is to harden the lead and make it less susceptible to chemical action. Other metals, such as silver, are also used in some grids to increase their durability.

A typical grid is illustrated in Fig. 3-13. The heavy border adds strength to the plate, and the small horizontal and vertical bars form cavities to hold the active material. The structural bars also act as conductors for the current, which is distributed evenly throughout the plate. Each plate

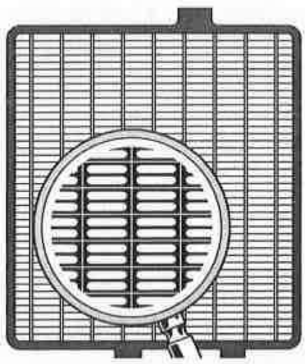


FIGURE 3-13 Grid for a lead-acid cell plate.

is provided with extensions, or feet, which rest upon ribs on the bottom of the cell container. These feet are arranged so the positive plates rest upon two of the ribs and the negative plates upon the two alternative ribs. The purpose of this arrangement is to avoid the short-circuiting that could occur as active material is shed from the plates and collects at the bottom of the cell.

The plates are made by applying a lead compound to the grid. The paste is mixed to the proper consistency with diluted sulfuric acid, magnesium sulfate, or ammonium sulfate and is applied to the grid. The paste for the positive plates is usually made of red lead (Pb_3O_4) and a small amount of litharge (PbO). In the case of the negative plates, the mixture is essentially litharge with a small percentage of red lead. The consistency of the various materials and the manner of combining them have considerable bearing on the capacity and life of the finished battery.

In compounding the negative-plate paste, a material called an **expander** is added. This material is relatively inert chemically and makes up less than 1 percent of the mixture. Its purpose is to prevent the loss of porosity of the negative material during the life of the battery. Without the use of an expander, the negative material contracts until it becomes quite dense, thus limiting the chemical action to the immediate surface. To obtain the maximum use of the plate material, the chemical action must take place throughout the plate from the surface to the center. Typical expanding materials are carbon black, barium sulfate, graphite, fine sawdust, and ground carbon. Other materials, known as hardness and porosity agents, are sometimes used to give the positive plates desired characteristics for certain applications. One or more manufacturers reinforce the active material of the battery plates with plastic fibers 0.118 to 0.236 in. [3 to 6 mm] long. This adds substantially to the active life of the battery.

After the active-material paste is applied to the grids, the plates are dried by a carefully controlled process until the paste is hardened. They are then given a forming treatment in which a large number of positive plates are connected to the positive terminal of a charging apparatus and a like number of negative plates, plus one, are connected to the negative terminal. They are placed in a solution of sulfuric acid and water (electrolyte) and charged slowly over a long period of time. A few cycles of charging and discharging convert the lead compounds in the plates into active material. The positive plates thus formed are chocolate brown in color and of a hard texture. The negative-plate material has been converted into spongy lead of a pearl-gray color. After forming, the plates are washed and dried. They are then ready to be assembled into **plate groups**.

Plate groups are made by joining a number of similar plates to a common terminal post (see Fig. 3-14). The number of plates in a group is determined by the capacity desired, inasmuch as capacity is determined by the amount (area) of active material exposed to the electrolyte.

Since increasing plate area will increase a battery's capacity, many manufacturers strive for the maximum in internal battery dimensions. That is, if the inside of the battery can be kept as large as possible, the plate area can be increased. To do this, ultrathin plastic cases have been employed to "squeeze" the maximum plate area inside the battery of a given size. It also stands to reason that increasing the battery's outer (and inner) dimensions could be a means to increase capacity. However, for aircraft use, we typically strive for the smallest, lightest battery with a relatively high capacity.

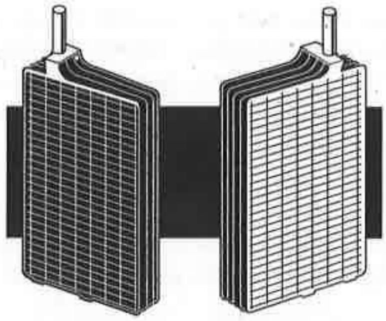


FIGURE 3-14 Plate groups.

Each plate is made with a lug at the top to which the **plate strap** is fused. A positive-plate group consists of a number of positive plates connected to a plate strap, and a negative group is a number of negative plates connected in the same manner. The two groups meshed together with separators between the positive and negative plates constitute a **cell element** (see Fig. 3-15). It will be noted in the illustrations that there is one less positive plate than negative plates. This arrangement provides protection for the positive plates, inasmuch as they are more subject to warping and deterioration than the negative plates. By placing negative plates on each side of every positive plate, the chemical action is distributed evenly on both sides of the positive plate, and there is less tendency for the plate to warp.

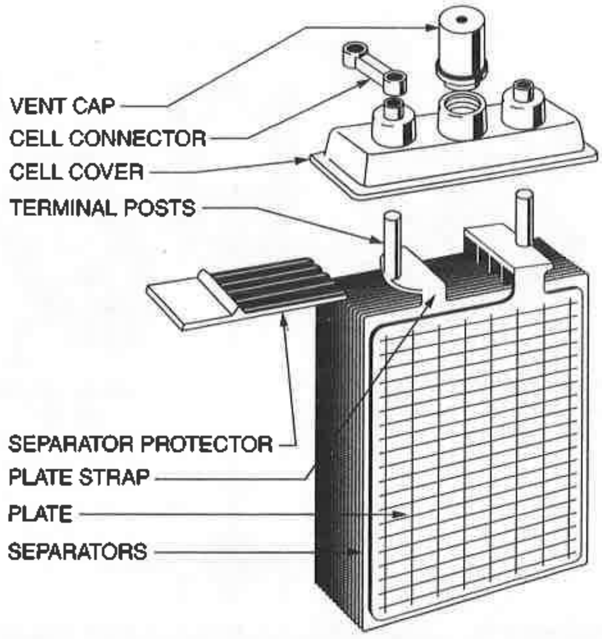


FIGURE 3-15 Cell element for a lead-acid cell.

The **separators** used in lead-acid storage batteries are typically made of fiberglass, rubber, or other insulating materials. Their purpose is to keep the plates separated and thus prevent an internal short circuit. Without separators, even if the containers were slotted to keep the plates from touching, material might flake off the positive plates and fall against the negative plates. Negative material might expand sufficiently to come in contact with the positive plates, or the positive plates might buckle enough to touch the negative plates.

The material of the separators must be very porous so that it will offer a minimum of resistance to the current passing through. The separators are saturated with electrolyte during operation, and it is this electrolyte that conducts the electric current. It is obvious also that the separators must resist the chemical action of the electrolyte.

Glass-wool separators are used by some manufacturers. Fine glass fibers are laid together at different angles and cemented on the surface with a soluble cement. The glass wool is placed in the cell adjacent to the positive plate. Because of the compressibility of glass wool, it comes into very close contact with the positive plate and prevents the loosened active material from shedding. It is claimed that batteries with this type of separator have a longer life than those without it.

Another very effective method for providing plate separation is to enclose the positive plates in microporous polyethylene pouches. This increases the efficiency of the battery because the plates are much closer together, approximately 0.05 in. [1.25 mm], than they are with other types of separators. The pouches also prevent the shedding of active material from the positive plates.

When the cell elements are assembled, they are placed in the **cell container**, which is made of hard plastic composition. Cell containers are usually made in a unit with as many compartments as there are cells in the battery. In the bottom of the container are ribs. Two of these ribs support the positive plates, and the other two support the negative plates. This arrangement leaves a space underneath the plates for the accumulation of sediment, thus preventing the sediment from coming in contact with the plates and causing a short circuit.

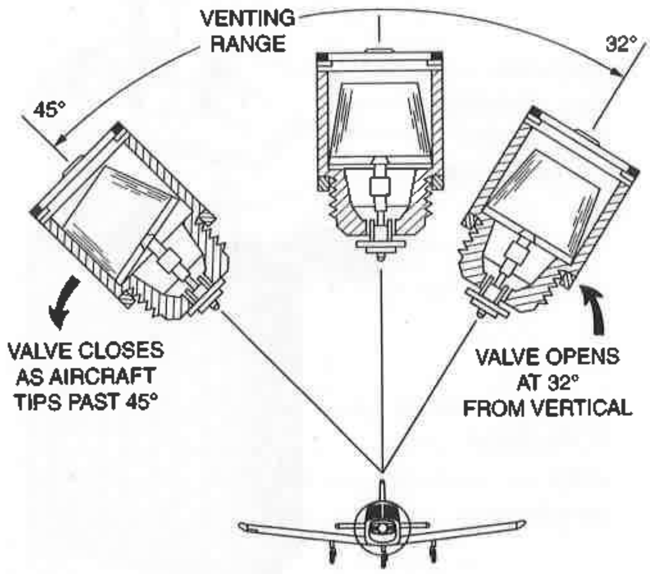


FIGURE 3-16 Vented cell cap for acrobatic aircraft. (*Teledyne Battery Products.*)

The sediment space provided in storage batteries is of such capacity that it is not necessary to open the cells to clean out the sediment. When the sediment space is full to the point at which the spent material may come in contact with the plates, the cell is worn out.

The assembled cell of a storage battery has a cover made of material similar to that of the cell container. The cell cover is provided with two holes through which the terminal posts extend and a threaded hole into which is screwed the vented cell cap. When the cover is placed on the cell, it is sealed in with a special sealing compound. This is to prevent spillage and loss of electrolyte.

When a storage battery is on charge and approaching the full-charge point or is at the full-charge point, there is a liberal release of hydrogen and oxygen gases. It is necessary to provide a means whereby these gases can escape, and this is accomplished by placing a vent in the cell cap. The ventilated cap used to seal all lead-acid battery cells must allow any hydrogen/oxygen gas to escape from the enclosed cell and at the same time create a seal to ensure that the liquid electrolyte will not spill from the battery. This becomes a somewhat difficult task on aircraft batteries since all aircraft will tilt and roll during various flight maneuvers. Flying through turbulent air also creates a challenge in the design of the ventilated cell cap.

A battery vent cap that is particularly well adapted to acrobatic and military aircraft is shown in Fig. 3-16. As shown in the drawing, there is a valve in the bottom of the unit, and this valve is opened and closed by the action of the conical weight in the upper part of the cap. When the battery is tilted approximately 45°, the weight drops against the side of the cap, pulling upon the valve stem and closing the valve.

When the battery is brought back to a position approximately 32° from vertical, the weight centers itself again, allowing the valve stem to lower and open the vent valve.

Battery Design Features

Although the majority of lead-acid storage batteries are constructed with similar features, there are many differences in size and detail design, depending on the use to which the battery is to be put. A metal-encased battery (aluminum or steel) is constructed with an external case coated with acid-resistant paint.

This box provides mechanical protection as well as electrical shielding and is fitted with a metal cover secured in place with hold-down rods. The design also provides an airtight space above the cells so that the gases being emitted will not escape into the aircraft in which the battery is installed. The vent space is provided with a connection for a tube installed to carry the battery gases overboard. This is a requirement for any battery that emits gases during operation.

FIGURE 3-17 A 12-V (6-cell) lead-acid aircraft battery.

The main negative and positive terminals of the battery are connected to external terminals in the side of the metal case. These terminals are adequately insulated from the case by washers and bushings.

A storage battery installed in a light aircraft is shown in Fig. 3-17. This battery is made with a lightweight polystyrene case and is designed for use in an aircraft with an enclosed and ventilated battery compartment. The plates in this battery are reinforced with plastic fibers, and the positive plates are enclosed in microporous pouches to provide plate separation and protection. The intercell connectors are internal and permanently sealed with an epoxy resin. *Note:* There are 6 cell caps on this battery; therefore, this battery contains 6 cells and is considered a 12-V battery (6 cells × 2 V/cell = 12 V).

The battery shown in Fig. 3-18 is installed in a typical light aircraft. This battery is designed for installation where there is no enclosed battery compartment. As shown in the figure, the gas-collecting manifold at the top of the battery is connected to an inlet and outlet tube which allows any hydrogen/oxygen gas to be vented outside the aircraft. The vent tubes are designed to extend approximately 2 in. outside the fuselage. The vent tubes typically exit the aircraft at a low point of the fuselage somewhere near the engine exhaust. This helps to ensure that the corrosive gasses created during battery charging do not come in contact with critical aircraft components.

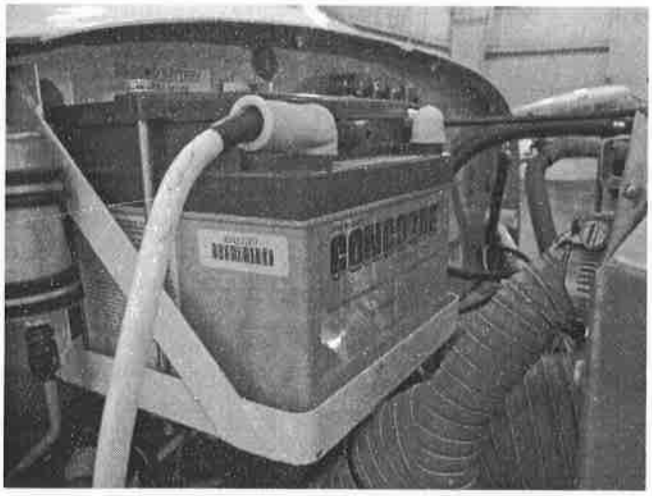


FIGURE 3-18 A 24-V lead-acid aircraft battery with self-contained battery box. See also color insert.

Valve-Regulated Lead–Acid Battery

In an effort to reduce the corrosive/explosive gasses produced by traditional lead-acid batteries, a new generation of storage batteries have been developed known as a **valve-regulated lead-acid battery** (VRLA). This battery is commonly known as a **sealed battery** and is found in many modern aircraft applications. Sealed lead-acid batteries are made from rechargeable secondary cells and employ the same chemical reactions as a traditional lead-acid battery. Because of their construction, VRLA batteries do not require regular addition of water to the cells, and no gas is allowed to vent outside the battery case during charging. Any gas produced is stored in a chamber inside the battery housing. The reduced venting is an advantage since VRLA batteries can be used in confined or poorly ventilated spaces. However, sealing the cells prevents the addition of water to the electrolyte if needed. Therefore, VRLA batteries are still in limited use on aircraft and often for specialty applications which do not require regular discharge/charge cycles.

VRLA batteries are designed in two common categories; the **absorbed glass mat** (AGM) battery and the **gel battery** (gel cell).

An AGM battery has the electrolyte absorbed in several fiber-glass mat separators. Very thin glass fibers are woven into a mat, which increases the surface area enough to hold sufficient electrolyte. The fibers that compose the fine glass mat neither absorb nor are affected by the acidic electrolyte. The electrolyte simply clings to the many fibers, and the mat acts like a sponge. A gel cell has the electrolyte mixed with silica dust to form an immobilized gel. The relatively thick gel surrounds the plate material and replaces the liquid electrolyte in a traditional lead-acid battery. Both types are often called "sealed" lead-acid batteries; however, they always include a safety pressure relief valve for emergency venting if needed. VRLA batteries will not spill electrolyte if the battery is tilted or inverted. This characteristic is very advantageous for aircraft use. In general, VRLA batteries use much less electrolyte than traditional lead-acid batteries. The small amount of electrolyte is contained in a glass mat or gel substance; hence, the common names for these batteries.

The name "valve regulated" does not completely describe the batteries' technology. These are more accurately called "recombinant" batteries; this means the oxygen produced at the positive plates will largely recombine with the hydrogen formed on the negative plates inside the sealed chamber of the battery. This process prevents water loss and the need to add water to the electrolyte as the battery ages. The valve is a safety feature in case the rate of hydrogen production becomes dangerously high. In traditional cells, the gases escape before the hydrogen and oxygen can recombine, so water must be added periodically.

The pressure relief valve will activate if the battery is recharged at high voltage, typically greater than 2.30 V per cell. This may occur during a malfunction of the charging system or a defective battery. Valve activation allows some of the gas or electrolyte to escape, thus decreasing the overall capacity of the battery. If this overcharge occurs, be sure to consult the aircraft manual for proper repair of the system and possible battery replacement.

VRLA batteries typically require special charging equipment. Most VRLA battery chargers have built-in circuitry to monitor the battery condition and cycle the charges as needed to prevent damage to the cells and/or a gas release through the pressure relief valve. It is not recommended to use a conventional battery charger on VRLA batteries. Constant-voltage charging is the usual, most efficient, and safest charging method for VRLA batteries, although other methods can be used. VRLA batteries may be continually "float" charged at around 2.30 V per cell at 77°F [5°C]. Some designs can be fast charged [1 h] at high rates. Always consult the current manufacture's technical data prior to servicing any aircraft battery.

Cold-Weather Operation

Temperature is a vital factor in the operation and life of a storage battery. Chemical action takes place more rapidly as temperature increases. For this reason, a battery will give much better performance in temperate or tropical climates than in cold climates. On the other hand, a battery will deteriorate faster in a warm climate, and the battery will have to be replaced more often.

In cold climates, the state of charge in a storage battery should be kept at a maximum. A fully charged battery will not freeze even under the most severe weather conditions, but the electrolyte of a discharged battery will freeze very easily.

When water is added to a battery in extremely cold weather, the battery must be charged at once. If this is not done, the water will not mix with the acid and will freeze. Table 3-1 gives the freezing point for various states of charge.

TABLE 3-1 Freezing points for different states of charge in a lead-acid storage battery.

Specific gravity	Freezing point °F	Freezing point °C
1.300	−95	−70.6
1.285	−85	−65.0
1.275	−80	−62.2
1.250	−62	−52.2
1.225	−35	−37.2
1.200	−16	−26.7
1.175	−4	−20.0
1.150	+5	−15.0
1.125	+13	−10.6
1.100	+19	−7.2

LEAD-ACID BATTERY MAINTENANCE PROCEDURES

Precautions

Follow these precautions when servicing aircraft batteries:

1. Always wear safety glasses.
2. Remove the negative lead first and install it last when disconnecting a battery.
3. Do not cause a short circuit between the battery terminals. Be cautious of jewelry and watches. Some are good conductors and may short-circuit the battery, causing severe injury to the technician.
4. Never service the batteries near an open flame or sparks.
5. In preparation for a flight, never jump-start an aircraft from another power source if the airplane's battery is discharged. The battery within the aircraft is not an airworthy battery because of its discharged state. A battery requires several hours to recharge completely when fully discharged and will be unable to support the aircraft's electrical system in the event of an emergency. During jump-starting of an airplane, a strong current flow into the airplane's battery may damage the cell plates, which will lead to premature battery failure.

Lead-Acid Battery Inspection and Service

Most aircraft are scheduled for 50-h, 100-h, annual, or periodic inspections. During these inspection periods, the battery should be inspected and serviced as required. A service schedule of 50-h of flight time or once a month (whichever comes first) will ensure that the battery will continue to perform properly.

As a general rule, one should always follow the manufacturer's maintenance instructions whenever possible. The following is offered as a general guide for inspection and service of batteries:

1. Batteries are very heavy and their mounting assembly must be inspected thoroughly. Make sure that no part of the supporting structure is cracked or weakened in any way.
2. Remove the cover from the battery case, if it is the covered type, and inspect the interior. Look for evidence of leakage and corrosion. The top of the battery should be clean and dry. A small amount of corrosion around the terminals can be removed with a stiff brush and a mild soda solution. A wire brush should not be used because of the danger of short-circuiting the battery.

It is important to note that a battery whose top is damp with electrolyte and dirt will discharge itself quite rapidly. The electrolyte on the outside of the case will create a steady current flows from the negative terminal of the battery to the positive terminal. Hence it is essential that the top of any storage battery be kept clean and dry. When using a soda solution to neutralize lead-acid battery spills, take care to see that none of the solution enters the battery cells. If it does, the solution will neutralize the electrolyte, and the battery is likely to go "dead." After cleaning the battery with soda solution, rinse it with clean water and dry the battery.

If a large amount of corrosion is found in the battery case, the battery should be removed and the case cleaned thoroughly. If appreciable damage has been done, either to the battery case or to the battery mounting structure, the damaged parts should be repaired or replaced.

3. Check the electrolyte level in the battery. If the liquid is below the plates of the battery cell, add clean distilled water until it is approximately $\frac{3}{8}$ in. (0.95 cm) above the plates. Most batteries have an electrolyte level indicator just above the plates. If a battery is so equipped, the electrolyte should be filled to this level. Figure 3-19 illustrates the correct electrolyte level for a lead-acid battery. Remember, always add distilled water only, never electrolyte. The proper level should be above the plates and about 1 in. below the top of the battery.

4. If the battery is suspected of being defective, perform a battery load test or a hydrometer test (lead-acid batteries only). If the battery indicates that it is weak during either test, recharge the battery and retest after the battery has stabilized (about 1 h). Remember, a hydrometer test should never be performed on lead-acid batteries immediately after water is added to the cells. The readings will be erroneous until the water and the electrolyte are thoroughly mixed.

5. Inspect the electrical connections. See that they are tight and free from corrosion. If a quick-disconnect plug is used on the battery, remove it and inspect the contacts. If they are dirty or corroded, clean them thoroughly and apply a small amount of terminal lubricant. Replace the plug, making sure that the handwheel is light.

6. Inspect the battery cables for condition of insulation, evidence of chafing, and security of connections.

7. Replace the cover on the battery case, making sure that the hold-down nuts are tightened sufficiently and safetied if needed.

8. Inspect the ventilation system of the aircraft and battery box. Be sure the vent tubes are clear and without damage. Inspect the airplane near the area of the discharge tube exit. This area often corrodes and must be cleaned and neutralized periodically.

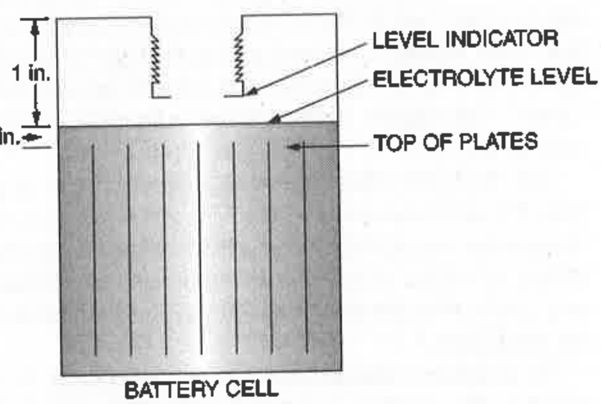


FIGURE 3-19 Cell electrolyte level.

Hydrometer Test

For aircraft lead-acid batteries, it is typical to use a hydrometer test to determine the batteries' state of charge. A **hydrometer** is a tool used to measure the specific gravity, or density, of a liquid. The **specific gravity** of a substance is defined as the **ratio of the weight of a given volume of that substance to the weight of an equal volume of pure water at +4°C.**

The specific gravity of the electrolyte in a lead-acid cell decreases as the charge in the cell decreases. This is because the acid in the electrolyte becomes chemically combined with the active material in the plates as the battery produces current; hence, less acid remains in the electrolyte. Since the specific gravity of the acid is considerably greater than that of water, the loss of acid causes the specific gravity of the electrolyte to drop.

A hydrometer is used to determine the specific gravity of the electrolyte in a lead-acid cell. A typical hydrometer used for battery testing is shown in Fig. 3-20. It consists of a small sealed glass tube weighted at the end to make it float in an upright position. The amount of weight in the bottom of the tube is determined by the specific gravity range of the fluid

FIGURE 3-20 Performing a specific gravity test using a hydrometer.

to be tested. In the case of a battery hydrometer, the specific gravity range is 1.100 to 1.300. This small tube is placed inside a larger glass-tube syringe. With this arrangement, the electrolyte can be drawn from a cell into the glass tube and the reading noted.

The specific gravity reading is taken where the fluid level meets the float inside of the hydrometer, floating freely in the electrolyte. To ensure test accuracy, the indicator must be floating freely in the electrolyte. When the test is complete, the electrolyte is then returned to the cell from which it was taken.

When a battery is tested with a hydrometer, the temperature of the electrolyte must be taken into consideration because the specific gravity readings on the hydrometer will vary from the true specific gravity as the temperature goes above or below 80°F [26.7°C]. No correction is necessary when the temperature of the electrolyte is between 70 and 90°F [21.1 and 32.2°C] because the variation is not great enough to be considered. At higher or lower temperatures it is necessary to apply a correction according to Table 3-2.

The corrections in Table 3-2 should be added to or subtracted from the reading on the hydrometer. For example, if the temperature of the electrolyte is 10°F [−12.2°C] and the hydrometer reading is 1.250, the corrected reading will be 1.250 − 0.028, or 1.222. Notice that the correction points represent thousandths.

Some hydrometers are equipped with a correction scale inside the tube: the temperature correction then can be applied as the hydrometer reading is taken.

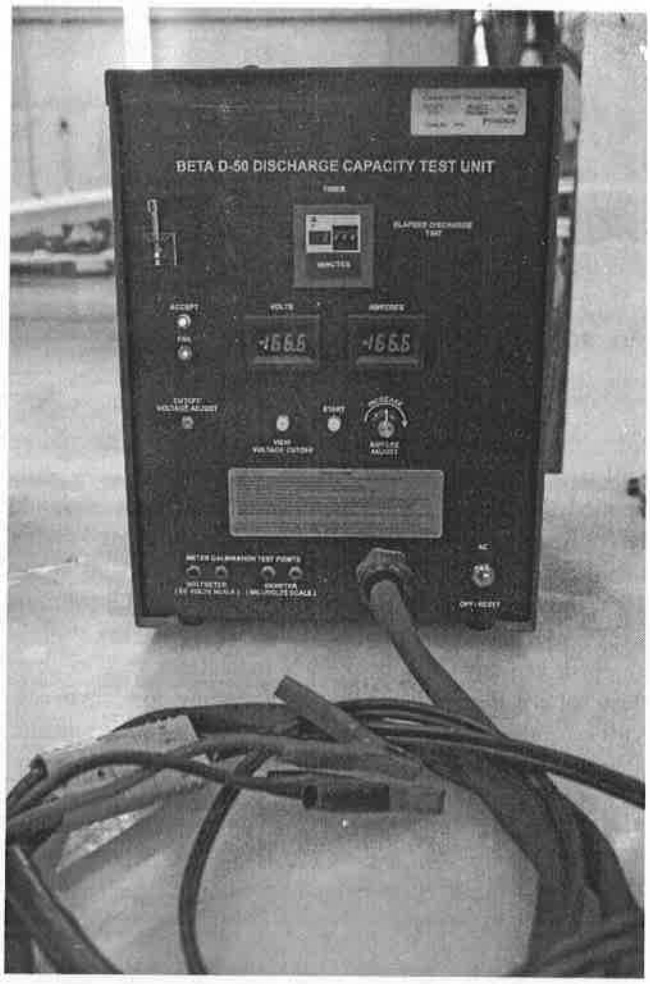


FIGURE 3-21 Battery load tester.

TABLE 3-2 Hydrometer corrections for temperature.

Electrolyte temperature °F	Electrolyte temperature °C	Correction points (thousands)
120	48.9	Add 16
110	43.3	Add 12
100	37.8	Add 8
90	32.2	No correction
80	26.7	No correction
70	21.1	No correction
60	15.6	Subtract 8
50	10.0	Subtract 12
40	4.4	Subtract 16
30	−1.1	Subtract 20
20	−6.7	Subtract 24
10	−12.2	Subtract 28
0	−17.8	Subtract 32
−10	−23.3	Subtract 36
−20	−28.9	Subtract 40
−30	−34.4	Subtract 44

Battery Load Testers

There are various automatic **battery load testers** available; one is illustrated in Fig. 3-21. This machine will test not only batteries but also the aircraft's charging system if so desired. While an automatic battery test is being performed, a load is applied for 15 s, and the *open-circuit voltage (OCV)* and *closed-circuit voltage (CCV)* are automatically compared. The OCV is the voltage of the battery with no load applied; the CCV is the measure of battery voltage while the battery is under load. If the CCV falls below 9.6 V, the indication "bad" appears on the test unit. If the CCV is maintained above 9.6 V during the entire load test, the unit will indicate "good." Once again, discharged batteries must be charged prior to testing.

The high-rate discharge battery capacity test is probably the most common and practical test used. This test is designed to simulate the load typically placed on the battery during an engine start. This load can reach several hundred amps for a few minutes, definitely the most strenuous time for any battery.

To simulate a starting load, the test equipment, as illustrated in Fig. 3-22, is connected to the battery in parallel. Then the operator applies a load approximately two or three

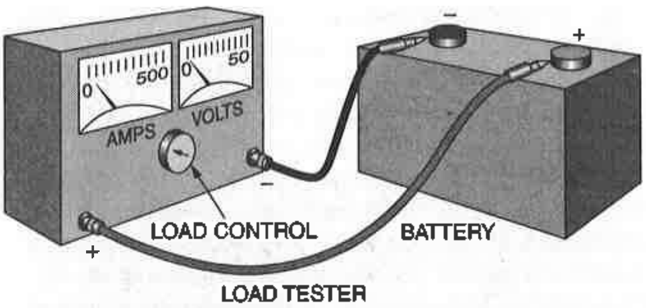


FIGURE 3-22 Battery load tester.

times the battery's ampere-hour rating. (Ampere-hour rating will he discussed later in this chapter.) While the load is applied, the CCV of the battery is measured. The load should be applied for less than 2 min and the CCV monitored during this time. If the CCV drops below 11 V but remains above 10 V, the battery is only slightly discharged. If the battery's CCV stays between 10 and 9 V, the battery is only slightly charged, and any CCV below 9 V indicates a very weak or dead battery. Remember, a low CCV reading does not necessarily mean a defective battery. A low reading only indicates a weak battery charge. This can be caused by a defective battery or a good battery that has been partially discharged earlier. To determine whether the battery is defective, recharge the battery and retest. If the CCV is still low, the battery is defective. If the CCV remains high after the recharge, the battery capacity is good.

Battery Charging

Secondary cells are charged by passing a direct current through the battery in a direction opposite to that of the discharge current. This means that the supply current's positive connection must be connected to the battery's positive connection and the negative connected to negative. Various methods of supplying the charge current are available. Onboard the aircraft, the generator or alternator will supply the charging current. Other ground-based charging equipment will convert common 115-V ac voltage into the dc voltage needed for battery charging. The two general types of charging equipment are **constant-current chargers** and **constant-voltage chargers.**

Constant-Current Chargers

As the name implies, a constant-current battery charger supplies a consistent current to a battery for the entire charge cycle. The charging equipment monitors current flow and varies the applied voltage in order to charge the battery. As the battery begins to charge, its voltage is lower than when the battery becomes fully charged. The constant-current charger will increase its voltage supplied to the battery during charge in order to maintain the current flow set by the operator.

Figure 3-23 illustrates the proper connection of more than one battery to a constant-current charger. The batteries are

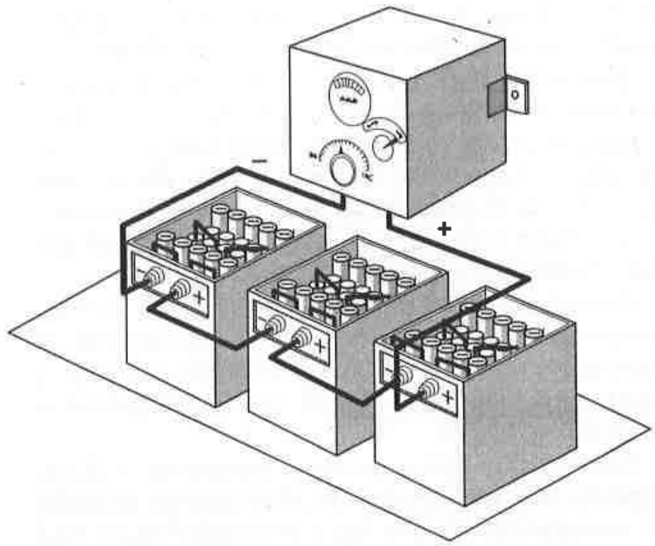


FIGURE 3-23 Constant-current charging.

connected in series with respect to each other and the charger, thus allowing for a constant current flow through each battery. Constant-current chargers require careful supervision while in use. Because of the risk of overcharging, most constant-current chargers will automatically turn off after a predetermined time. The exact current flow and time of charge must be known and programmed into the charging equipment to prevent over- or undercharging of batteries. The specifications are normally available from the battery manufacturer; however, unless the original state of charge remaining in the battery is known, an improper charge is still likely. For this reason, constant-current chargers are often used on new batteries where the initial charge state is known, but they are seldom used on lead-acid batteries that have already been placed in service. Nickel-cadmium batteries often use constant-current charging equipment, as will be discussed later.

Constant-Voltage Chargers

As the name implies, this charging equipment supplies a constant voltage to the battery and allows current to change as the battery becomes charged. The constant-voltage charger supplies approximately 14 V for charging 12-V batteries and 28 V for charging 24-V batteries. A higher potential at the charger is necessary to ensure current flows from the charger to the battery. If the battery is nearly discharged, it will offer very little opposition to the electrons flowing into the battery. As the battery becomes charged, it will offer more resistance to the current supplied by the charger. Since that charger supplies a constant voltage, a relatively high current will flow into a discharged buttery, and that current will slowly diminish as the battery becomes charged.

When the battery is fully charged, its voltage will be almost equal to the charger voltage; hence, the charging current will drop to less than 1 A. When the charging current is low, the battery may remain on charge for a short period of time, less than 24 hours, without any appreciable effect.

During charging the electrolyte level should be watched closely to see that it does not fall below desired levels.

Because the current supplied to the battery drops to a very low value as the battery becomes charged, constant-voltage charging is usually considered the safest method of battery charging. A constant-voltage charger is, by far, the most common type of ground-based battery charger. A constant-voltage charge is also the type supplied by the aircraft generator or alternator system.

When more than one battery is connected to a constant-voltage charger, all the batteries and the charger must be connected in parallel. This will ensure a constant voltage to each battery. The batteries must be connected in parallel as shown in Fig. 3-24.

Various types of constant-voltage chargers are available. Typically, they range from 5- to 50-A capacity, indicating the maximum current flow into a discharged battery. Each charger will lower current to about 1 A when the battery becomes charged. Some chargers come with timers or voltage monitors to shut the system off when the battery reaches the fully charged state. Typically, a low current (about 1 A) can be supplied to a fully charged battery for 24 h or less without damage to the battery. After 24 h, the liquid electrolyte level is at risk of becoming too low.

Many modern constant-voltage battery chargers often employ an automatic charge function. This feature will monitor the battery's state of charge and automatically shut off the charger as needed. This allows the operator to place a battery on charge without the need to monitor the system. In some cases an automatic charger is designed to be connected to a battery for an extended period. This is often the case if the battery will not be used for several months because it may slowly discharge over time. These chargers are often called "battery tenders" since they automatically monitor a

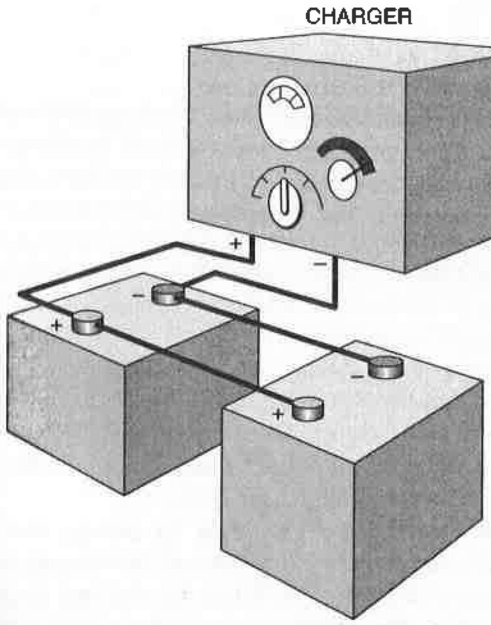


FIGURE 3-24 Constant-voltage charging of multiple batteries.

battery's condition and charge as needed. This allows a pilot to park an aircraft for several months and ensure that the battery will be ready for the next flight. Of course it would require that the battery tender be disconnected before flight and reconnected when the aircraft returns.

Whenever using any type of constant-voltage charger, always make sure to match the charger to the battery. As mentioned earlier, valve-regulated lead–acid batteries require a charger with specific voltage outputs to ensure battery life. VRLA batteries will eventually be damaged if connected to a charger designed for traditional lead-acid batteries. Also, both 12-V and 24-V batteries are common in aircraft systems. It could cause serious damage if a 12-V battery is connected to a 24-V charger. A 24-V battery connected to a 12-V charger would not be damaged, but it would not become charged.

Charging Precautions

There are several precautions that should he observed when handling lead-acid batteries, especially during charging. The most dangerous problem occurs when a battery is charged and hydrogen and oxygen gases are emitted by the cells. Since this is an explosive mixture, it is essential to take precautions against igniting the gas by a spark or an open flame. Some precautions to prevent explosion are as follows:

1. Always charge batteries in a well-ventilated area. Exhaust fans to help remove any dangerous fumes are recommended; simply assuming that a large room, such as a hangar, is well ventilated is incorrect.

2. Always turn off the battery charger before removing any connections between the battery and the charger. This will help eliminate the possibility of sparks at the battery terminals.

3. When removing the battery from the aircraft, always disconnect the negative lead first. When installing the battery, always connect the negative lead last. This will help prevent accidental shorts between the airframe and the battery's positive terminal.

4. Make sure that the caps of each cell of the battery are vented and that the vents are clean. If the caps appear old and dirty, soak them in plain hot water in order to clean the vents. If the vents remain clogged, replace the caps prior to charging.

5. Remove the battery from the aircraft prior to charging whenever possible. The corrosive electrolyte tends to vaporize during charging and escape through the vented battery caps. This electrolyte will corrode the aircraft if the battery is charged while in the airplane. If the battery should be charged while it remains in the aircraft, never operate any radios or other aircraft electronic equipment. A battery charger does not regulate voltage accurately enough to ensure trouble-free operation of electronic equipment.

6. Always take precautions not to spill electrolyte on skin or clothes; the liquid is very corrosive and will burn. **Always wear safety glasses** or another form of eye protection when servicing lead-acid batteries. This will protect your eyes

from accidental acid contact. If electrolyte should spill from the battery, the affected area should be washed with water and neutralized with a solution of bicarbonate of soda and water, then thoroughly rinsed again with plain water. A solution of common baking soda and water is typically used to neutralize lead-acid electrolyte spills.

Placing New Lead-Acid Batteries in Service

The principal rule to observe when placing new lead-acid batteries in service is to follow the manufacturer's instructions. Because these instructions may vary considerably, care must be taken to follow them accurately.

Often, new lead-acid batteries that are stored in warehouses for long periods of time or placed in storage pending sale are not filled with electrolyte. The plates are dry-charged before assembly, and no electrolyte is placed in the cells until the battery is put in service.

When new batteries are received in the dry state, they should be filled with electrolyte having the specific gravity recommended by the manufacturer. After one or more hours, the electrolyte level should be checked, and if it has fallen, more electrolyte should be added to bring it up to the recommended level. The battery can be placed in service after the electrolyte has been in the cells for at least 1 h; if time is available, however, it is better that the battery be charged slowly for approximately 18 h. The rate of charge will depend on the type and capacity of the battery; this information is usually included in the instructions supplied with the battery.

When a lead-acid storage battery containing electrolyte is placed in storage, it should first be fully charged. All electrolyte spilled on the top of the battery should be removed, and the battery should then be washed with clean water and thoroughly dried. The terminals of the battery should be coated with terminal grease, petroleum jelly or a protective cap. While the battery is in storage, it should be recharged every 30 days to compensate for the self-discharge that takes place when it is not in use or the battery could be connected to a battery-tender-type charger as discussed earlier in this chapter.

BATTERY RATINGS

A **battery** consists of a number of primary or secondary cells connected in series. The cells are arranged in this manner to increase the battery's voltage above the voltage available from only one cell. When cells are connected in series, the total battery voltage is equal to the sum of all the voltages of each cell. That is, total battery voltage = voltage of cell 1 + voltage of cell 2 + voltage of cell 3, etc. Figure 3-25 shows the cells of a lead-acid battery connected in series to obtain 12 V. Each lead-acid cell produces approximately 2 V; therefore, six cells are needed to produce a 12 volt battery. **Capacity** is the measure of a battery's total available current. The capacity for all batteries is rated in a unit of current for a length of time. Small batteries are usually rated in **milliampere-hours** (mAh), because their load drain is usually less than 1 A for several hours. Larger batteries, typical of those found on aircraft, are usually rated in **ampere-hours**. These batteries can supply several amps for a much longer time period than smaller batteries; i.e., they have a higher capacity than smaller batteries. A battery's capacity is equal to the time required to fully discharge that battery multiplied by the current draw applied to the battery. In other words, if a battery can supply 2 A for 2 h, it has a capacity of 4 Ah ($2 A \times 2 h = 4 Ah$), or 1 A for 4 h, or 8 A for 0.5 h. A battery with any combination of current flow and time that will give the product of 4 is considered a 4-Ah battery. The ampere-hour or milliampere-hour rating is usually determined by the manufacturer for any particular battery. This capacity rating is important when determining which battery to choose for a given load situation or when determining the charge rate for certain batteries. The recharging of a small nickel-cadmium cell should be at a rate in milliamperes that is equal to approximately 10 percent of the nominal milliampere-hour capacity. For example, a 900-mAh cell or battery should be charged at 90 mA. Cells should be charged at this rate for 14 to 16 h. This will supply 140 to 160 percent of the cell's total capacity, or $90 mA \times 14 h = 1260 mAh$; 1260 mAh is equal to 140 percent of 900 mAh. Aircraft nickel-cadmium batteries are typically recharged at a rate equal to 140 percent of the capacity rating. A battery with a 30-Ah capacity would require 42 Ah of charging. These charge rates will be discussed later in further detail.

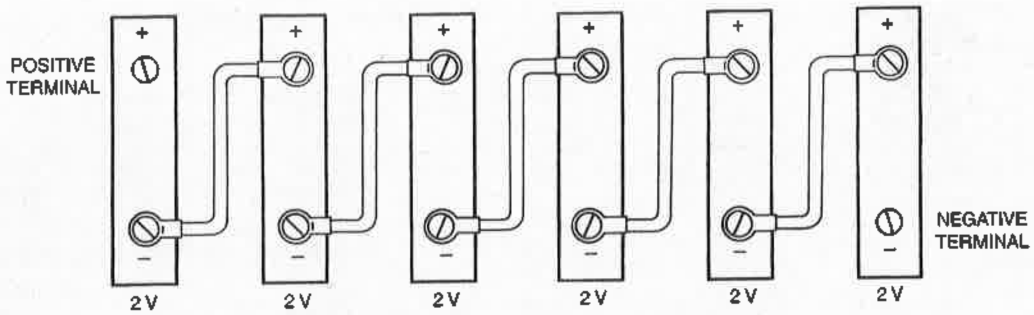


FIGURE 3-25 The connection of six 2-V cells in series to form a 12-V battery.

The capacity of any battery will vary as a function of the time the battery is allowed to discharge. Due to the chemical nature of all batteries, if a cell is discharged quickly, it will supply less total power than a cell that is discharged slowly. This phenomenon exists because the chemicals in a battery require time to react and produce electric power. If a quick discharge occurs, not all the chemical material will have time to react, and some of the battery's capacity will remain in the chemical state. You may have experienced this when using a flashlight for a long period of time; the batteries become weak and the light goes out. If the flashlight is turned off and the chemicals have several minutes or hours to interact, the flashlight will once again emit light when turned on. This "extra" power produced by the flashlight batteries will only last a short while; however, the quick discharge of large batteries will leave significant amounts of extra power suspended in the chemical state.

Since it becomes important, at times, to determine the exact capacity of a battery, all aircraft batteries must be discharged over a consistent time when determining capacity. The standard of a 5-h discharge rate is typically used. This means that all batteries will be discharged for 5 h to determine their capacity rating.

A battery that supplies 6 A for a period of 5 h is a 30-Ah battery at a 5-h rate (6 A × 5 h = 30 Ah). This same battery may only supply 25 Ah if it was completely discharged in only 1 h (25 A × 1 h = 25 Ah). Also, if it was discharged in only 10 min, the total capacity may drop as low as 10 Ah ($60 \text{ A} \times \frac{1}{6} \text{ h} = 10 \text{ Ah}$).

The exact differences among capacities at different discharge rates are a function of the chemicals used in the battery, their purity, and the internal structure of the battery. It is apparent, however, that every battery will supply less total power when discharged quickly. Table 3-3 shows examples of the different discharge rates for different batteries.

Voltage Ratings

Storage batteries of all types are rated according to voltage and ampere-hour capacity. It has been pointed out that the voltage of a fully charged lead-acid cell is approximately 2.1 V when the cell is not connected to a load. A nickel-cadmium cell is rated at about 1.28 OCV.

Under a moderate load, the lead-acid cell will provide about 2 V. With an extremely heavy load, such us the operation of an engine starter, the voltage may drop to 1.6. A lead-acid cell that is partially discharged has a higher internal resistance than a fully charged cell; hence, it will have a higher voltage drop under the same load. This internal resistance is partially due to the accumulation of lead sulfate in the plates. The lead sulfate reduces the amount of active material exposed to the electrolyte; hence, it deters the chemical action and interferes with the current flow.

Figure 3-26 shows the discharge characteristics of a typical aircraft battery of the lead-acid type. The OCV remains almost at 2.1 V until the battery is discharged. It then drops rapidly toward zero. The CCV gradually decreases from 2 to approximately 1.8 V as the cells discharge. Again, the voltage drops rapidly when the cell nears discharge.

Even though battery cells vary considerably in voltage under various conditions, batteries are nominally rated as 6 V (3 cells), 12 V (6 cell), and 24 V (12 cells). In replacing a battery, the technician must ensure that the replacement battery is of the correct voltage rating.

Power Ratings

As stated above under "Battery Ratings," most storage batteries are rated in ampere-hours at a 5-h discharge rate. This means that (he battery was discharged to 0 V in 5 h to determine its capacity. Most 12-V batteries used for single-engine aircraft have a capacity rating between 25 and 35 Ah; however; larger capacities are available. A direct comparison of ampere-hours alone does not indicate a battery's total power output. To determine total power, the battery's voltage must be considered because power (wattage) is the product of voltage and amperage. Two 12-V batteries can be compared on the basis of ampere-hours alone, as can two 24-V batteries. But one should remember that a 30-Ah, 12-V battery (360 Wh) contains half the power of a 30-Ah, 24-V battery (720 Wh).

If the power desired for a specific job is not available in a single battery, often two or more batteries are connected in parallel. Connecting batteries in parallel will increase the available amperage capacity and maintain a constant voltage.

Another rating applied to storage batteries is known as the 5-min discharge rate. This rating is based on the maximum current a battery will deliver for a period of 5 minutes at a starting temperature of 80°F [26.7°C] and a final average

TABLE 3-3 The relationships of ampere-hour capacity to the length of discharge. A slower discharge rate produces a higher total capacity (ampere-hour).

Voltage, V	Amperes supplied for 5 H	Ampere-hours at 5 H rate	Amperes supplied for 20 min	Ampere-hours at 20-min rate	Amperes supplied for 5 min	Ampere-hours at 5-min rate
12	5	25	48	76	140	11.7
12	7	35	66	22	180	15
12	17.6	88	145	48	370	31
24	5	25	48	16	140	12
24	7.2	36	70	23.3	180	15

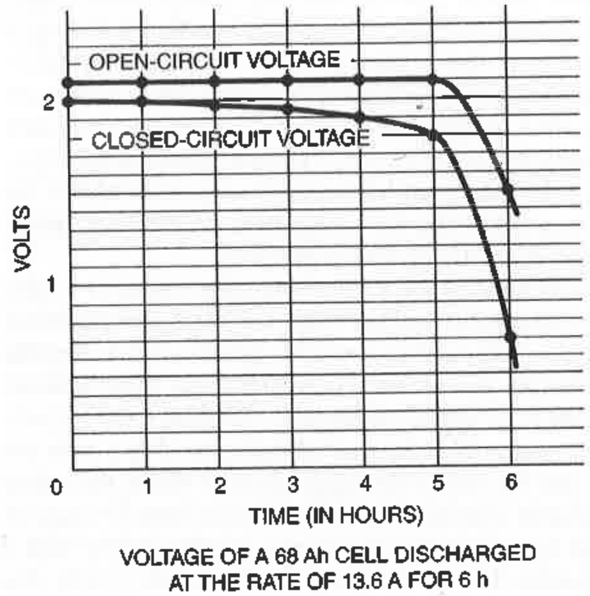


FIGURE 3-26 Discharge characteristics of a lead-acid cell.

voltage of 1.2 V per cell. This applies only to lead-acid batteries. The 5-min rating gives a good indication of the battery's performance for the normal starting of engines.

When a fully charged battery is connected to a very heavy load, it becomes discharged in a short time. A good example of this is the starting of an engine on a very cold morning. After turning the engine for a short time, the starter may refuse to operate. This failure occurs largely because the heavy flow of current has caused a rapid sulfate of the active material on the surface of the plates, while the material inside the plates is still in a charged condition. The lead sulfate on the surface of the plates offers a high resistance to the flow of current, which lowers the output voltage of the battery.

Capacity Loss Due to Low Temperatures

Operating a storage battery in cold weather is equivalent to using a battery of lower capacity. For example, a fully charged battery at 80°F [26.6°C] may be capable of starting an engine twenty times. At 0°F [17.8°C], the same battery may start the engine only three times.

Low temperatures also greatly increase the time necessary for charging a battery. A battery that could be recharged in 1 h at 80°F may require approximately 5 h of charging when the temperature is 0°F. These effects on a battery's capacity are caused by the slow chemical reactions created by the cold temperatures.

NICKEL-CADMIUM STORAGE BATTERIES

Aircraft nickel-cadmium storage batteries are constructed of wet cells. One advantage of the nickel-cadmium cell is that it contains a greater power-to-weight ratio than a lead-acid

FIGURE 3-27 A 20-cell nickel-caladium battery, top removed.

battery. Also, the CCV of a nickel-cadmium battery remains nearly constant during the entire discharge cycle. Nickel-cadmium batteries are much more costly than a typical lead-acid battery and therefore are usually found on turbine-powered aircraft. The extra capacity available from a nickel-cadmium battery will help prevent a hot start of the turbine engine, and thus the extra cost is justified. Nickel-cadmium batteries are often referred to as "ni-cad" (short for nickel-cadmium) batteries.

Cell and Battery Construction

The nickel-cadmium cell is a vented cell similar to that of a lead-acid battery. The cells are placed in an insulated metal or plastic case in proper order and then connected in series by the cell connectors. The end cells may be connected to external posts or to a quick-disconnect unit. A complete battery is illustrated in Fig. 3-27.

Most nickel-cadmium-aircraft batteries contain vented cell caps as illustrated in Fig. 3-28. They are designed so that the rubber seal will allow any expanding gases inside

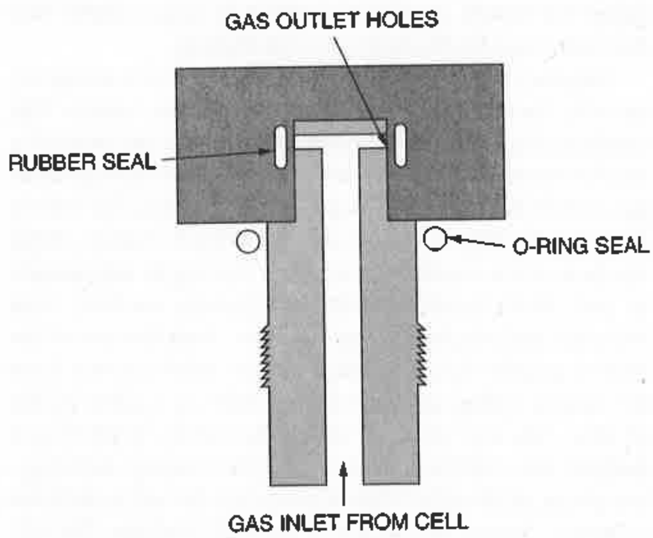


FIGURE 3-28 Nickel-cadmium vented cell cap.

the cell to escape. However, if the gas inside the cell is not under pressure, the rubber seal will close against the cap's outlet and seal the electrolyte from accidental spills during flight. The vents of each cell are required in case the battery becomes overcharged. Only at this time does a ni-cad cell emit gas. So little vapor is emitted during normal operation that the battery box is typically sealed. No venting is required; any and all gases remain inside the battery case, which is designed to accept and hold the gas that may be emitted from the cells.

Each cell of the battery consists of negative and positive plates, separators, electrolyte, cell container, cell cover, and vent cap. The plates are made from sintered metal plaques impregnated with the active materials for the negative and positive plates. The plaques are made of nickel carbonyl powder sintered at a high temperature to a perforated nickel-plated steel base or a woven nickel wire base. This results in a porous material that is 80 to 85 percent open volume and 15 to 20 percent solid material. The porous plaque is impregnated with nickel salts to make the positive plates and cadmium salts to make the negative plates. After the plaques have absorbed sufficient active material to provide the desired capacity, they are placed in an electrolyte and subjected to an electric current, which converts the nickel and cadmium salts to the final form. The plaques are then washed and dried and cut into plates. A nickel tab is welded to a corner of each plate and is the means by which the plates are joined into plate groups.

The **separator** in a nickel-cadmium cell is a thin, porous multilaminate of woven nylon with a layer of cellophane. The separator serves to prevent contact between the negative and positive plates. The separator is continuous and is interposed between the plates as each successive plate is added to the plate pack or stackup. The cellophane portion of the separator acts as a barrier membrane to keep the oxygen that is formed at the positive plates during overcharge from reaching the negative plates. Oxygen at the negative plates would recombine with cadmium and create heat that might lead to **thermal runaway**; thus the cellophane serves to inhibit thermal runaway. Thermal runaway is a condition where the battery chemicals overheat to such a degree that the battery can be destroyed or even explode.

Thermal runaway or **vicious cycling** does not accurately describe the overheating of a nickel-cadmium battery. The overheating of a nickel-cadmium battery is not self-sustaining and *can* be controlled. An aircraft charging system perpetuates this condition, and it can be stopped by isolating the battery from the charging system. A nickel-cadmium battery cannot overheat unless something internal is causing its temperature to rise. Nickel-cadmium batteries typically overheat from improper maintenance or improper use. Improper use of the battery usually occurs by drawing too much current from the battery during multiple engine starts in a short period of time. The heat retained within the battery weakens and destroys the material that separates the positive and negative plates in the cells. When this occurs, the cell's electrical resistance lowers and decreases the cell's voltage. The battery receives excessive amounts of charge current from the aircraft's constant potential charging system, which generates a great deal of heat within the battery. Temperature and/or overcurrent sensors are required by the FAA on all nickel-cadmium batteries used for engine starting. These sensors are connected to warning indicators, which allow the pilot to take corrective measures in case of extreme battery stress. Typically, if the battery reaches a thermal runaway condition, the pilot must disconnect the battery from the electrical system and land the aircraft as soon as practical.

The **electrolyte** for a nickel-cadmium battery is a solution of 70 percent distilled water and 30 percent potassium hydroxide, which gives a specific gravity of 1.3. **Specific gravities** for nickel-cadmium batteries may range between 1.24 and 1.32 without appreciably affecting battery operation. The electrolyte in a nickel-cadmium battery does not enter into the charge-discharge reaction: this is the reason you cannot determine a nickel-cadmium battery's state of charge by testing the electrolyte's specific gravity with a hydrometer. There is no change in the specific gravity of a nickel-cadmium battery.

The cell container consists of a plastic cell jar and a matching cover, which are permanently joined during assembly. It is designed to provide a sealed enclosure for the cell, preventing electrolyte leakage or contamination. The vent cap is mounted in the cover of the cell and is constructed of plastic. It is fitted with an elastomer (flexible rubber or plastic) sleeve valve to permit release of gases as necessary, especially when the battery is on overcharge. The cap can be removed whenever necessary to adjust the electrolyte level. The vent valve automatically seals the cap to prevent leakage of electrolyte.

A cell core and the assembly of a complete cell for a nickel-cadmium battery are shown in the drawings of Fig. 3-29.

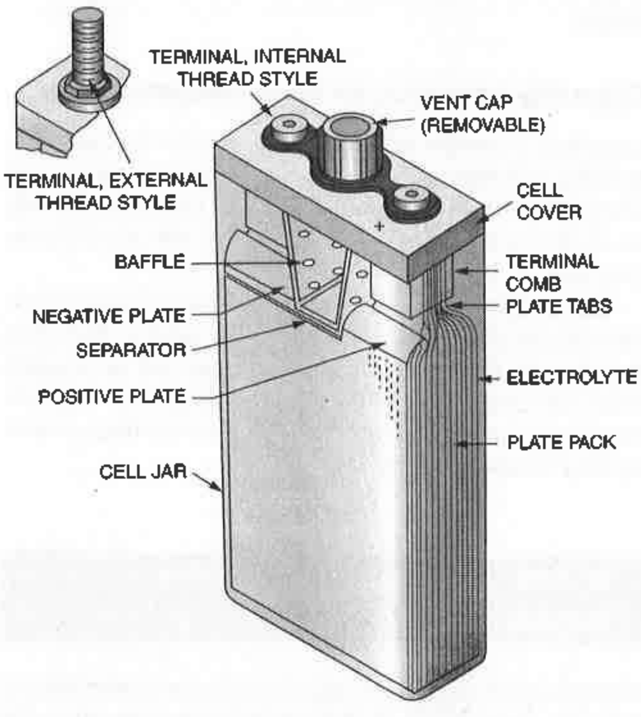


FIGURE 3-29 Nickel-cadmium cell components.

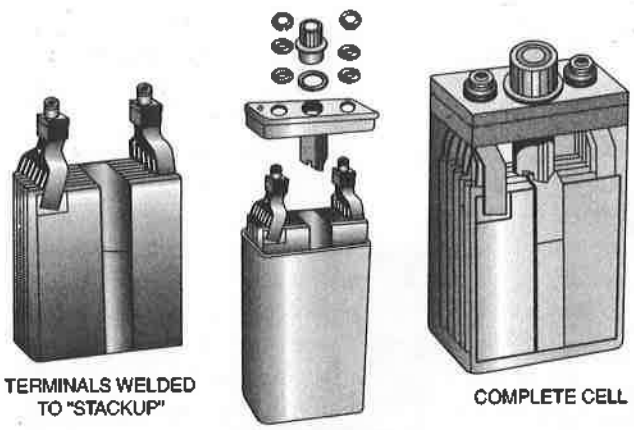


FIGURE 3-30 Nickel-cadmium cell construction. (*Marathon Battery Company.*)

Another type of complete nickel-cadmium cell is illustrated in Fig. 3-30. The cell is assembled by welding the tabs of the plates to their respective terminal posts. The terminal and plate-pack assembly is then inserted into the cell container, and the baffle, cover, and terminal seal are installed. The cover is permanently joined to the cell container to produce a sealed assembly.

The cells are assembled into a battery container and connected together with stainless steel conductor links. Usually, 19 or 20 cells (depending on the total voltage required) are connected in series. The battery container is typically made of stainless steel, carbon steel, or a fiberglass material. All metal cases require an internal insulator. Stainless steel cases use a plastic liner, while most carbon steel cases are coated with an alkali-resistant epoxy that contains high dielectric properties. A typical battery assembly is illustrated in Fig. 3-31.

Principles of Operation

The advantage of a nickel-cadmium battery is that the active materials of the cell plates change in oxidation state only, not physical slate. This means that the active material is not dissolved by the electrolyte of potassium hydroxide. As a result, the cells are very stable even under a heavy load, and the chemicals last a long time before the battery requires replacement.

As previously explained, the active material of the negative plate of a charged nickel-cadmium cell is of metallic cadmium (Cd), and the active material of the positive plate is nickel oxyhydroxide (NiOOH). As the battery discharges, hydroxide ions (OH) from the electrolyte combine with the cadmium in the negative plates, and electrons are released to the plates. The cadmium is converted into cadmium hydroxide [$Cd(OH)_2$] during the process. At the same time, hydroxide ions from the nickel oxyhydroxide positive plates go into the electrolyte, carrying extra electrons with them. Thus electrons are removed from the positive plates and delivered to the negative plates during discharge. The composition of the electrolyte remains a solution of potassium hydroxide because hydroxide ions are added to the electrolyte as rapidly as they are removed. For this reason, the specific gravity of the electrolyte remains essentially constant at any state of discharge. It is, therefore, impossible to use specific gravity as an indicator of the state of charge.

When a nickel-cadmium battery is being charged, the hydroxide ions are forced to leave the negative plate and enter the electrolyte. Thus the cadmium hydroxide of the negative plate is converted back into metallic cadmium. Hydroxide ions from the electrolyte recombine with the nickel hydroxide of the positive plates, and the active material is brought to a higher state of oxidization called nickel oxyhydroxide. This process continues until all the active material of the plates has been converted. If charging is continued, the battery will be in overcharge, and the water of the electrolyte will be decomposed by electrolysis. Hydrogen will be released at the negative plates, and oxygen will be released at the positive plates. This combination of gases is highly explosive, and care must be exercised to avoid any possibility of ignition of the gases.

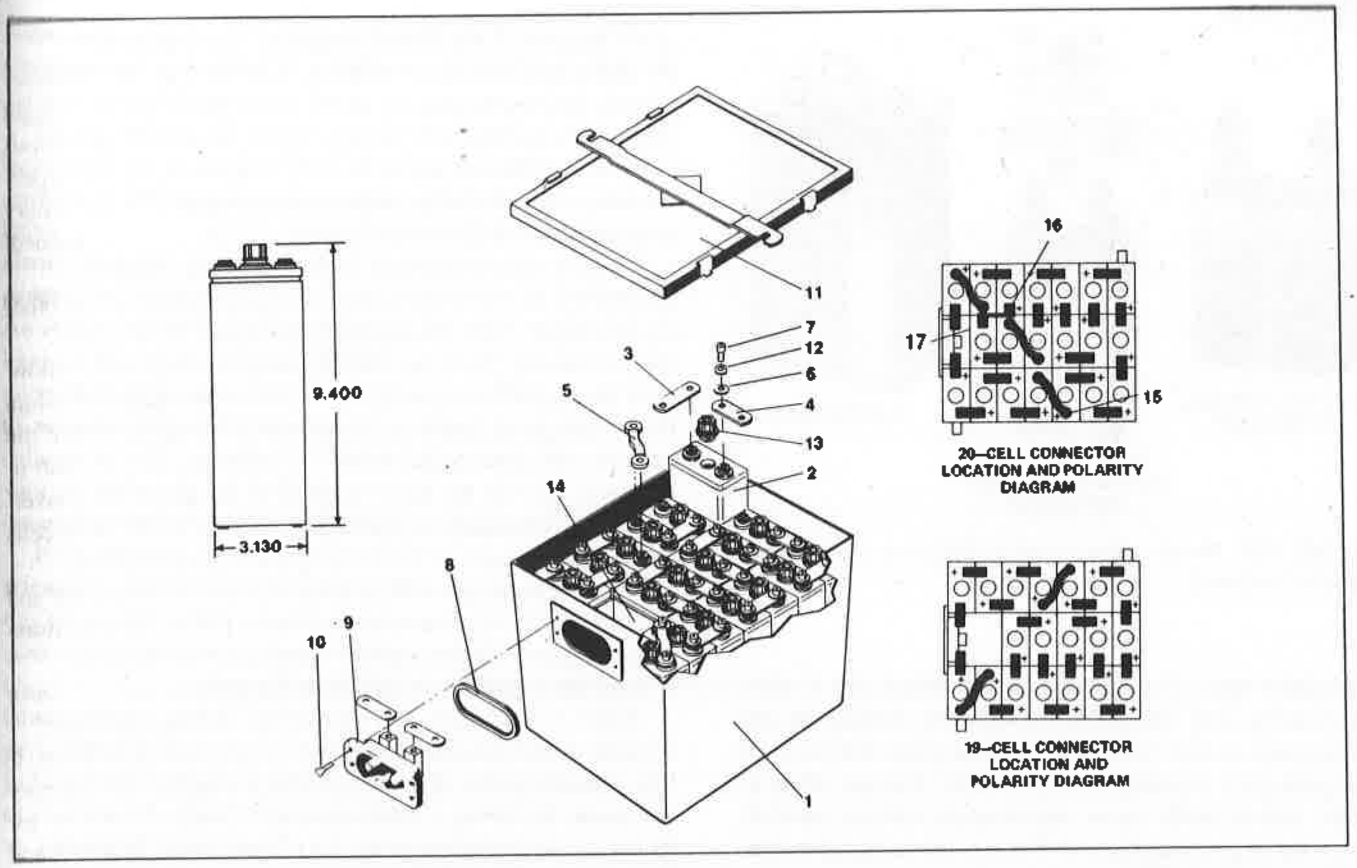
Water is lost from the electrolyte during overcharge because of electrolysis. Some water is also lost by evaporation and entrapment of water particles during the venting of cell gases. By theory, 1 cubic centimeter (cm^3) of water will be lost by electrolysis tor every 3 h of overcharge. In practice the loss is not this high, because there is some recombination of hydrogen and oxygen within the cell.

The separator located between the plates provides electrical insulation and a gas barrier between the negative and positive plates. The nylon fabric provides separation to prevent contact between plates of opposite polarity. The cellophane acts as a gas barrier to prevent oxygen from reaching the negative plates. Oxygen reaching the negative plates will cause the plates to heat, with resulting plate damage, as explained earlier.

Voltage Rating

The OCV of 1.28 V is consistent for all nickel-cadmium vented cells, regardless of cell size. The OCV does vary slightly with temperature and elapsed time since the battery's last charge. Immediately after charge, the OCV may reach 1.40 V; however, it soon lowers to between 1.35 and 1.28 V. A 20-cell ni-cad battery would, therefore, have an OCV between 25.6 and 27 V. The voltage obtained by a cell immediately after charging is typically slightly higher than the average OCV. A nickel-cadmium battery may reach 27.5 V immediately after charging, or 1.5 V per cell for a 19-cell battery. Near the end of the charge cycle, the same battery may reach 28.5 V if the charging current is still applied. This voltage diminishes quickly after the battery is removed from the charger and will soon reach near 25 V.

The CCV of a vented-cell nickel-cadmium battery ranges between 1.2 and 1.25 V, This voltage will vary depending on the battery temperature, the length of time since the battery's last charge, and the discharge current applied. The CCV of a nickel-cadmium cell remains nearly constant under moderate



Item	Description	Part Number CA-5, CA-5-1 CA-5-20	Part Number CA-5H CA-5H-20, CA-16	Quantity
1	Can Assembly	26604	26604	1
2	Cell Assembly	36M220	36H120	19 (20)
3	Connector	16102-6	16102-6	12
4	Connector	16102-7	16102-7	6
5	Connector	16167-1	16167-3	2
6	Belleville Spring	16128-1	16128-1	40
7	Socket Head Cap Screw	10488-20	10488-20	40
8	Rectangular Ring	24583	24583	1
9	Receptacle Assembly	16163-7	16163-7	1

Item	Description	Part Number CA-5, CA-5-1 CA-5-20	Part Number CA-5H CA-5H-20, CA-16	Quantity
10	Phillips Head Screw	23084-1	23084-1	4
11	Cover Assembly	23147-3	23147-3	1
12	Double "D" Washer	23591-1	23591-1	40
13	Filler Cap & Vent Assembly	18318-1	16934-1	1
14	Spacer	27292	27292	1
15	Connector	16167-2*	16167-3*	3
16	Connector	25091*	25091*	1
17	Spacer	27291*	27291*	1
19-cell to 20-cell Conversion Kit – part number 29005				

NOTE: The batteries are 19- and 20-cell versions of Marathon's 36-40 Ah units. This figure does not necessarily represent the design of other batteries produced by Marathon.

*Used only on 20-cell batteries.

FIGURE 3-31 A typical battery assembly. (*Marathon Power Technologies.*)

load until the cell is near the completely discharged stale. Figure 3-32 illustrates the CCV of a nickel-cadmium cell.

Capacity and Internal Resistance

A nickel-cadmium battery has tremendous peak power and delivers far more power than a lead-acid battery of the same size and weight. The large amount of instantly available power produced by a nickel-cadmium battery is why it is so well suited for starting turbine engines. The **capacity of a nickel-cadmium battery** is a function of the total plate area contained inside the cells (more plate area, more capacity). Most ni-cad batteries are designed for 24-V systems with a capacity between 22 and 80 Ah. The ampere-hour rating is determined at a 5-h discharge rate unless otherwise denoted.

The capacitance of any battery is partially a function of that battery's internal resistance. The **internal resistance of most vented nickel-cadmium cells** is very low (less than 1 mΩ per cell), which allows these cells to maintain a high discharge current and still maintain acceptable voltage levels. The low internal resistance of a nickel-cadmium battery allows it to recharge very rapidly. This resistance in part

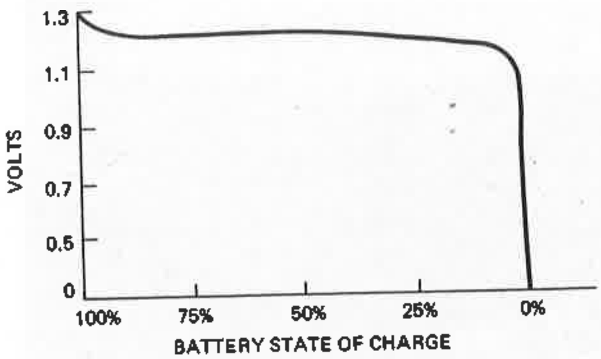


FIGURE 3-32 Typical discharge voltage curve under moderate load. (*Marathon Power Technologies.*)

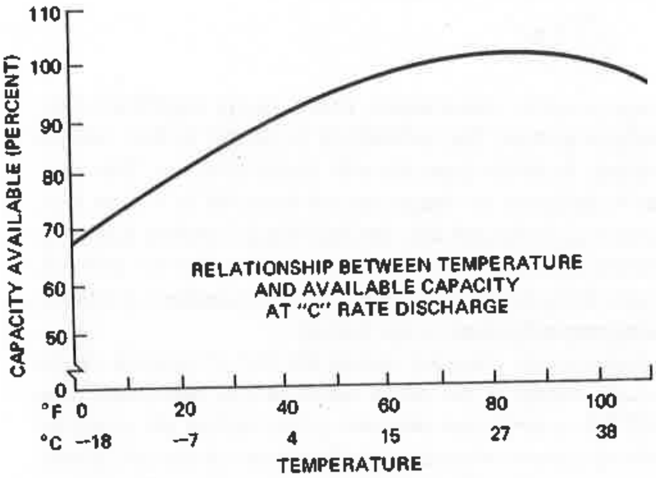


FIGURE 3-33 Relationship between temperature and available capacity. (*Marathon Power Technologies.*)

results from the large surface area of active materials made available through the use of a highly porous plate.

The output of a nickel-cadmium battery is relatively constant, even in harsh operating conditions such as very cold weather. The optimum temperature range is between 60 and 90°F; above or below these values, total capacity will diminish slightly, as illustrated in Fig. 3-33.

NICKEL-CADMIUM BATTERY MAINTENANCE PROCEDURES

The nickel-cadmium storage battery requires specific maintenance procedures; always follow the battery manufacturer's recommendations during service. The following general guidelines illustrate typical maintenance practices, including proper log entries. Each battery should have its own specific maintenance record. This will aid in the isolation of defects and will help to ensure optimum battery performance.

•CAUTION: During all maintenance procedures, follow the precautions previously discussed in this chapter.

Battery Inspection

Every aircraft maintenance schedule will specify a battery inspection period. This schedule should not exceed 50 flight hours for new batteries to ensure proper battery and aircraft compatibility and operation. After a few months, the inspection periods can be lengthened. Before removing the battery from the aircraft, inspect the following and repair as needed:

1. Inspect the battery case for cracks, distortion, or other damage.
2. Inspect the vent system (if installed) for proper airflow.
3. Inspect the cells and clean as needed. Often potassium carbonate will deposit as a white powder on the top of the cells. This should be removed with a nonmetallic brush or damp cloth. If excessive deposits are present, suspect overcharging or leaking cells, and remove and clean the cells individually.
4. Inspect the cell connectors for corrosion, cracks, and overheating. If these problems exist, discharge and disassemble the battery in order to repair the damage.
5. Inspect the cell caps for proper O-ring and vent sleeve condition. Wash any dirty cell caps in clean, warm water.
6. Check the cell electrolyte level for proper amounts. If the battery is overfilled and spillage has occurred, the battery should be removed, discharged, and then disassembled for cleaning and repair. If a low level of electrolyte is found, add clean distilled water only after the battery has been idle for at least 2 h after charging. **Never add water to a discharged battery or a battery of unknown charge.** The electrolyte level increases significantly during charging; therefore, if water is added before charging, an overfill situation is likely.

Nickel-Cadmium Battery Reconditioning and Charging

The reconditioning of nickel-cadmium aircraft batteries is usually performed between 100 and 500 flight hours. The exact reconditioning time period depends mainly on the aircraft starting procedures, operating temperatures, and generator voltage regulator setting. These factors will also determine the frequency of water additions to the battery cells.

Reconditioning of the battery is necessary to prevent any **cell imbalance,** which may result in a temporary loss of battery capacity. Cell imbalances occur during recharging by an aircraft's constant voltage charging system. This "out-of-balance" condition is caused by differences in temperature, or charge efficiency or by varying self-discharge rates in cells. Low electrolyte levels also contribute to a loss in capacity. To ensure optimum performance and battery life, any cell imbalance should be corrected through reconditioning.

Any service area used to recondition nickel-cadmium batteries should be separated from the service area for lead-acid batteries. The chemical materials of a lead-acid battery will neutralize a nickel-cadmium battery and vice versa. Two separate ventilated rooms are recommended for servicing the two types of batteries. Also, the tools used for maintenance should never be interchanged; interchanging tools may cause damage to the nickel-cadmium cell that is due to partial electrolyte neutralization.

The typical reconditioning procedures include a battery inspection as previously stated, a battery discharge, disassembly, and cleaning or repairing as needed. Finally, the battery is reassembled and recharged. **During reassembly, always observe correct cell polarity and always use the proper torque values on each cell connector bolt or nut.** An improperly torqued, dirty, or corroded cell connector is likely to cause battery failure. To correct a cell imbalance during reconditioning, the battery is typically discharged to zero capacity and then recharged. This process is often called a battery **deep cycle**. The specifics of this deep cycle vary between batteries, so always refer to the proper maintenance data.

If the battery is received in a charged condition, an **electrical leak check** should be performed. Prior to discharge, this test detects current leakage from the cells to the battery case. A leakage exceeding 50 mA measured from any positive cell connection to the case is usually excessive. If the battery arrives in a discharged state, a leak test should be performed after charging. The current flowing from the cell to the battery case (electrical leakage) is usually caused by excessive liquid on top of or around the cells. Therefore, if an excessive electrical leakage is detected, remove, clean, and dry all cells and the battery case. During this procedure, inspect each cell for a liquid leak that may have caused the excess liquid around the cells. Any cells from which electrolyte is found to be seeping or leaking should be replaced.

Typically, to discharge the battery completely during reconditioning, discharge equipment made specifically for nickel-cadmium batteries should be used. Once the battery cells reach 0.5 V or less, shorting clips should be placed across each cell. By shorting the positive to negative terminals of each cell, the battery will become completely discharged.

Recharging the battery during reconditioning can be performed by a constant-current or constant-voltage charger. In either case, the battery will require a charge of 120 to 140 percent of its 5-h capacity rating. If a constant-current charger is used for recharging a 40-Ah battery, the applied charge should be 8 A for 7 h. This is determined as follows: 40 Ah = 8 A for 5 h (8 A × 5 h = 40 Ah) times 140 percent = 8 A for 7 h = 56 Ah.

Two common charger/analyzer systems are the Marathon PCA-131 and the Christie RF80-K. The Marathon PCA-131 charger/analyzer was designed to charge and analyze nickel-cadmium batteries automatically and simplify reconditioning procedures. This charger/analyzer features a Go, No-Go indication of battery condition. The correct charge and discharge current is preselected with the setting of the switch position. The battery can be left unattended during charge, and the system automatically adjusts for changes in line voltage. It will automatically terminate the discharge if the average battery voltage falls below a preselected voltage.

The Christie RF80-K (Fig. 3-34) performs the same charger/analyzer functions as the PCA-131; however, this charger reduces maintenance time with its DigiFLEX Pre-Analysis system. The technology is similar to that used to recharge flashlight-type dry-cell ni-cad batteries. This system is designed to charge aircraft batteries in 1 h or less, increase capacity and life, and rejuvenate batteries that were rejected after conventional charging. The Christie RF80-K is also designed to overcome any cell imbalance problems during reconditioning of the battery.

FIGURE 3-34 A typical nickel-cadmium battery charger/analyzer. (*The Christie Corporation.*)

Low-current charging during the last 15 percent of the ni-cad's charge is the major cause of cell imbalance. The ReFLEX system uses negative pulses during the charging cycle to remove internal gases that form on the cell plates. The gases on the cell plates increase the current density and result in the heating of the battery. The Christie charger/analyzer makes use of microcontroller technology to quickly analyze and charge ni-cad batteries.

In general, always follow the manufacturers' recommendations when charging batteries. All vented nickel-cadmium batteries will charge at approximately 140 percent of their total capacity. To achieve this value, the length of charge is typically increased by 40 percent above the total time required for 100 percent of the battery's ampere-hour rating.

Always observe precautions when charging nickel-cadmium batteries. Avoid accidental short circuits. The exposed cell connectors are very vulnerable to shorts from dropped tools or metallic jewelry.

***CAUTION: Always use tools that are insulated when servicing batteries. Always remove all metallic jewelry prior to working on or around batteries. Always wear eye protection during battery service. Before charging, always inspect the cell connectors for cleanliness, physical condition, and proper torque value. Repair any improper conditions.**

Constant-Voltage Chargers

Just as with lead-acid batteries, a **constant-voltage charger** will supply a constant voltage to the battery during charging. The current supplied by this type of charger is high during the start of the charge cycle and lowers as the battery reaches a fully charged state. The exact current flows will be a function of the capacity of the charger, temperature, and the battery's state of discharge.

The correct voltage setting is very important when using a constant-voltage charger. The charging equipment must be set and regulated to ensure a complete battery charge without battery overcharge. Too low a charge voltage will not charge or will undercharge the battery. Too high a charge voltage will overcharge the battery and may damage the cells by thermal runaway.

Constant-Current Chargers

Constant-current charging of nickel-cadmium batteries is recommended to ensure better cell balance and a total battery charge, as well as to prevent the possibility of thermal runaway. However, constant-current charging typically requires a longer charging time and creates a greater water loss during overcharge than constant-voltage charging.

Once again, the manufacturer's charging data must be strictly adhered to while using constant-current chargers. Generally speaking, completely discharged batteries are charged at their ampere-hour capacity, 5-h rate for 7 h. This will apply approximately 40 percent "extra" current during charging to allow for battery charging inefficiencies.

Both the charging equipment and the battery should be monitored periodically during the charge cycle, especially during the first and last hour of charge. During the initial portion of the charge, the charge current and voltage must be monitored to ensure that they are the correct values. Until the battery reaches its maximum charge voltage, the charge current may not stabilize. During the last hour of charge, the battery should be checked for excessive boiling of the electrolyte; this is an indication that the battery has reached full charge and should be removed from the charger.

There are several variations of the two charging methods just discussed that may be used under limited applications. For the most part, however, constant-voltage or constant-current charging methods are employed. For long-term storage of nickel-cadmium batteries, a float or trickle charge can be used. These charging methods ensure that the battery will remain in a fully charged condition during storage. Both the float and trickle charge supply a very low current flow to compensate for the battery's normal self-discharge loss; or the charger will automatically monitor the battery and apply charging current only when needed.

Foaming Electrolyte

If **foaming** occurs while any charging method is being used, always monitor the battery or cell in question. If the cell recently received additional water, the electrolyte may foam during charging. This typically will diminish upon further use and does not indicate a defective cell. However, if foaming continues and electrolyte spills from the vented caps continuously, the cell is probably contaminated with a foreign material. In this case the cell should be replaced.

Battery Storage

Unlike lead-acid batteries, nickel-cadmium batteries can be stored for long periods of time in a charged or discharged state without damage. This assumes that the battery is cleaned properly prior to storage to prevent excessive corrosion. At room temperature a charged nickel-cadmium battery will retain most of its power for 6 months in storage. If the battery is expected to be used immediately, however, it is suggested that a trickle charge (a very low current charge) be maintained while the battery is in storage. While the battery is on trickle charge, proper ventilation should be available to it, the electrolyte level should be monitored periodically, and lost water should be replenished.

It the battery is to be stored without replenishing its charge for a long period, it is recommended that the battery be completely discharged prior to storage. This includes the use of shorting clips to bring each cell to zero capacity. During storage, the main battery positive and negative terminals should then be shorted together to help prevent any cell imbalance. Prior to storage, place a light coat of nonconductive grease, such as petroleum jelly, over the cell hardware. This will inhibit corrosion.

To return a battery to service after storage, clean the battery, remove any shorting clips (if applicable), and recharge the battery at the proper voltage and current settings. Prior to charging, the cleaning process should ensure that the cell caps are free of potassium carbonate and that the vents will function properly.

INSTALLATION OF AIRCRAFT BATTERIES

Battery Compartment

The battery compartment in an airplane should be easily accessible so that the battery can be serviced and inspected regularly; it should also be isolated from fuel, oil, and ignition systems and from any other substance or condition that could be detrimental to its operation. Any compartment used for a storage battery that emits gases at any time during operation must be provided with a ventilation system. The inside of the compartment must be coated with a paint that will prevent corrosion caused by electrolyte.

The battery must be so installed that spilled electrolyte is drained or absorbed without coming into contact with the airplane structure. The shelf or base upon which the battery rests must be strong enough to support the battery under all flying and landing conditions. The battery must be held firmly in place with bolts secured to the aircraft structure. Metal-case batteries are held down by means of bolts that extend through ears on the battery cover. Nonmetallic batteries are held down by metal clamps that hook over the handles of the battery or over the edge of the battery case.

Batteries should not be located in engine compartments unless adequate measures are taken to guard against possible fire hazards and the injurious effects on a battery of excessively high temperatures. Battery manufacturers have determined that temperatures of 110 to 115°F [43 to 46°C] and higher are likely to cause rapid deterioration of the separators and plates. The critical temperature specified by the manufacturer should not be exceeded at any time. Forced ventilation of the battery compartment may be necessary to guard against excessive battery temperatures, and this can be provided by means of a tube leading from the slip stream into the container and a suitable vent tube leading out of it.

Battery Installation

Always perform a thorough battery inspection prior to installation in any aircraft. This inspection should include an electrolyte level check (remember, add water only after charging), a cell connector inspection, and a check of general battery condition. The battery quick-disconnect plug should be inspected on both the battery and the aircraft. If any pitting, corrosion, or looseness is detected, the plug should be replaced or repaired. Be sure both the aircraft and battery connectors have the same polarity.

If a nickel-cadmium battery is installed to replace an old lead-acid battery, always neutralize the battery compartment with a soda and water solution and dry the area completely. The compartment should then be painted with an alkali-resistant paint. Also ensure that the new battery will have proper ventilation to remove any heat that may be produced during battery use. A battery that fits too tightly into its compartment may overheat. Always check that the battery charging specifications and the aircraft charging system's voltage coincide. The nickel-cadmium battery must be charged at a specific voltage for proper operation.

Finally, upon installation connect any battery temperature monitors and inspect their systems according to the aircraft manual. Make sure that all areas requiring safety wire are properly secured. If the battery output terminals are uninsulated, they may require the installation of protective covers or insulating boots. These insulators will prevent the possibility of a short circuit, which could create a serious electrical failure or fire. After completing the installation, perform a battery operational check, including a battery engine start if applicable, and a charging system verification.

Ventilating Systems

Battery compartments (battery boxes) are typically vented to remove unwanted gases and/or heat produced by the battery during charging and discharging. Figure 3-35 illustrates a typical battery vent system found on light aircraft. These systems provide a consistent ventilation airflow created by a low pressure at the output tube while the aircraft is in flight.

The ventilation systems for nickel-cadmium batteries are typically designed to remove heat from the battery compartment. The gas generated during operation is minimal, and the battery case is sealed to prevent leakage; consequently, removal of chemical gases is not typically necessary. Some nickel-cadmium battery compartments are therefore unventilated. Those systems that are vented for cooling often use ram air or even forced air regulated by a thermostatically controlled air valve. The air valve is closed if the battery temperature is below a certain level; the valve opens when the battery requires cooling.

During the inspection of any battery system, it is important to ensure that ventilation tubes remain unclogged. Compressed airflow or a water wash through the vent tubes will help ensure proper operation of the ventilation system.

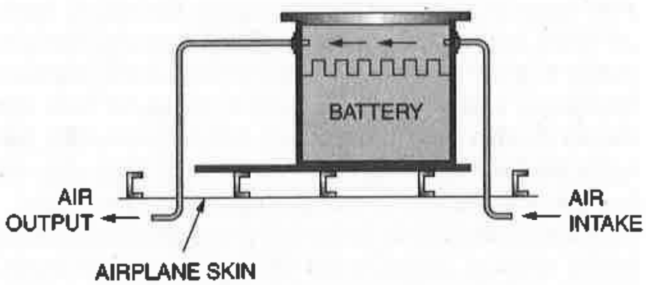


FIGURE 3-35 Battery ventilating system.

Battery Cables

The electric leads to a battery in an airplane must be large enough to carry any load imposed on the battery at any time. They must be thoroughly insulated and protected from vibration or chafing and are usually attached to the airplane structure by means of rubber-lined or plastic-lined clamps or clips. Battery cables must be securely attached to the battery terminals; they are usually held in place as shown in Fig. 3-36. A heavy metal lug is soldered or swaged to the end of the cable and then attached to the terminal by means of a wing nut with a flat washer and a lock washer. It must be noted that this is only one method for attaching battery terminals; others are also satisfactory.

Battery terminals must be protected from accidental shorting by means of a terminal cover. This may be a plastic or rubber boot over the terminal, or the terminals may be contained within the protective battery box.

Quick-Disconnect Plugs

Quick-disconnect battery connectors are found on some lead-acid batteries and practically all nickel-cadmium batteries. The quick-disconnect consists of an adaptor secured

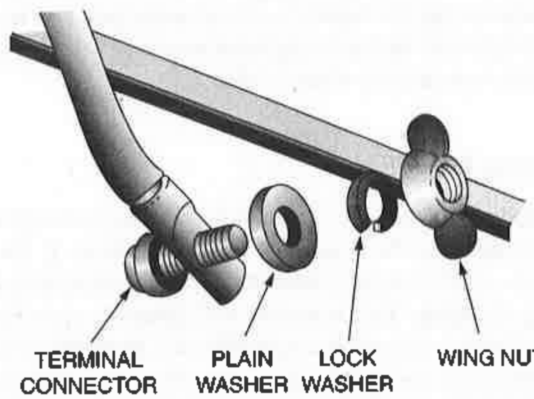


FIGURE 3-36 Battery terminal connection.

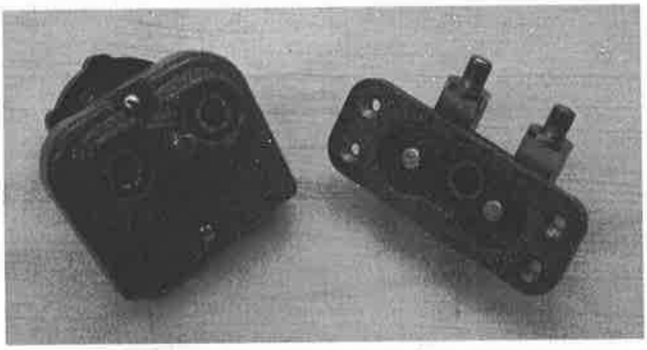


FIGURE 3-37 Battery quick disconnect.

to the battery case in place of the terminal cover and a plug to which the battery leads are attached. Two smooth contact prongs are screwed onto the battery terminals, and the plug is pulled into place on the battery by means of a large screw attached to a handwheel. This screw also pushes the plug off the terminals to disconnect the battery.

A popular battery connector is shown in Fig. 3-37. The connector consists of two main assemblies: the terminal assembly, which is attached to the battery to serve as a receptacle, and the connector plug assembly, to which the battery cables are connected. The plug assembly is inserted into the receptacle on the battery and is seated firmly by means of the center screw (worm) in the plug.

The design of the contacts provides for many contact surfaces with the mating male pin, thus assuring a low-resistance contact. The contacts are made of silver-plated soft copper wire and are designed to fit snugly onto the pins of the battery terminal. The pins and sockets of the connectors should be inspected at regular intervals. If loose connections, burned spots, corrosion, or pitting are noticed, the contacts should be replaced.

REVIEW QUESTIONS

1. What is the difference between a primary cell and a secondary cell?
2. What is a dry cell?
3. Describe how various voltages are obtained in different cells.
4. Describe the difference between a battery and a cell.
5. What are the active materials in a lead-acid storage cell?
6. Describe the construction of a lead-acid storage cell.
7. What electrolyte is used in a lead-acid storage cell?
8. What is the purpose of the separators found in a lead-acid cell.
9. Explain the means used to prevent the spillage of electrolyte from a vented aircraft storage battery.
10. How are aircraft storage batteries constructed to provide for elimination of explosive gases?
11. What determines the voltage of an aircraft storage battery?
12. What ratings are used to describe aircraft storage batteries?
13. What is the approximate open-circuit voltage of a fully charged lead-acid cell?
14. If a storage cell will deliver 20 A for 5 h, what is the ampere-hour rating?
15. Why will a lead-acid storage battery appear to be discharged after the application of a heavy load for a short time but will again deliver power after the load has been disconnected for a few minutes?
16. What occurs with respect to ampere-hour rating when the discharge rate is increased?
17. Give the *specific gravity range* for a fully charged lead-acid cell.
18. Under what condition may new electrolyte be added to a lead-acid cell?
19. Describe the method for testing a lead-acid cell under load by means of a voltmeter.
20. Give the principal safety precaution that must be observed in working with lead-acid storage batteries.
21. If an aircraft has a dead battery, why is it considered improper procedure to jump-start that aircraft?
22. Explain the difference between constant-voltage charging and constant-current charging.
23. What type of battery charging method is employed in an aircraft electric system?
24. What hazards exist with respect to lead-acid batteries during charging?
25. Describe a battery compartment in an aircraft.
26. How are explosive gases from a battery eliminated from an aircraft?
27. Describe the proper procedure to remove and install a lead-acid battery in an aircraft.
28. Describe the difference between a *vented lead-acid battery* and a *valve-regulated lead-acid battery.*
29. What is meant by an absorbed glass mat battery?
30. Describe the proper disposal procedures for a lead-acid battery.
31. What electrolyte is used in nickel-cadmium batteries?
32. Describe the construction of a nickel-cadmium cell.
33. Explain the chemical operation of a nickel-cadmium cell.
34. What are the factors affecting the performance of nickel-cadmium batteries?
35. What is the specific gravity of a nickel-cadmium aircraft battery?
36. What is the danger caused by loose cell connectors in a nickel-cadmium battery?
37. What are satisfactory charging methods for nickel-cadmium batteries?
38. When a completely discharged nickel-cadmium battery is being charged, how much electric energy must

be returned to it as a percentage of its ampere-hour rating for a full charge?

39. What is the typical closed voltage of a nickel-cadmium battery?

40. Explain a thermal runaway.

41. What condition of charge is most suitable for nickel-cadmium batteries that are to be stored?

42. What is the internal resistance of a typical nickel-cadmium battery?

43. What is meant by an electrical leak check?

44. List precautions that should be observed in handling nickel-cadmium batteries.

45. Why should service areas for lead-acid and nickel-cadmium batteries be separated?

46. What is capacity reconditioning, and why is it performed?

47. What conditions are observed in making an inspection of nickel-cadmium batteries?

48. How should a nickel-cadmium battery's potassium carbonate deposits be cleaned?

49. Describe the procedure for reconditioning a nickel-cadmium battery.

50. What practice should be observed when installing and tightening cell connectors?

51. What final inspections should be made when the assembly of a nickel-cadmium battery has been completed and the battery is to be installed in the aircraft?

Electric Wire and Wiring Practices 4

INTRODUCTION

The electric wiring in an aircraft must be properly installed and maintained in order to ensure the safety of the aircraft's passengers and crew. On light, single-engine aircraft there is a relatively small amount of wire; on large commercial aircraft, there are literally miles of wire controlling every facet of flight. Modern airplanes are often referred to as "fly-by-wire" or "the-more-electric-airplane." Indeed the newest aircraft contain more electronic and more electrical systems than ever before; therefore, safe wiring practices are critical and must be thoroughly understood. On any civilian aircraft operated within the United States, the electric wiring must be installed and maintained according to the Federal Aviation Administration (FAA) guidelines. This chapter describes these FAA specifications and shows their relationships to aircraft wiring practices.

Fiber-optic cable has also been introduced on many modern aircraft over the past decade. Optical cable, as a replacement for copper wire, is often used for the transfer of digital data. Although fiber-optic cable is suitable for the transfer of information using light signals, fiber cannot carry electrical current.

CHARACTERISTICS OF ELECTRIC WIRE

There are several conditions to be considered when choosing an aircraft electric wire. The design temperature, flexibility requirements, abrasion resistance, strength, insulation, electrical resistance, weight, and applied voltage and current flow all affect the wire selection. These factors will determine the type of conductor and insulation necessary for a given installation. Most aircraft wire is made with a stranded copper conductor, either 7 or 19 strands for small wire and 19 or more for larger wire. The use of stranded, or twisted, wire increases the flexibility of the conductor, thus decreasing the chance of fatigue failure. Flexible wire is made of several small strands; less flexible wire is made of fewer, coarser strands. Solid wire (one single strand) is very inflexible and may only be used in limited areas of the aircraft.

Copper conductors are typically coated to prevent oxidation and to facilitate soldering. Tinned copper wire is generally used for installations where temperatures do not exceed 221°F [105°C]. Silver-coated copper wire is used for temperatures up to 392°F [200°C], and nickel-coated copper wire must be used at temperatures between 392 and 500°F [200 and 260°C]. This coating becomes quite apparent when viewing stripped wire. The copper strands are tin or silver in color (not copper). This is due to the thin coating applied to each copper strand. Under certain conditions, aluminum wire may also be used under 221°F [105°C].

Any type of single conductor or stranded group surrounded by insulation is usually referred to as a **wire**. A **cable** is any group of two or more conductors separately insulated and grouped together by an outer sleeve. One cable can be routed through the aircraft and be used for several circuits. A cable's primary disadvantage is created by the inability to repair or replace a single wire. Figure 4-1 shows various types of wire and cable.

Generally speaking wire can be installed in protective tubing, typically referred to as a **conduit**; or wire can be routed without conduit in a technique called **open wiring** or **open-air wiring**. In either case, all aircraft wire must meet current FAA specifications. The FAA specifications are typically based on military standards (often referred to as "MIL specs"). For this reason common aircraft wire specification numbers will resemble *MIL-W-5088L*.

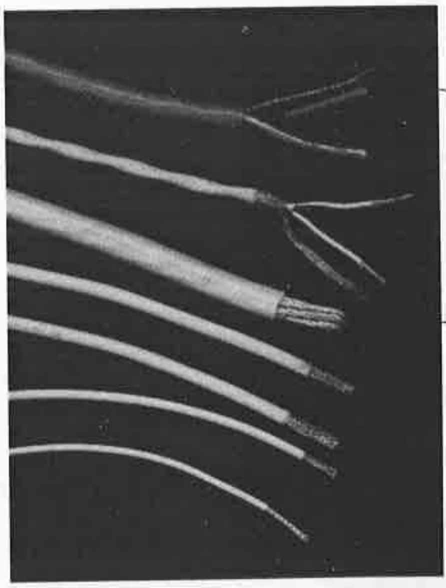


FIGURE 4-1 Typical electrical wire and cable. (*Prestolite*)

When choosing aircraft wire, one must select both the type and size of the conductor as well as the type of insulation. There are several types of insulation approved for aircraft and aerospace vehicles; most are extremely abrasive-resistant. Other characteristics that must be considered are temperature ratings, electrical insulation ability (dielectric strength), fuel and corrosion resistance, as well as potential smoke emissions if the wire is overheated. Of course, the conductor must be of the appropriate size to carry the circuit's needed current flow. Common aircraft conductors are copper and aluminum; each available in various wire sizes.

Over the past decade, there have been significant improvements in the design of aircraft wire insulation. Heat resistance, smoke emissions, and abrasion resistance qualities have all been improved using high-tech polymer compounds for insulation. Some older wires have insulation that is no longer approved for aircraft use, and when installing new wiring, technicians must pay particular attention to the wire specification numbers. The FAA and/or the current manufacturer's data will list all approved wire for a specific installation. A partial list of FAA-approved aircraft wire for general-purpose open-wire installations is shown in Table 4-1. This table shows maximum voltage, temperature rating, insulation, and conductor type for a variety of military specification numbers approved for aircraft open wiring. The complete list is published in FAA advisory circular AC 43.13-1B.

The copper conductors of an aircraft wire are typically plated with an extremely thin layer of a noncorrosive metal. The plating forms protective coating around each strand of copper. This helps to ensure that the conductor will maintain electrical integrity when subjected to the humidity and temperature extremes often found on aircraft. Common plating includes tin, silver, and nickel. Each of these materials has different temperature and corrosion resistance properties as spelled out by the military specification. It should also be noted that the plating changes the appearance of the conductors' outer surface from "copper" to "silver" color.

There are obviously many criteria to consider when choosing an aircraft wire. FAA advisory circular AC 43.13-1B can be used as a guide for selecting wire; however, it is recommended that all wire installations follow current manufacturers' recommendations and approved data.

Specialty Wire

There are several variations to a multiconductor wire, such as cables manufactured for specific applications. For example, strobe light installations employ multiconductor cable to connect each strobe lamp to the strobe power supply. For this purpose the manufacturer produces a specific cable containing several wires; all surrounded by an outer conductor that protects other systems from the electrical interference caused by the strobe. A specialty wire with shielded inner conductors is shown in Fig. 4-2 (*a*) and (*b*). Shielded cable is used in various applications where the designer wishes to block electrical interference from either leaving or entering the wire. In almost all cases, the outer conductor of shielded cable is connected to ground. In this case, the wire is manufactured with an outer sheath (shielding) of woven wire over the inner conductor. Or the inner conductor may be surrounded by a sheath made up of thin metal foil (usually aluminum) wrapped around the insulation that surrounds the inner conductor. In both cases the inner and outer conductor are insulated from each other to prevent short circuits. Various forms of shielded cable are used for connecting radio antennas, piston-engine spark plugs, and data bus cables as well as other applications.

Cable designed to send information signals between computer systems transfer low-power rapidly changing digital signals. These signals are particularly susceptible to electrical interference, and therefore specialty shielded wire known as **data bus cable** is typically used. The specification for one common data bus cable is MIL-W-16878. Data bus cables will be discussed later in this text.

Another special application of shielded wire is known as **coaxial cable**. Coaxial cable is commonly used for connection of antennas to a radio receiver or transmitter. Coaxial cable is extremely critical because the electrical signals sent to/from a radio antenna are very weak. If the cable is pinched, bent, or coiled too tight, the radio signal will degrade. Always use caution when handling coaxial cable.

TABLE 4-1 Wire approved for open air installation.

Document	Voltage rating (maximum)	Rated wire temperature (°C)	Insulation type	Conductor type
MIL-W-22759/1	600	200	Fluoropolymer insulated TFE and TFE coated glass	Silver coated copper
MIL-W-22759/2	600	260	Fluoropolymer insulated TFE and TFE coated glass	Nickel coated copper
MIL-W-22759/3	600	260	Fluoropolymer insulated TFE-glass-TFE	Nickel coated copper
MIL-W-25038/3/2	600	260	See specification sheet	See specification sheet
MIL-W-81044/6	600	150	Crosslinked polyalkene	Tin coated copper
MIL-W-81044/7	600	150	Crosslinked polyalkene	Silver coated high strength copper alloy
MIL-W-81044/9	600	150	Crosslinked polyalkene	Tin coated copper
MIL-W-81044/10	600	150	Crosslinked polyalkene	Silver coated high strength copper alloy

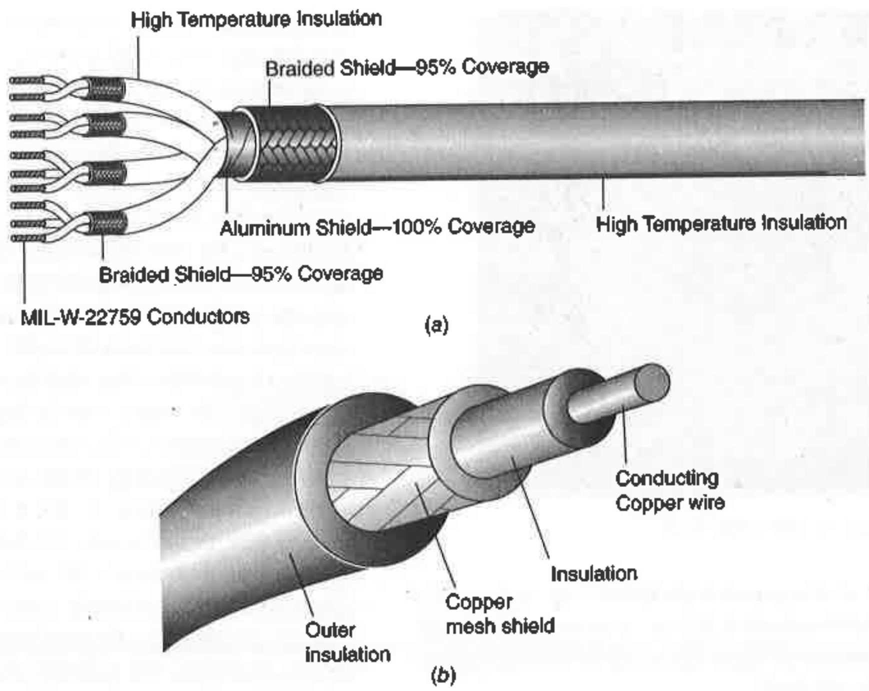


FIGURE 4-2 Common cable types: (a) multiconductor shielded cable, (b) coaxial cable.

Other specialty wires and cables are required in various locations of the aircraft or for various types of equipment. Temperature sensors, called **thermocouples**, require special wire cut to a specific length in order to maintain accuracy. Wires installed in extremely high-temperature zones, like engine compartments, are often of special design. Also, wires installed in designated **severe wind and moisture problem** (SWAMP) areas must meet rigorous testing and are often unique to a specific aircraft or manufacturer. In general all specialty wires and cables adhere to stringent specifications, which must be followed during all aircraft manufacturing and maintenance.

The wires and cables described above are a few that are approved for aircraft use. Other types are also approved and are selected by engineers to meet certain specifications as required by the circuit design. In some cases these wires may be specific to a given airplane or they may be used by a given manufacturer for a series of aircraft.

Whenever possible, wires should be routed in areas of the aircraft that are not subject to extreme heat. Some electric devices, however, such as engine exhaust temperature monitors, must operate at elevated temperatures. Electric wiring or cable used in areas where high temperatures exist must have heat-resistant insulation. Fiberglass, asbestos. Teflon, and silicone are commonly used high-temperature insulators. During specific high-temperature installations, one should always follow the manufacturers' recommendations pertaining to the wire and its installation.

Electric wire used on aircraft is either white, stamped with identifying code numbers, or color-coded to allow the technician to identify specific wires. In either case, the wiring diagram of the maintenance manual will identify which wire number, or color, is connected to which circuit. This becomes very important when troubleshooting electric circuits containing several wires. Specialty wires, such as data bus cable, are often identified by a specific color. Always use caution when dealing with specialty wires since these are typically critical to flight safety. Wire identification codes are discussed later in this chapter.

Wire Size

The wire used for aircraft electrical installations is sized according to the **American Wire Gage (AWG)**. The size of the wire is a function of its diameter and is indicated by a unit called the **circular mil**. One circular mil is equal to the cross-sectional area of a 1-ml [0.001-in.] diameter wire, measured in thousandths of an inch. To determine the size in circular mils of a wire, simply square the wire's diameter measured in thousandths of an inch; for example, the size of a wire that is 0.025 in. in diameter is 625 circular mils. It is calculated as follows:

$$0.025 \text{ in.} = 25 \text{ thousandths of an inch}$$
$$25^2 = 625 \text{ circular mils}$$

The **square mil** is the unit of measure for rectangular conductors, such as bus bars or terminal strips. One square mil is the measure of a rectangular conductor having sides that are 0.001 in. in length. Figure 4-3 illustrates this concept. To simplify the wire size, the AWG standard has applied numbers to the various diameters of wire. Only even numbers are used. Small wires have higher numbers, typically starting at AWG 24; large wires have smaller numbers, down to AWG 4/0

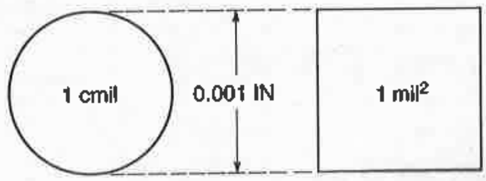


FIGURE 4-3 Circular mil and square mil dimensions.

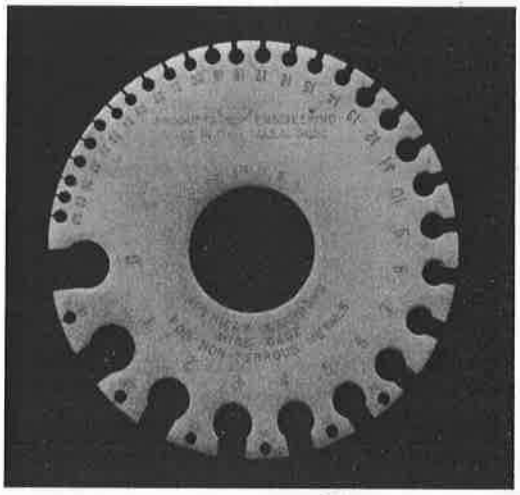


FIGURE 4-4 A typical wire gage tool.

(0000). A 20-gage wire is approximately 0.032 in. in diameter, and a 0 gage is approximately 0.325 in. in diameter. It should be noted that conductors of other sizes can be used on an aircraft if approved by the FAA.

To determine the size of any given wire, a wire gage tool may be used. As illustrated in Fig. 4-4, the typical tool consists of a slotted piece of steel approximately 3 in. in diameter. Each slot, being a specific size, represents a given wire gage. The stripped portion of a wire is inserted into a slot, which fits snugly around the conductor. The wire size is marked adjacent to that slot.

There are two principal requirements for any wire carrying current in an aircraft electric system: The wire must be able to carry the required current without overheating and burning, and it must carry the required current without producing a voltage drop greater than that which is permissible for aircraft circuits. For the guidance of technicians engaged in the replacement or installation of electric wiring in civil aircraft, the FAA has prepared charts and tables setting forth the wire sizes needed to meet various conditions of installation and load. Table 4-2 gives the maximum allowable voltage drop between the bus and the electric components according to the nominal voltage of the system.

Table 4-2 establishes the maximum voltage drop that may occur between the power distribution bus and any unit of electric equipment. The voltage applied to any power user is determined by the voltage supplied by the power source (typically the battery or engine-driven alternator) less the voltage drop created by connecting wires. If the wire creates too large of a voltage drop, the power using equipment will not operate properly due to inadequate voltage. Remember all wire has some resistance, and although very small, this resistance will create a voltage drop as current travels through the wire. This "inefficiency" in the wire creates heat and a drop in voltage to the power user. In general, the larger the wire, the less heat produced and the greater voltage supplied to the electrical load. The maximum allowable voltage drops listed in Table 4-2 should be used as a guide for all aircraft equipment and wire installations. When making the correct wire selection, the voltage drop becomes negligible and all equipment operates properly. The electric wire charts take into consideration both the maximum allowable voltage drop and the current-carrying capability of the wire for various situations. The charts are arranged for copper wire (milspec MIL-W-27759) only and should not be used for the selection of aluminum wire.

TABLE 4-2 Maximum allowable voltage drop.

Nominal system voltage	Allowable voltage drop. Continuous operation	Intermittent operation
14	0.5	1.0
28	1.0	2.0
115	4.0	8.0
200	7.0	14.0

Whenever selecting a wire, eight characteristics about the circuit must be known: (1) the wire length; (2) the maximum current flow of the circuit; (3) the maximum allowable voltage drop for that circuit; (4) will the circuit be operated continuously or intermittently (intermittent is considered two minutes or less); (5) the maximum temperature of the wire during operation; (6) will the wire be installed in a conduit or a bundle of wires; (7) will the wire be installed as a single wire in free air; and (8) the maximum altitude in which the wire will operate.

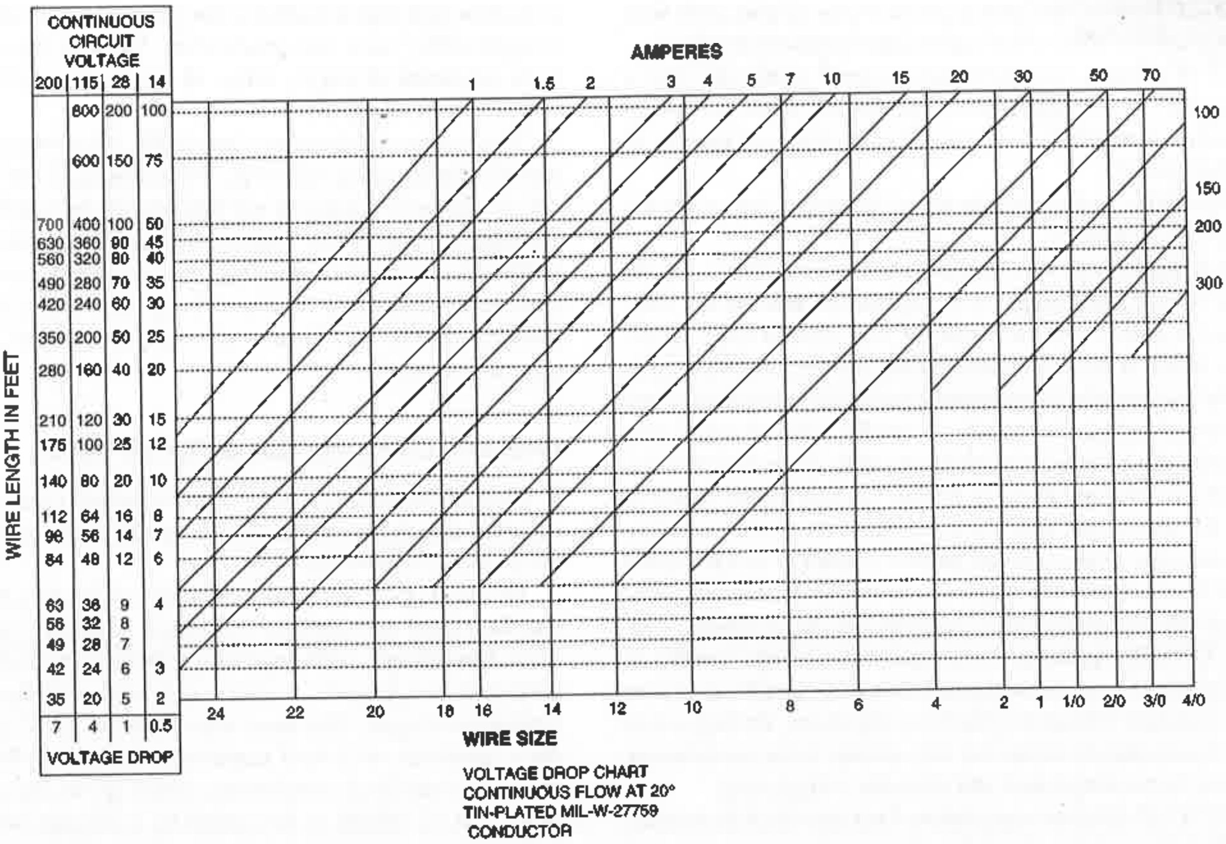
Figure 4-5 contains two charts: Fig. 4-5(*a*) is used for circuits continuously operated, and Fig. 4-5(*b*) is used for circuits which are intermittently operated. **Intermittent operation** is defined as any circuit that is used for two minutes or less. An example of an intermittent circuit might be a flap motor used to raise/lower the flaps that only requires 1 min 45 S of operation.

The following steps should be employed when using the electric wire charts for wire operated at 68°F [20°C] or less:

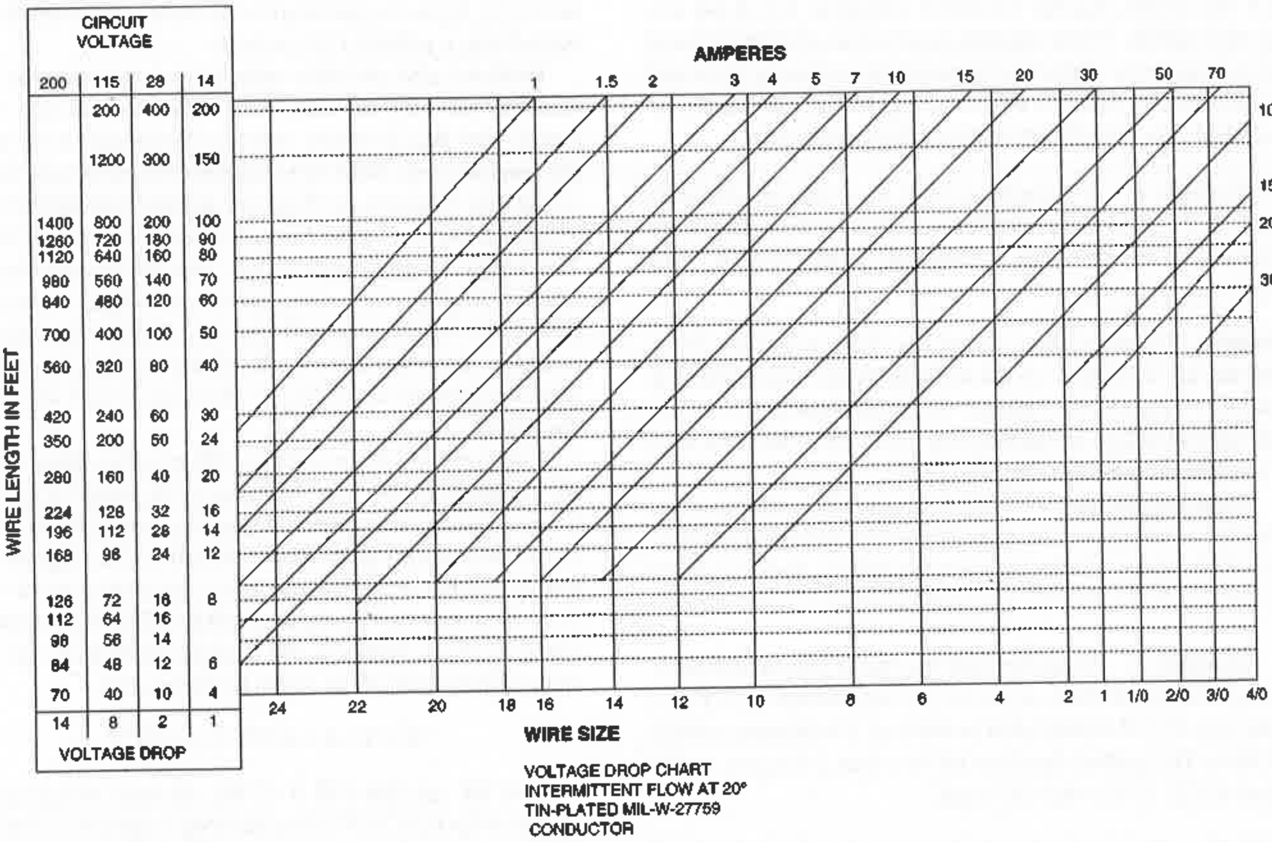
1. Determine which chart to use for the application being considered. The chart in Fig. 4-5*a* is used to determine wire sizes for circuits that have a **continuous** flow of current. A continuous flow is considered to be any circuit that carriers current for a period longer than 2 min. The continuous flow conductor chart has two limiting curves, **curve 1** and **curve 2**.

   The chart in Fig. 4-5*b* is used to determine wire size for circuits that have an **intermittent** flow of current. Intermittent circuits carry current for intervals of 2 min or less.

2. After determining which chart to use, note the circuit's voltage at the top of the left-hand side of the chart. Choose the correct value for your applications, either 200, 115, 28, or 14 V.
3. Note the total wire length in the voltage column (left side of the chart). This will determine the correct horizontal line used to find the wire size. The correct horizontal line is just to the right of the wire-length value. (*Note:* The total wire length is considered to be from the circuit bus to the load. Do not assume that a single wire segment is the entire length of the circuit's wire.)
4. Locate and note the circuit's maximum current flow on the diagonal lines of the chart. (*Note:* The maximum current flow for any circuit is determined by the current rating of the circuit breaker or fuse, not the current draw of the load.)
5. Find the intersection of the diagonal (amperage) line and the horizontal (wire length) line. Find the wire size using this intersection. Move straight down from this intersection, and read the wire size on an adjacent vertical line.



(*a*)



(*b*)

FIGURE 4-5 Contains two charts: (*a*) is used for circuits continuously operated, and (*b*) is used for circuits which are intermittently operated.

6. If the wire size is between two vertical lines (two wire sizes), always choose the largest wire (smallest number).

7. In general, always be conservative when choosing a wire size. A wire that is too large will not adversely affect a circuit. A wire that is too small could cause overheating or circuit failure.

In order to understand the use of the wire charts, study the following examples.

It is important to note, the wire charts shown in Fig. 4-5 apply only to tin-plated copper wire operated in free air at a temperature of less than 68°F [20°C]. One chart is used for the wire which powers a continuous load; the other chart is used to determine wire size for intermittent loads. Obviously, many wires are routed through the aircraft in a bundle, inside of a protective conduit, or within a multiconductor cable. If the wire is not a single-insulated conductor in free air, the wire charts shown in Fig. 4-5 are only the first step to determine the precise wire size. For example, wire contained inside a conduit or bundle cannot expel heat as easily as a single wire in free air. In this case, additional calculations are needed to determine the appropriate wire size. Generally speaking, wires installed in a bundle, conduit, or in high-temperature areas typically require a slightly larger wire size than those indicated by the basic wire charts. The larger wire size is necessary to ensure the wire adheres to the requirements for maximum temperature and allowable voltage drop.

AC 43.13-1B shows calculations for wires which do not meet the limited requirements of the wire selection charts shown in Fig. 4-5. The calculations take into consideration the maximum expected wire temperature, the number of wires within a conduit (or bundle), and the maximum altitude in which the wiring may operate. These calculations are relatively extensive and beyond the scope of this text; however, in most cases an aircraft technician will install wires according to the manufacturers' technical data and will not need to calculate wire size.

Example 1. If a single electric wire with specification MIL-W-27759 is to be installed in a 28-V system, 12 ft from the bus bar, and fused for a maximum current of 50 A, what is the correct wire size?

Solution. Use the wire chart in Fig. 4-5*a* as follows: First, find the 28-V column on the left side of the chart, and note the 10-ft length in that column. The technician would follow the horizontal line adjacent to the 12-ft, 28-V location until it intersected the 50-A diagonal line.

At the intersection of the 50-A diagonal line and the 12 ft., 28 V horizontal line move straight down to determine the wire size. The wire needed is between the vertical lines numbered 10 and 12. A No. 10 wire is selected because it is the larger.

Example 2. To understand the use of the intermittent-rating conductor chart, consider the installation of a 112-ft wire in a 115-V system that is fused to a maximum current of 20 A. This system operates for less than 2 minutes, so the chart in Fig. 4-5(*b*) must be used.

Solution. First, find the 115-V column on the left side of the chart, and note the 112-ft length in that column. Follow the horizontal line adjacent to the 112-ft, 115-V location, and move right until it intersects the 20-A diagonal line. Move straight down from this intersection between the vertical lines numbered 14 and 16. A No. 14 wire is selected because it is the larger of the two.

Whenever using the wire charts in Fig. 4-5 always be conservative in choosing wire size. For example, if the specifications for your circuit do not fall exactly on a horizontal, vertical, or diagonal line within the chart, always move up or to the right on the chart. Moving this direction is a conservative approach and may result in a larger wire being selected; however, it will also ensure safe operation of the aircraft electrical system.

Current-Carrying Capacity of Wire

It is often desirable to obtain more information about wire capacity and characteristics than is provided in Fig. 4-5. For this purpose Table 4-3 is useful.

This table gives the continuous duty current flow for various wire sizes and different maximum conductor temperatures. For example, a 20-gage wire with maximum allowable conductor temperature of 105°C can safely handle 4 A of continuous current. This same wire rated for 200°C can handle a maximum of 9 A of continuous current. In this case, the higher maximum temperature rating allows for an additional 5 A of current to be carried by a 20-gage wire. The higher maximum temperature is due to the wire design; both the conductor and insulation must be designed for higher temperature operations. In general, wires designed to safely operate at higher temperatures can carry more current without causing a potential fire hazard.

Table 4-3 also provides information on conductor resistance for various wire sizes. From this table it is easy to see that as wire size increases (moving downward on the table), the resistance of 1000 feet of conductor decreases significantly. For example, a 20-gage wire has 9.88 Ω/1000 ft of resistance and a 12-gage has a resistance of 2.02 Ω/1000 ft. The larger 12-gage wire offers less resistance than the smaller 20-gage wire. Less resistance means current can flow easier and the wire will stay cool. It is always important to ensure that wires do not exceed the maximum safe operating temperature according to their design and installation specifics.

From Table 4-3 it is possible to compute the voltage drop for any length of copper wire with any given load. For example, if it is desired to know the voltage drop in 100 ft [30.5 m] of No. 18 wire carrying 10 A, we use Ohm's law, but we must first determine the resistance from the figures given in the table. Note that the resistance of 1000 ft [304.8 m] of No. 18 wire is 6.23 Ω. Then for 100 ft of the same wire, the resistance would be 0.623 Ω. Then, by Ohm's law,

$$E = 10\text{ A} \times 0.623\ \Omega = 6.23\text{ V}$$

Thus we see that 100 ft of No. 18 wire will produce a voltage drop of 6.23 V when carrying a current of 10 A. To find the length of this wire that will produce a voltage drop of 1 V with a 10-A load, we merely divide 100 by 6.23. The result is approximately 16.05 ft [4.89 m].

TABLE 4-3 Capacity, weight, and resistance for stranded copper electric wire.

Wire Size	Continuous duty current (amps)-wires in bundles, groups, harnesses, or conduits. (See Note #1) — Wire conductor temperature rating: 105°C	150°C	200°C	Max. resistance ohms/1000ft@20°C tin-plated conductor (See Note #2)	Nominal conductor (area-cir mil)
24	2.5	4	5	28.40	475
22	3	5	6	16.20	755
20	4	7	9	9.88	1216
18	6	9	12	6.23	1900
16	7	11	14	4.81	2426
14	10	14	18	3.06	3831
12	13	19	25	2.02	5874
10	17	26	32	1.26	9354
8	38	57	71	0.70	16983
6	50	76	97	0.44	26818
4	68	103	133	0.28	42615
2	95	141	179	0.18	66500
1	113	166	210	0.15	81700
0	128	192	243	0.12	104500
00	147	222	285	0.09	133000
000	172	262	335	0.07	166500
0000	204	310	395	0.06	210900

Note #1: Rating is for 70°C ambient, 33 or more wires in the bundle for sizes 24 through 10, and 9 wires for size 8 and larger, with no more than 20 percent of harness current carrying capacity being used, at an operating altitude of 60,000 feet.
Note #2: For resistance of silver- or nickel-plated conductors see wire specifications.

Although it is permissible to use aluminum wire in aircraft installations, the size of the wire must be larger than that of a copper wire for the same load. In general, an aluminum wire two sizes larger than the copper wire will be acceptable. Table 4-4 gives capacity, resistance, size, and weight for aluminum wire.

Table 4-4 lists aluminum wire only of sizes 8 through 0000 because smaller aluminum wires are not recommended for aircraft use. It is interesting to note that aluminum wires of the larger sizes can be used advantageously to save weight, even though the aluminum wires are larger in diameter. Note that No. 00 aluminum wire has almost as much capacity as No. 0 copper wire but that in lengths of 1000 ft [304.8 m], the aluminum wire weighs only 204 lb [92.5 kg] against 382 lb [173.3 kg] for the copper wire. This is a saving of 178 lb [80.7 kg] for 1000 ft of wire. When No. 0000 aluminum wire is substituted for No. 000 copper wire, it is found that the weight of the aluminum wire is less than half the weight of the copper wire.

Data Bus Cable

One special type of cable used exclusively for various digital electronic systems is called **data bus cable**. This cable

TABLE 4-4 Capacity, weight, and resistance for stranded aluminum wire.

Wire Size	Continuous duty current (amps) Wires in bundles, groups, or harnesses or conduits — Wire conductor temperature rating: 105°C	150°C	Max. resistance ohms/1000 ft @20°C
8	30	45	1.093
6	40	61	0.641
4	54	82	0.427
2	76	113	0.268
1	90	133	0.214
0	102	153	0.169
00	117	178	0.133
000	138	209	0.109
0000	163	248	0.085

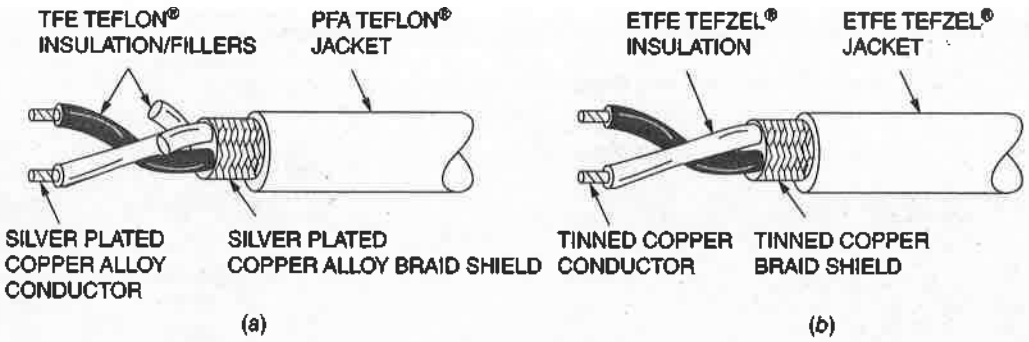


FIGURE 4-6 Two types of data bus cables: (*a*) MIL-STD-1553B with fillers and (*b*) data bus cable without filler rod.

typically consists of a twisted pair of wires surrounded by an electrical shielding and insulators. There are several different types of data bus cables; each meets a different standard and is used for specific applications. Figure 4-6 shows two different cables; one uses a filler rod to separate the inner conductors. It should also be noted that there are slight differences with regard to the inner conductors: one cable contains silver-plated copper conductors, the other has tinned copper conductors.

The data bus cables shown in Fig. 4-6 adhere to the MIL-STD-1553 standard. This is probably the most common data bus standard currently used in aircraft. As shown, the 1553 standard can have slight variations in design. These design variations will affect the ability of the cable to successfully transmit a data signal. Since digital data is typically comprised of low voltage, low amperage, and quickly changing signals, it is critical that signal loss is kept to a minimum. Selection of the correct data bus cable, connectors, and proper installation techniques are essential when dealing with most digital systems.

Since data bus cable is often shielded, the termination of the conductors becomes challenging. It is essential that both the inner conductor and the outer shielding are each connected properly. The outer shield is typically connected to ground and the inner conductor(s) connected to the specific pins of a connector. Figure 4-7 shows one common method of connecting to the outer shield of the cable. In this example, a heat shrink sleeve is installed over the stripped wire and a stub wire is connected to the outer shield using a conductive strip inside the plastic shrink sleeve.

Data bus cables perform very specific tasks for their associated systems. Digital systems operate on different frequencies, voltages, and current levels. It is extremely important to ensure that the correct cable is used for the system installed. The cable should not be pinched or bent during installation. Data bus cable lengths may also be critical, and proper connectors must always be used. Refer to the current manufacturers' manuals for cable specifications.

Fiber-Optic Cable

Many modern aircraft now employ fiber-optic cable for the transmission of data between various digital systems. Aircraft such as the Boeing 777 and 787 as well as the Airbus A-380 use fiber cable for operation of flight controls, flight deck instruments, and other flight critical systems. Fiber-optic cable is constructed with one or more very small glass fibers surrounded by a protective sheath, which creates a wire-like cable used to transmit light. The optical fiber elements are typically individually coated with plastic layers and contained in a protective tube suitable for the environment where the cable will be deployed; see Fig. 4-8. As can be seen, a braided jacket is typically included within the cable design to provide strength. The optical fiber and related coatings determine what frequencies (wavelengths) are best transmitted by the glass fiber. During the design process, it is critical to choose the correct optical cable to ensure compatibility with the transmitter and receiver.

Fiber-optic cable does not carry information using traditional electrical signals; instead, a light source is used to carry a digital signal through the fiber. Keep in mind, the signals transmitted by fiber optics are all digital and comprised

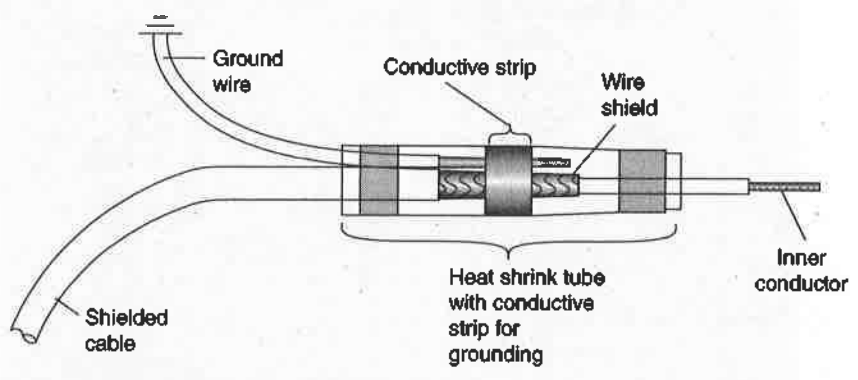


FIGURE 4-7 Termination of shielded cable.

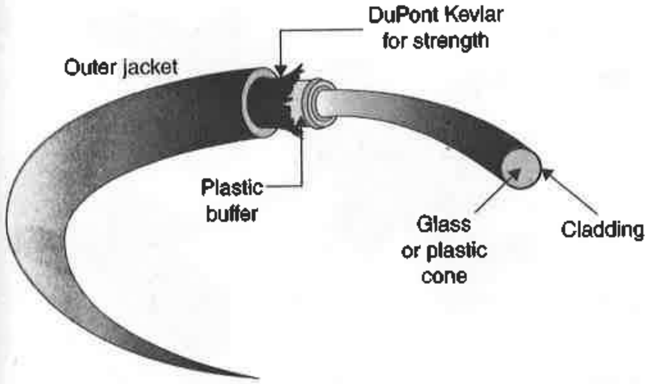


FIGURE 4-8 Fiber optic cable.

of *Ones (1s)* and *Zeros (0s)*. For example, a simple means of transmitting information using light would be to turn the light *on* for *digital 1* and light *off* for *digital 0*. The various combinations of 1s and 0s will contain information that can be read (decoded) by a fiber-optic receiver. Of course, the actual digital signals are very complex and are transmitted at a very fast rate. Digital data will be discussed in Chap. 7 of this text.

Fiber-optic cable typically connects one or more LRUs which communicate using digital light signals. For example, a digital processor may use fiber-optic cable to send video information to a flat-panel display on the flight deck. Of course, both the processor and display are electronic units which operate using electrical signals; only the video information is transmitted using light. As seen in Fig. 4-9, the transmitting end of a fiber-optic cable must contain a circuit used to change the digital electric signal into a digital light signal; at the receiving end of the fiber, a circuit is required to change the incoming light into an electric signal. The light source used for the transmission of data can be one of two types; a laser or a light-emitting diode (LED). It is essential that the optical fiber and the light source are matched in order to ensure signal transmission. The laser light source is typically used for long runs of cable or large quantities of data transfer.

At quick glance, both fiber and electric cables are similar in many ways; however, the fiber connectors, installation procedures, and required tooling are all specific to fiber cable only. In many cases, the fiber cable routed through the aircraft will be of special color for easy identification. Fiber-optic cable may be routed separately or in a traditional wire bundle with no adverse effects to the light transmission. Care must be taken not to kink or create tight bends in fiber cable since it will create a signal loss or may damage the internal glass fiber completely. Elimination of dirt, oil, or other contaminants in all optical connectors is also extremely critical to ensure proper operation of the optical circuit.

Fiber Cable Safety

The inner core of a fiber cable is made of glass formed into extremely fine strands or fibers. These glass fibers are surrounded by protected layers and typically create no hazard. However, when the inner fiber is exposed, a hazardous situation is at hand. The extremely fine strands of glass fiber can penetrate the skin and are very difficult to remove. When installing or removing a fiber connector, the fine glass strands are exposed; do not touch the end of the cable and always wear safety glasses. It is also important to never look in the end of the fiber cable; if a laser is transmitting through the cable serious eye damage is likely. Whenever performing any maintenance procedures on optical fiber, always follow all manufactures safety precautions.

REQUIREMENTS FOR OPEN WIRING

When wires or wire bundles are routed through the aircraft without the mechanical protection of conduit, it is called **open wiring**. Most aircraft use the open wiring system, and mechanical protection is provided in critical areas by proper clamping of wires, adding rubber or plastic grommets, and routing wires behind decorative or structural panels.

Open wiring is more vulnerable to wear, abrasion, and damage from liquids than wiring installed in conduits; hence care must be taken to see that it is installed where it is not exposed to these hazards and in a manner to prevent damage. The number of wires grouped in a bundle should be limited in order to reduce the problems of maintenance and to limit damage in case a short circuit should occur and burn one of the wires in the bundle. Shielded cable, ignition cable, and

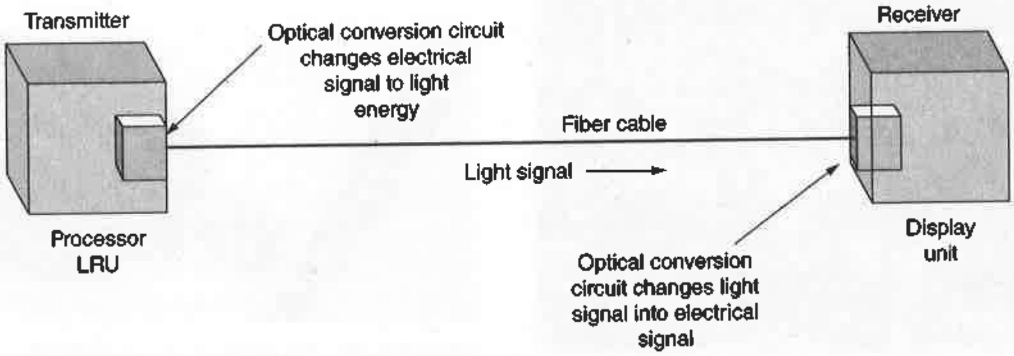


FIGURE 4-9 Optical conversion circuits used with fiber optic cable.

wire that is not protected by a circuit breaker or fuse are often routed separately. The bending radius of a wire bundle should not be less than 10 times the outer diameter of the bundle. This is required to avoid excessive stresses on the insulation. Specialty wire like data bus or coaxial cable also has a minimum bend radius. Always consult current manufacturer's data for proper bend radius minimums.

Cable Lacing

Single conductor wires are often routed through the aircraft in groups or bundles. This ensures most wiring is routed in a known location and wire bundles provide additional strength compared to a single wire. When a group of two or more single conductor wires are routed through the aircraft, they must be secured to both the aircraft structure and any adjacent wires. This type of installation is known as wire bundling. In many aircraft, a lacing cord may be used to bundle wire groups. Lacing cord is basically a specially designed string which is used to tie the individual wires into a group or **bundle**. Of course the lacing cord must meet specific strength requirements, be resistant to moisture and heat failure, and is typically coated with a sticky wax-like substance which makes the cord less likely to untie or slip.

Most modern lacing cord is actually constructed using many small fibers braided into a flat strap or tape. The flat surface of the lacing tape is less likely to cut into the insulation of the wires and create a potential hazard. The use of flat-tape lacing is quickly replacing round cord in most modern aircraft; be sure to consult the aircraft manual and/or the latest FAA documentation for proper lacing requirements.

The lacing of wire bundles should be performed according to accepted specifications. Approved **lacing cord** complying with specification MIL-T-43435 specification may be used for wire lacing. If wire bundles will not be exposed to temperatures greater than 248°F [120° C], **cable tie straps** complying with specification MS-17821 or MS-17822 can be used. Typical tie straps are shown in Fig. 4-10. Tie straps have replaced lacing cord in many aircraft installations; but always consult the

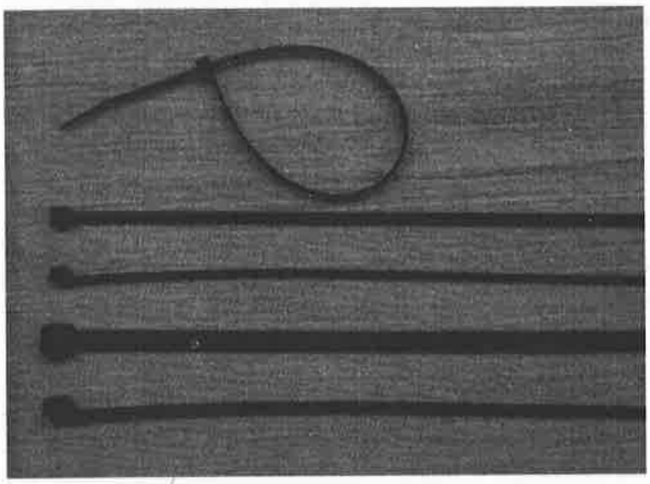


FIGURE 4-10 Tie straps for wire bundles.

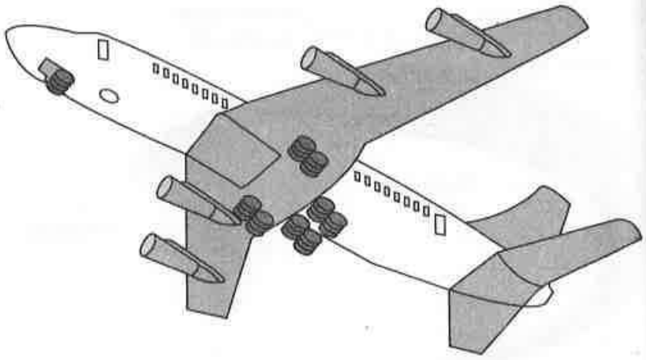


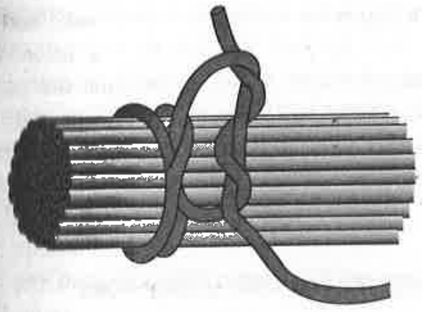
FIGURE 4-11 High vibration of typical aircraft.

current maintenance data to ensure that straps can be substituted for lacing cord. As seen in Fig. 4-11, many aircraft have certain areas subject to high vibration or excessive heat where tie straps are not acceptable. Wire straps should not be used in SWAMP areas. In general, straps are not recommended where strap failure would permit excess wire movement, which may damage wire insulation or cause wires to restrict movement of mechanical linkages, such as a flap actuator. It is also critical that special ultra violet (UV) resistant plastic cable ties be used in any area exposed to sunlight. Over time UV light will damage some cable ties and create a potential hazard. To install a tie strap, simply wrap the tie around the wire bundle, being sure not to twist the strap. Insert the strap through the locking eyelet, and tighten the strap, using the proper tool. The tool is also used to cut off any excess strap, leaving a flush edge. Figure 4-12 illustrates the use of a typical tie strap installation tool.

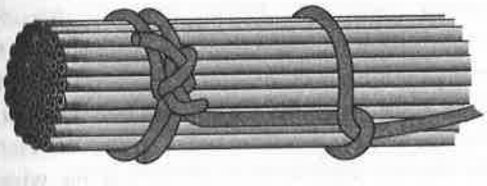
Single-cord lacing is used for cable bundles 1 in. [2.5 cm] in diameter or less. For larger bundles, double-cord lacing should be employed. Cable bundles inside a junction box should be laced securely at frequent intervals to assure that a minimum of movement can take place. In open areas, the bundles should be laced or tied if supports for the cable are more than 12 in. [30.5 cm] apart.

Wire bundles may be, laced with a continuous series of loops around the bundle as shown in Fig. 4-13 or with single ties as in Fig. 4-14. When the continuous lacing is applied, the first loop is a clove hitch locked with a double overhand knot as shown in Fig. 4-13*a*. The knot is pulled tight as shown in Fig. 4-13*b*, and the continuing end is then looped around the wire bundle with the cord brought over and under

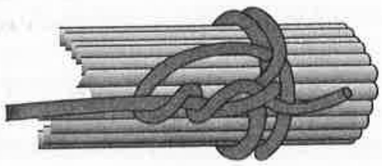
FIGURE 4-12 Typical tie strap installation tool. (*Thomas & Betts Corp.*)



(a)



(b)



(c)

FIGURE 4-13 Lacing of wire bundles.

the cord from the previous loop to form the type of loop shown in Fig. 4-13*b*. These loops are continued at suitable intervals, and the series is then terminated with another clove hitch. The free end is wrapped twice around the cord from the previous loop and is then pulled tight to lock the loop. The terminating ends of the cord are trimmed to provide a minimum length of $\frac{3}{8}$ in. [0.95 cm]. The method for making the terminal loop is illustrated in Fig. 4-13*c*.

When it is desired to use single ties to secure a wire bundle, the locked clove hitch is used. The clove hitch is formed as shown, and it is then locked with a square knot. Single ties

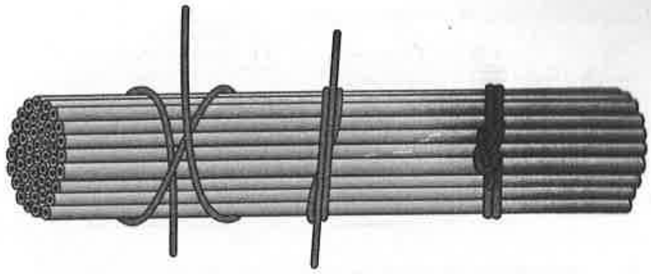


FIGURE 4-14 Single-tie lacing.

are sometimes used to separate a group of wires from a bundle for identification purposes, as shown in Fig. 4-15. This helps maintenance technicians locate particular circuit wiring.

When **double-cord lacing** is required for large cable bundles, the first loop is made with a special type of slip knot similar to the "bowline-on-a-bight." This is shown in Fig. 4-16. The double cord is then used to make additional loops as required in the same manner as the single cord is used. The terminal lock knot is made by forming two single loops around the bundle and then tying the two ends with a square knot.

Wire and Cable Clamping

Electric cables or wire bundles are secured to the aircraft structure by means of metal clamps lined with synthetic rubber or a similar material. Specification MS-21919 cable clamp meets the requirement for civil aircraft use. Such a clamp is illustrated in Fig. 4-17.

During instillation of all cable clamps, care must be taken so any stress applied will not bend the clamp. The clamp must support the weight of the cable during normal flight, as well as extreme bank angles and flight through turbulent air. When a clamp is mounted on a vertical member, the loop of the clamp should always be at the bottom. Correct methods for installing clamps are shown in Fig. 4-18.

When a wire bundle is routed through a clamp, the bundle must be held within the rubber lining of the clamp, and no wires must be pinched between the metal flanges of the clamp. Pinching of the wire could cause the insulation to be damaged, and a short circuit could result.

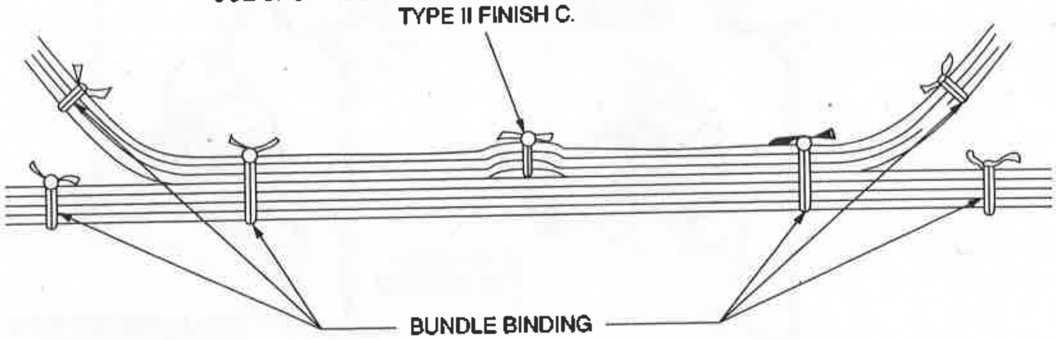


FIGURE 4-15 Separation of wire groups for identification.

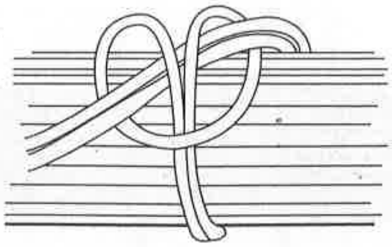


FIGURE 4-16 Beginning loop for double-cord lacing.

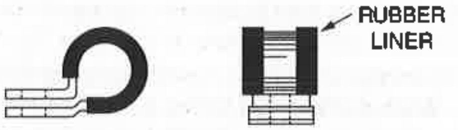


FIGURE 4-17 Clamp for electric cable.

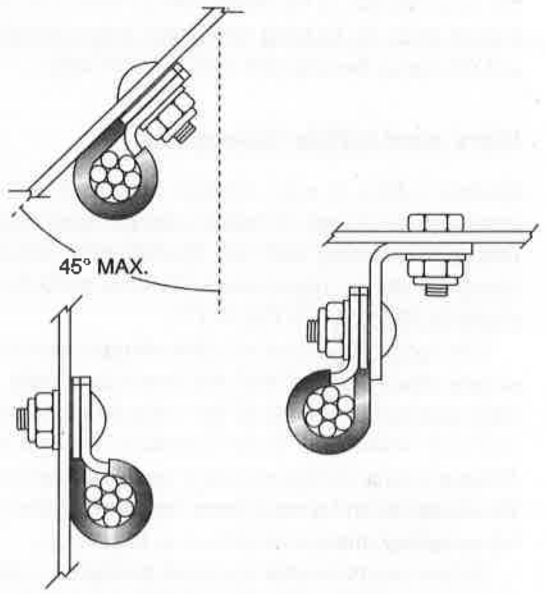


FIGURE 4-18 Correct methods for installing clamps.

When installing wiring in a particular make and model aircraft, it is the best practice to make the installation in accordance with the manufacturer's original design unless a specific change has been ordered. The clamps, wiring, and connectors should be of the same types specified and used by the manufacturer.

Routing of Electric Wire Bundles

The routing of electric wire should be done in a manner that will provide the protection previously mentioned, namely protection against heat, liquids, abrasion, and wear. Clamps should be installed in such a manner that the wires do not come in contact with other parts of the aircraft when subjected to vibration or extreme bank angle. Sufficient slack should be left between the last clamp and the electric equipment to prevent strain at the wire terminals and to minimize adverse effects on shock-mounted equipment. Where wire bundles pass through bulkheads or other structural members, a grommet or suitable clamping device should be provided to prevent abrasion as shown in Fig. 4-19. A minimum of $\frac{3}{8}$ in. [0.95 cm] must be maintained between all wires and the bulkhead. Less than $\frac{3}{8}$ in. is approved if a grommet is installed as shown in Fig. 4-19. A grommet is a nonabrasive rubber or plastic material commonly used to protect wiring.

When electrical wiring is mounted in the vicinity of fluid lines which carry flammable liquids, extreme care must be taken to avoid the possibility of fire. A small leak and loose electrical connection could be catastrophic and create a serious hazard. Consequently, every effort should be made to avoid this hazard by physical separation of the cables from lines carrying oil, fuel, hydraulic fluid, or alcohol. When separation is impractical, the electric wire should be placed above the flammable-fluid line and securely clamped to the structure. Whenever possible, wires should be mounted 6 in. [15.24 cm] above fluid lines. If this distance becomes less

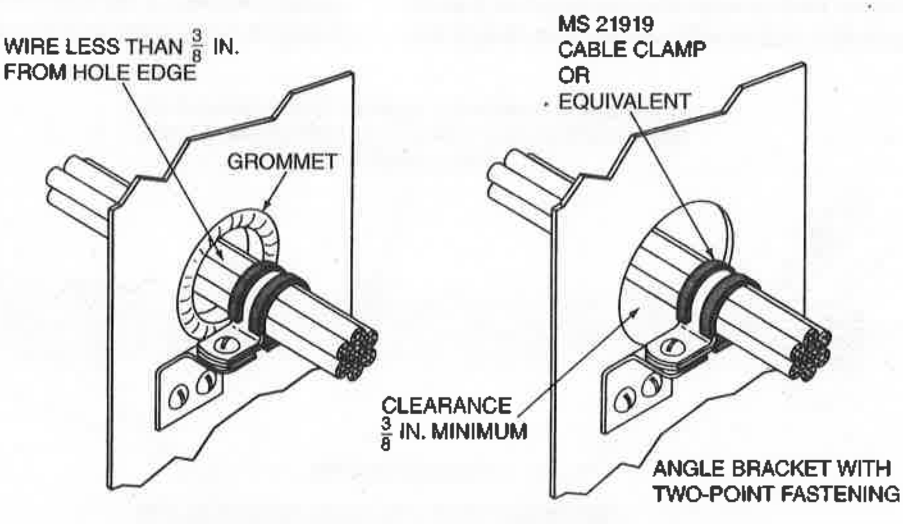


FIGURE 4-19 Wire bundle passing through bulkhead.

than 2 in. [5 cm] at maximum wire deflection, the wire must be secured by clamping.

Particular care must be used in installing electric wire on and in the vicinity of landing gear, flaps, and other moving structures. Slack must be allowed for required movement, but the wire must not be too loose. Routing of the wire must be such that it is not rubbed or pinched by moving parts during operation. During aircraft inspection, the technician should pay particular attention to all wires installed in these critical areas.

Electric wiring must be protected from excessive heat. As noted previously, electric wiring is insulated and protected with various types of materials, some of which can withstand temperatures as high as 500°F [260°C]. In areas where a wire must be subjected to high temperatures, it is necessary to use wiring with insulation made of the current heat-resistant material. Wires should not be routed near exhaust pipes, resistors, or other devices that produce high temperatures except as required for special purposes and then only if the wires are protected with adequate heat-resistant insulation.

ELECTRICAL CONDUIT

Electrical **conduit** consists of thin-walled aluminum tubing, braided metal tubing called **flexible conduit**, and nonmetallic tubing. The purpose of conduit is to provide mechanical protection, and metal conduit is often used as a means of shielding electric wiring to prevent radio interference.

Approved flexible conduit is covered by specification MIL-C-6136 for aluminum and specification MIL-C-7931 for brass. The aluminum conduit is made in two types. Type I is bare, and type II is rubber-covered.

The size of conduit should be such that the inside diameter is about 25 percent larger than the largest diameter of the cable bundle. To obtain the correct inside diameter of a conduit, subtract twice the wall thickness from the outside diameter. Typically, conduits are specified according to their outside diameter.

The inside of the conduit should be clean and free of burrs, sharp edges, or obstructions. When conduit is being cut and prepared, all edges and holes should be deburred to assure a smooth surface that will not damage the cable. The conduit should be inspected carefully after the end fittings are installed to assure that the interior is clean and smooth. If a fitting is not installed on the end of a conduit section, the end should be flared to prevent the edge of the tubing from rubbing and wearing the insulation of the cable.

Installation of conduit should be such that it is protected from damage of all types. It should be securely attached to the structure with metal clamps so there can be no movement or vibration. A clean metal-to-metal contact will assure good bonding to aid in shielding. The installed conduit should not be under appreciable stress and should not be located where it may be stepped upon or used as a hand support by a member of the crew. Drain holes must be provided at the lowest point in any conduit run.

Rigid conduit that is cut or has appreciable dents should be replaced to prevent damage to the electric cable. Bends in the conduit must not be wrinkled and must not be flattened to the extent that the minor diameter is less than 75 percent of the nominal tubing diameter. Table 4-5 shows the minimum tubing-bend radii for rigid conduit.

Flexible conduit cannot be bent as sharply as rigid conduit. This is indicated by Table 4-6, which gives the

TABLE 4-5 Minimum bend radii for rigid conduit.

Nominal tube outside diameter		Minimum bend radii	
in	cm	in	cm
$\frac{1}{8}$	0.32	$\frac{3}{8}$	0.96
$\frac{3}{16}$	0.48	$\frac{7}{16}$	1.11
$\frac{1}{4}$	0.64	$\frac{9}{16}$	1.43
$\frac{3}{8}$	0.96	$\frac{15}{16}$	2.38
$\frac{1}{2}$	1.27	$1\frac{1}{4}$	3.18
$\frac{5}{8}$	1.60	$1\frac{1}{2}$	3.81
$\frac{3}{4}$	1.92	$1\frac{3}{4}$	4.46
1	2.54	3	7.62
$1\frac{1}{4}$	3.18	$3\frac{3}{4}$	9.53
$1\frac{1}{2}$	3.81	5	12.7
$1\frac{3}{4}$	4.46	7	17.8
2	5.08	8	20.3

TABLE 4-6 Minimum bend radii for flexible conduit.

Nominal internal diameter of conduit		Minimum bending radius inside	
in	cm	in	cm
$\frac{3}{16}$	0.48	$2\frac{1}{4}$	5.72
$\frac{1}{4}$	0.64	$2\frac{3}{4}$	6.99
$\frac{3}{8}$	0.96	$3\frac{3}{4}$	9.53
$\frac{1}{2}$	1.28	$3\frac{3}{4}$	9.53
$\frac{5}{8}$	1.60	$3\frac{3}{4}$	9.53
$\frac{3}{4}$	1.92	$4\frac{1}{4}$	10.80
1	1.54	$5\frac{3}{4}$	14.61
$1\frac{1}{4}$	3.18	8	20.32
$1\frac{1}{2}$	3.82	$8\frac{1}{4}$	20.96
$1\frac{3}{4}$	4.46	9	20.86
2	5.08	$9\frac{3}{4}$	24.77
$2\frac{1}{2}$	6.35	10	25.40

minimum bending radii for flexible aluminum or brass conduit.

When sections of flexible conduit are being replaced and it is necessary to cut the conduit, the operation can be greatly improved by wrapping the area of the cut with transparent adhesive tape. Fraying of the end will be greatly reduced because the tape will hold the fine wires in place as the cut is made with a hacksaw. Before a wire or cable bundle is placed in a conduit, the bundle should be liberally sprinkled with talcum powder.

CONNECTING DEVICES

Wire and Cable Terminals

Since aircraft electric wires are seldom solid but are usually strands of small-gage, soft-drawn tinned copper or bare aluminum twisted together to provide flexibility, the separate strands must be held together and fastened to connectors. These connectors are commonly called **terminals** or terminal lugs and are required to connect the wires to terminal posts on electric equipment or on terminal strips.

Compatibility between the wire's material and the terminal's material is very important. Copper wires must be used with terminals suitable for copper wires, and aluminum wires must be used with terminals compatible with aluminum wires. If the incorrect terminal-wire combination is used, dissimilar-metal corrosion may create an insufficient electrical connection. Always verify the type of wire and terminal to be used before installation. Compatibility between the terminal and the terminal post is also necessary to reduce corrosion and possible electrical failure in this area.

Approved terminals of the **swaged** or **crimped** type are available from several manufacturers. They are designed according to wire size and the size of the terminal stud to which the terminal is to be connected. One size of terminal will usually fit two or three different sizes of wire; for example, one size of terminal will fit wire from No. 18 to No. 22. The terminal is attached to the wire by means of a special crimping tool. First, the insulation is removed with a wire stripper as shown in Fig. 4-20. Care must be taken that the stripper is of the correct size and type for the wire being stripped. This will help to ensure that the wire strands are not damaged during stripping. For each type of terminal, the length of insulation to be removed from the wire is specified. The bare wire is then inserted in the end of the terminal, and the terminal is crimped with the proper tool.

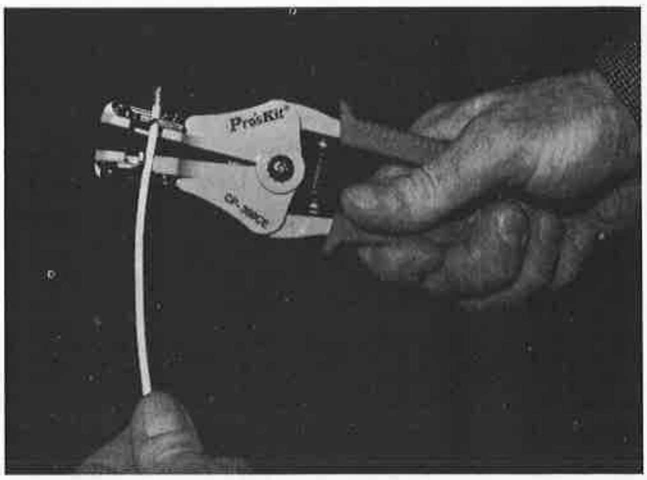


FIGURE 4-20 Use of a wire stripper.

In the stripping of electric wire, the technician should sec that the tool is sharp and is correctly adjusted. It is also important to ensure that the correct tool and cutting blades are used. It is important to check the manufacturers' recommendations for compatibility of tools and wire types. It is also very important to use the proper stripping procedures to avoid damaging the conductor. Damage can occur in the form of **nicked, broken,** or **scraped wire strands.** Minor longitudinal scrapes are acceptable; however, the allowable number of nicked or broken strands is regulated by the FAA. The data on allowable nicked or broken strands for a copper or copper alloy conductor are shown in Fig. 4-21. Nicked and broken strands are *not* acceptable for any size of aluminum conductor. Whenever stripping wires, the technician should always refer to the latest version of FAA Advisory Circular 43.13, or other pertinent data, to determine the exact number of permissible nicked or broken strands.

Maximum allowable nicked and broken strands.

Wire Size #		Number of strands per conductor	Total allowable nicked and broken strands
Copper Wire	24-14	19	2 nicked, none broken
	12-10	37	4 nicked, none broken
	8-4	133	6 nicked, 6 broken
	2-1	665-817	6 nicked, 6 broken
	0-00	1045-1330	6 nicked, 6 broken
	000	1665	6 nicked, 6 broken
	0000	2109	6 nicked, 6 broken
Aluminum Wire	6-000	All numbers of strands	None, None

FIGURE 4-21 Allowable nicked or broken strands.

Figure 4-22 shows a group of crimp-type terminals properly attached to electric wire. Note that the terminal sleeves are crimped on both bottom and top (once on the conductor of the wire, once on the insulation). Figure 4-23 shows the construction of a typical crimp-type terminal for aircraft. The terminal is equipped with a plastic, copper-reinforced insulating sleeve, which makes it unnecessary to install insulation after the terminal is attached to the wire. It is important to note that after the terminal is installed, the strands of the wire extend approximately $\frac{1}{32}$ in. [0.079 cm] beyond the terminal sleeve. This condition is required to make sure that the terminal has sufficient grip on the wire.

The crimping tool used with solderless-type terminals is designed so that it will not release until the terminal has been sufficiently crimped. This feature is provided by a ratchet installed between the handles of the tool. Care must be taken to ensure that the technician using the tool is well informed about its proper operation. Manufacturers of terminals and installation tools supply instructions and specifications that give all the necessary information and data for proper installation. Many tools are color-coded to match the color of the terminal sleeve or insulation. This coding assures that the tool of the proper size will be used for each terminal. The various colors are used to designate the different sizes of terminals and the wire gages that fit those terminals. Common color codes for copper wire are yellow for wire gage 10-12, blue for wire gage 14-18, and red for wire gage 16-22. Other wire sizes and color codes may also be used; always refer to the current manufacturer's technical data.

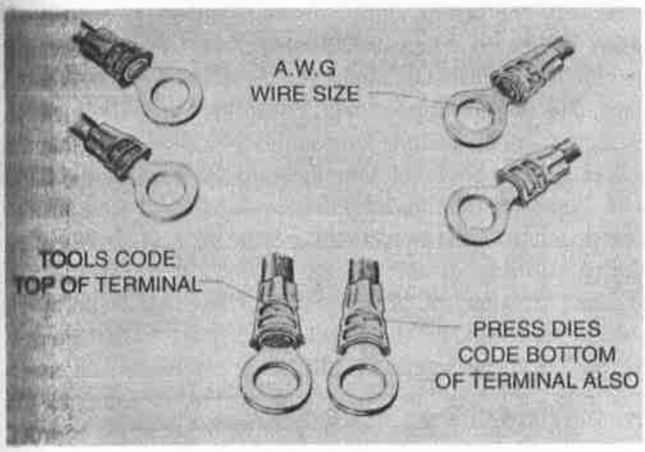


FIGURE 4-22 Crimp-type terminals. (*AMP Specialties.*)

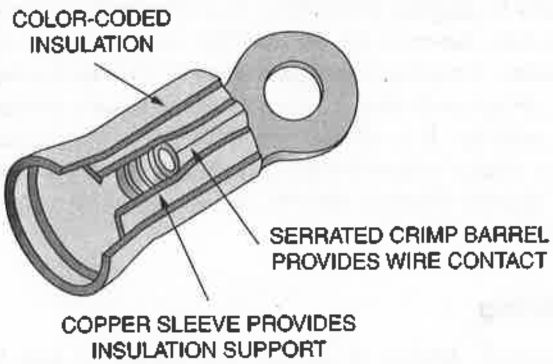


FIGURE 4-23 Construction of crimp-type terminal.

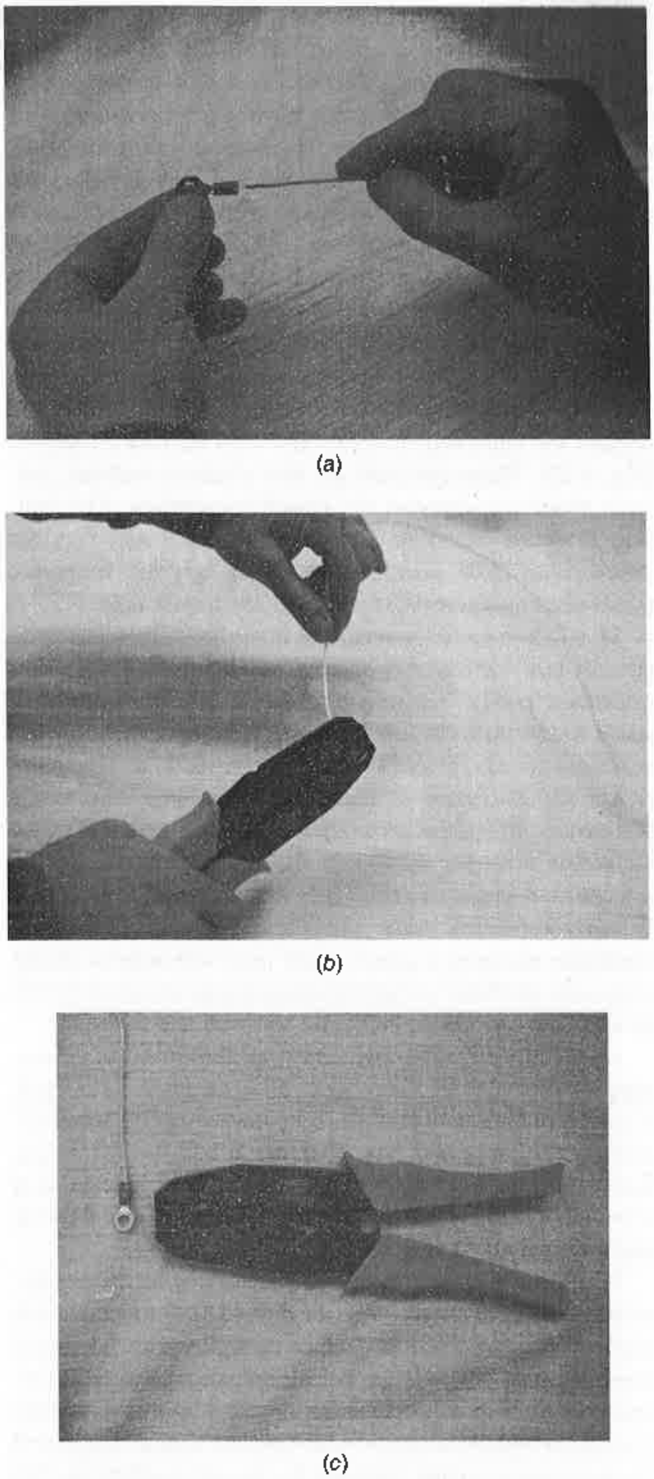


FIGURE 4-24 A typical crimped installation: (*a*) step one, prepare wire for installation; (*b*) step two, compress ring terminal using tool; (c) step three, inspect the installed terminal for proper installation. See also color insert.

Figure 4-24 shows a series of steps used to create a common crimped-type terminal connection. The result must be such that the terminal attachment has a tensile strength at least equivalent to the tensile strength of the wire. Always perform a good visual inspection of the installed terminal.

The crimp-type terminals used on aircraft are constructed with two metal sleeves, as illustrated in Fig. 4-23. One sleeve is part of the electric terminal and is crimped to the copper conductor. The second is a thin metal sleeve surrounded by the terminal's insulation cover. This sleeve is used to crimp the wire's insulation. When the wire's insulation is secured with a second crimped sleeve, the vibration stress is transmitted into the wire's insulation. This reduces the stress and the likelihood of fatigue failure of the wire's conductor. It is very important to ensure that the terminal is crimped twice: once to secure the conductor, once to secure the insulation.

Always ensure that the terminal you install is approved for aircraft use as just described. Other terminals are constructed without the inner copper sleeve that adds insulation support (Fig. 4-23). These terminals are less vibration resistant and most likely not approved for aircraft installations. The best way to ensure proper terminal selection is to verify that the specification (MIL spec) number of the terminal meets the minimum requirements for your specific installation.

In addition to the manual crimping tools, manufacturers provide power crimpers that are driven by either hydraulic or pneumatic power. When large numbers of crimps are to be made, the power tools save time and effort. Special tensile test machines are also available that can be used to test the security of the attachment of a terminal to the wire. The tensile test ensures equipment accuracy and proper installation by the technician. A tensile test should also be done in the field after a technician installs a crimp-type terminal. In the aircraft it is nearly impossible to use a tensile test machine on crimped terminals; however, a simple "pull" test will help to ensure connector reliability. A finished crimp should always be tested by applying a moderate pull to the terminal and the wire.

As mentioned previously, approved terminals for aircraft wire are produced by a number of different manufacturers. It is therefore important that the technician installing terminals identify the make and type of terminal and use the proper installation tools. If the wrong crimping tool is used on a terminal, it is likely that the crimp will be faulty, and the wire and terminal may fail in service.

Wire terminals are made in many styles to meet the requirements of different installations (see Fig. 4-25). For most aircraft applications, ring terminals, rather than slotted or hook-type terminals, must be used. This helps eliminate any circuit failure due to terminal disconnection. On aircraft, it is always the best practice to replace terminals with those of similar design and always to use terminals approved for aircraft installations. Not all terminals are produced alike; technicians should be sure that those they install are of aircraft quality.

Soldered terminals are typically considered unsatisfactory for general electrical use in aircraft electric systems, even though soldering is considered a good practice in electronic units such as radio receivers, electronic displays and other computer-based units. Electric wires in the main electric system of an aircraft are of the flexible type. When a terminal is soldered to such a wire, the solder lends to penetrate the wire and make it rigid in the vicinity of the terminal. This makes the wire and terminal less resistant to vibration, with the result that the wire may become crystallized by fatigue and break at the terminal.

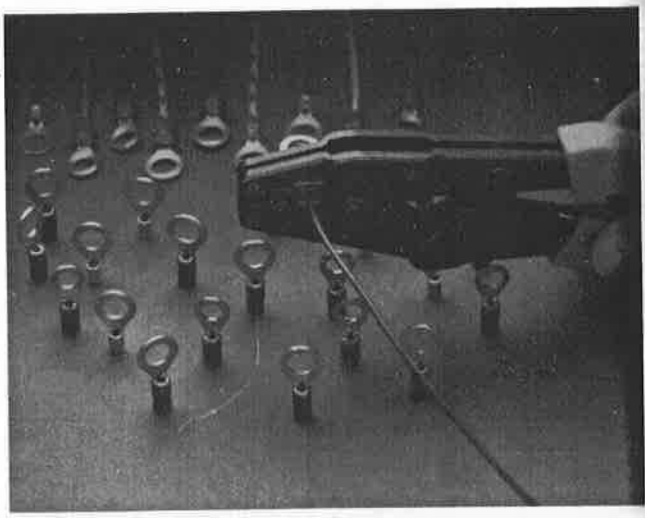


FIGURE 4-25 Crimp terminals and installation tool.

Because of the necessary unsoldering and resoldering, the maintenance of soldered-terminal systems is more difficult than that of systems with swaged crimped, terminals. A technician well-skilled in soldering techniques is required, because a poorly soldered terminal is a hazard in itself. An unskilled operator may burn the insulation, may fail to make sure that the solder is thoroughly sweated into the terminal, or may simply make a poor soldered connection due to overheating.

In the event that a joint must be soldered in an aircraft electric system, there are certain conditions that have to be observed. The flux should be of a noncorrosive type such as rosin. Rosin-core wire solder is most commonly used because the flux is automatically applied as the solder is melted on the joint. The two metal parts being joined by the solder must be brought up to the melting temperature of the solder so that the solder will flow smoothly into the joint and form a solid bond with the metal. Care must be exercised so that adjacent insulation or electric units are not damaged by the heat. Overheating during soldering can introduce contaminants into the solder and increase resistance of the connection. After completion of the solder connection, the flux should be removed from the terminal and the wire. **Denatured alcohol** or a commercially available **rosin remover** can typically be used for this purpose. On some solder installations (particularly printed circuit boards), the manufacturer may also recommend that the connection be covered with an environmentally protective coating.

Soldering is a procedure which requires regular practice in order to maintain proficiency. In general most technicians can solder; however, not all soldered connections are equal in quality. If a given installation requires a soldered connection, always seek help from an expert if you are unsure of your abilities. It is always best to practice first or call an expert when a soldered connection is needed. When dealing with aircraft electrical circuits, safety should be your first concern.

Splicing

In general, splicing of aircraft wire should be kept to a minimum; however, splicing may be done if approved for a

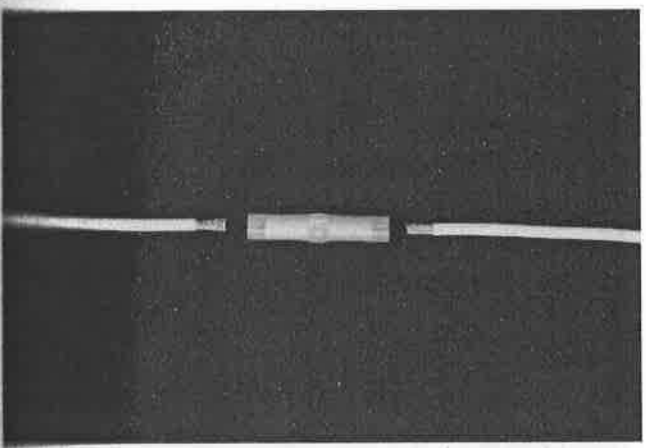


FIGURE 4-26 A crimp-type splice connector.

particular installation. Typically, the splice is made with an approved crimp-type splice connector. The **splice connector** is a metal tube with a plastic insulator on the outside or a plain metal tube that is covered with a plastic tube after the splice is made. The stripped wire is inserted into the end of the tube in the same manner in which wire is inserted into a terminal sleeve. The tube is then crimped with a terminal crimping tool. A typical crimp-type splice connector is shown in Fig. 4-26.

Splices made in bundled wires should be placed on the outside of the bundle. The bundle ties or straps are then located where there are no splices. If several splices are to be made in any wire bundle, the splices should be staggered to reduce the bundle's diameter, as illustrated in Fig. 4-27. The FAA regulations recommend that electric wire splices be kept to a minimum and be avoided entirely in locations of extreme vibrations.

A special type of splice connector has been designed for areas exposed to harsh environments (SWAMP areas). This splice must meet the MIL-T-928 specification, which ensures that the electrical connection is environmentally sealed. In most cases, this is done using a heat shrink insulated tubing over the conductor with a special heat-activated sealant. Once the crimp is complete, the technician uses a heat gun to warm the connector and seal out any potential moisture. Of course this technique for sealing crimped connectors may also be used anywhere in the aircraft and is becoming more common due to the reliability of the splice.

Insulation Tubing

Many electrical connections require the addition of insulation after the connection has been made. Typically, an insulation tube is slipped onto the wire before the connection is made and then slid over the exposed connection and secured in place. There are two basic types of insulation tubing. One is secured in place with lacing cord drawn tight and tied at each end of the tube. The other type of insulation tubing is called **heat shrink tubing**, since it is held in place on the connection through a shrinking process. The heat shrink insulation is more reliable when installed properly and can also provide some resistance to vibration stress of the connection.

Heat shrink insulation should be of the 200 to 300°C type and should always overlap the connection at least $\frac{1}{2}$ in. [1.27 cm.] after shrinking. It is important to choose a tube of the correct diameter that will shrink and form a tight fit around the conductor. If additional vibration or abrasion resistance is needed for an application, two or more layers of tubing should be installed. The innermost tube should be installed and shrunk first: the second tube, approximately $\frac{1}{2}$ in. [1.27 cm] longer than the first, should be installed next and a third added if needed. The heating process should be performed with the proper heat gun, adjusted for the correct temperature range. Reflective heat shields are often used to protect adjacent wiring or other components.

In some cases it is very important to seal electrical connections from the corrosive effects of the environment. Special heat shrink tubing is available with a sealant that is inside the tube. As the tube is heated, the sealant becomes soft and melts around the conductor, hence sealing out the environment. As discussed earlier some insulated crimp-type terminals and splices also contain this sealant and must be heated after the crimping process is complete.

Special **insulation tapes** are also approved for certain applications on aircraft terminals and splices. The tape is typically a high-temperature Teflon or silicon-type material and requires application in a spiral wrap over the splice. Tape may be used over insulation tubing as a second layer of protection. In all cases the tape is overlapped 50 percent on each wrap and should extend past the splice by a minimum of $\frac{1}{2}$ in. [1.27 cm] on each side.

Electric Terminal Strips

On vintage aircraft the joining of separate sections of electric wire is often accomplished by means of terminal strips like those shown in Fig. 4-28. A terminal strip is made of a strong insulating material with metal studs molded into the material or inserted through it. The studs are anchored so that they cannot turn and are of sufficient length to accommodate four terminals. Between each pair of studs are barriers to prevent wire terminals attached to different studs from coming into contact with each other.

When it is necessary to join more than four terminals at a terminal strip, two or more of the studs are connected with a metal bus or jumper wire, and the terminals are then connected

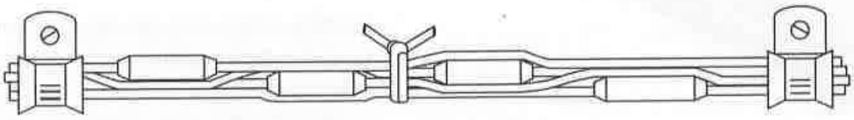


FIGURE 4-27 Staggered splice connections.

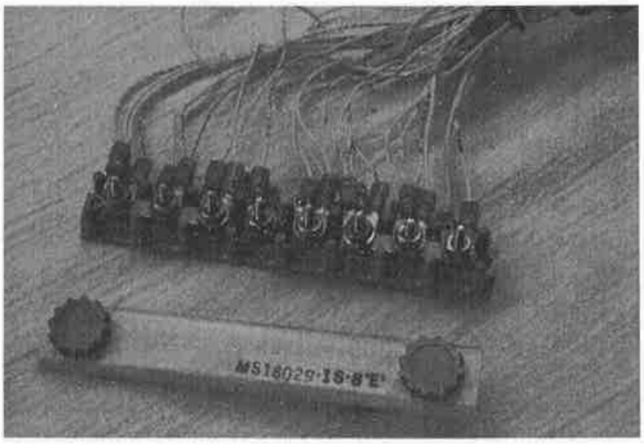


FIGURE 4-28 A common terminal strip and protective cover.

to the studs with no more than four terminals on any one stud. The stud sizes in terminal strips must be adequate to withstand the stresses imposed during installation and tightening of the nut. For this reason it is common practice to use No. 10, or $\frac{3}{16}$-in. [0.48-cm], studs for aircraft electric systems.

A stud in a terminal strip to which wire terminals are to be connected is usually mounted in the insulating strip with two flat washers, two lock washers, and two nuts as shown in Fig. 4-29.

Whenever installing wires to any type of terminal, be sure to use the correct assembly of plane (flat) and lock washers along with the correct tightening torque. This will help to ensure a reliable connection.

Terminal strips must be mounted in a manner and position such that loose objects cannot fall on the terminals. This may be accomplished by installing the strips on vertical bulkheads or overhead and providing them with suitable covers.

Modern aircraft have replaced most terminal strips with specially designed connectors known as **terminal blocks** (see Fig. 4-30). Wires assembled into these modern terminal blocks use crimp-style contacts. The contacts are each inserted into the terminal block through a water resistant seal. The terminal blocks come in various sizes and are typically mounted to the aircraft for support.

Aluminum Wires and Terminals

The installation of aluminum wiring and terminals requires exceptional care to ensure satisfactory operation. Aluminum wire hardens as a result of vibration more quickly than

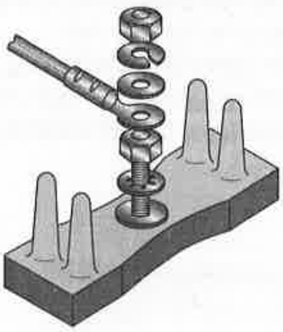


FIGURE 4-29 Attachment of a terminal to a stud.

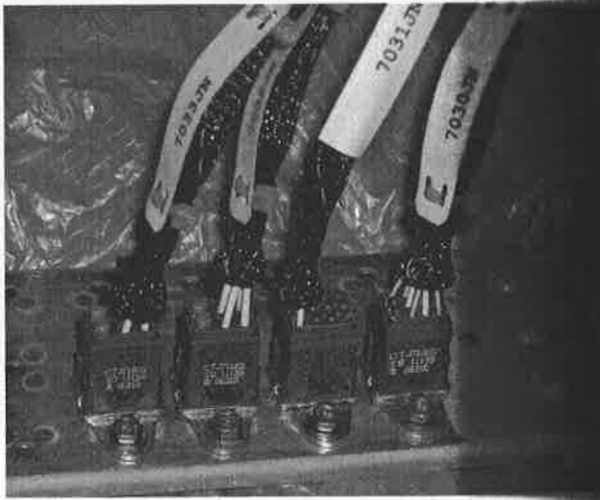


FIGURE 4-30 Modern terminal block assembly.

copper wire. For this reason aluminum wire should [illegible] used where there is appreciable movement of the wire [illegible] operation of the aircraft. Also, aluminum wire small[illegible] AWG size 8 is not acceptable. Aluminum wire is typ[illegible] found only on large aircraft for power distribution [illegible] requiring large-diameter wire.

Terminals, nuts, bolts, and washers used with alum[illegible] wiring must be compatible with aluminum to avoid [illegible] **electrolytic corrosion** that takes place between dis[illegible] metals when they are in contact. Such hardware is typ[illegible] made of aluminum or an aluminum alloy. It is ext[illegible] important that all components of any connection be ma[illegible] compatible materials, even when the terminals are con[illegible] to both aluminum wire and copper terminal studs.

Aluminum wire is especially susceptible to oxid[illegible] which forms on the outer surface of the conduct[illegible] oxidation increases the resistance of any aluminum [illegible] connection and extra care must be taken to avoid [illegible] In some cases, anticorrosive compound is added to [illegible] minum connection, special crimp terminals are typ[illegible] required, and the tool used to form a terminal crimp [illegible] be of special design. The anticorrosion compound [illegible] the oxide film from the aluminum wire and the termin[illegible] many cases special terminal lugs are available for the [illegible] connection of aluminum wire. The material and cons[illegible] are such that the crimping process automatically dest[illegible] oxide film and produces a good contact. It should [illegible] noted that in aluminum wire often requires a special [illegible] stripping tool to ensure that the strands are not nick[illegible] broken. Whenever installing aluminum wire, be sure to [illegible] all proper techniques and installation equipment.

Connectors

Electric connectors are designed in many sizes and sha[illegible] facilitate the installation and maintenance of electric [illegible] and equipment in all types of flying vehicles.

For the most part, connectors have replaced the use [illegible] minal strips on modern aircraft. There are several adva[illegible] to the use of connectors; for example, connectors are typically smaller and lighter than terminal strips. Connectors can also be designed to protect electrical contacts from moisture, dirt, and vibration problems. A typical aircraft wire harness may contain several connectors which are necessary to facilitate aircraft assembly. For example, it would be common to find connectors between wires in the wing and wires in the fuselage because these two sections of the aircraft are assembled during different stages of aircraft construction. Connectors are also used to connect electric and electronic assemblies, or **line replaceable units (LRUs)**, such as voltage regulators, flight management computers, inverters, and radio equipment. When it is necessary to replace an LRU, the connector makes it possible to disconnect the unit quickly and to reconnect the new unit with no danger of connecting any of the leads incorrectly.

A **connector assembly** actually consists of two principal parts. These parts are often called the **plug** and the **receptacle**. The plug section generally contains the **sockets**, and the receptacle contains the **pins**. The pins and sockets are connected to the individual wires that make up the circuit. When the plug and receptacle are assembled together, the pins slip inside the sockets and form the electrical connection.

When a connector assembly is designed and installed, the "hot," or voltage-positive, side of the circuit should be connected to the socket section, and the ground side of the circuit should be connected to the pin section whenever possible. This arrangement will reduce the possibility of shorting the circuit when the connector is separated. For this reason LRUs typically contain the pins, and the wiring harness is connected to the socket section of the plug.

Problems experienced with connectors are often due to corrosion caused by moisture condensation inside the shell of the connector. If a connector is to be installed where corrosion is a problem, a special waterproof connector should be installed, and any unused contact hole should be filled with a wire or plug to prevent the entrance of moisture or other foreign matter. The free end of a stub wire should be covered with potting compound or some other material to prevent electric contact.

In working on large aircraft electric systems, a technician will encounter many different types and makes of connectors. The earlier connectors were designed for the wires to be soldered to the pin and socket contacts; however, most connector assemblies are now designed with crimp-type pins and sockets. The pins and sockets are first crimped to the wires and then are installed in the connectors by means of special tools.

Because of the almost infinite variety of possible electric circuits and installations, it is readily understandable that there must also be a wide variety of connectors and other connecting devices. Several different types of connectors are shown in Fig. 4-31. For the installation of any particular connector assembly, the specifications of the manufacturer or the appropriate governing agency must be followed.

All connectors must be labeled as to the pin or socket locations within the connector's insulation housing. This identification label is necessary to ensure that the wire is connected to the correct pin or socket during installation.

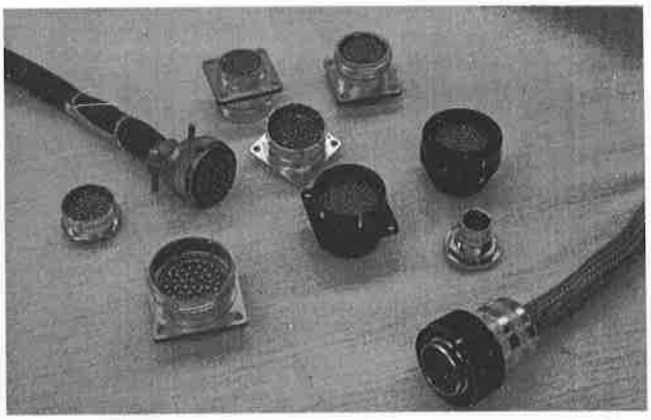


FIGURE 4-31 Common aircraft connectors. See also color insert.

Labeling also facilitates troubleshooting by allowing the technician to easily identify a particular circuit connection. Many aircraft connectors are labeled by stamping a letter on the connector's insulation housing adjacent to the correct pin or socket hole. The technician should be sure to correctly identify the electrical connection of a connector prior to performing maintenance.

Connectors currently being manufactured for aircraft use are often required to meet military specifications and are called MS electric connectors. **Military specifications (MIL specs)** are revised from time to time to incorporate performance requirements as dictated by design advances and more stringent operating requirements of equipment. Many older connectors adhere to the AN (Air Force-Navy or Army-Navy) specifications. These standards have been replaced with MS or MIL specifications.

The general specification MIL-DTL-5015 (formerly, MIL-C-5015) provides for several designations of connectors to meet different requirements. These connectors carry MS numbers such as MS3100A-20-27S. In this designation, the number *3100* indicates a wall-mounted unit, the letter *A* indicates general utility usage, the number *20* indicates shell size, and *27S* shows that the plug contains 27 socket-type connections. Typical MS connectors are shown in Fig. 4-32.

Connector assemblies are manufactured in many shapes and sizes to meet the requirements of modern electric and electronic equipment. The round connector is popular because it lends itself to easy joining and securing by means of a threaded collar. Many connectors are made in a rectangular shape, however, and these are often used when a harness is connected to an electronic unit (LRU).

The construction of the pins and sockets in a "MIL spec" or other type of connectors may be designed for solder connections to the electric wires, or the connector may be designed with crimp pins and sockets. In general, older aircraft employ soldered type connectors. At the end of the pin or socket in a solder-type connector is a small solder pocket. A short section of insulation is removed from the wire, and the bare stranded wire is then inserted in the pocket. Enough insulation should be removed from the wire so that none extends into the solder pocket. With the wire in the pocket, solder is applied with

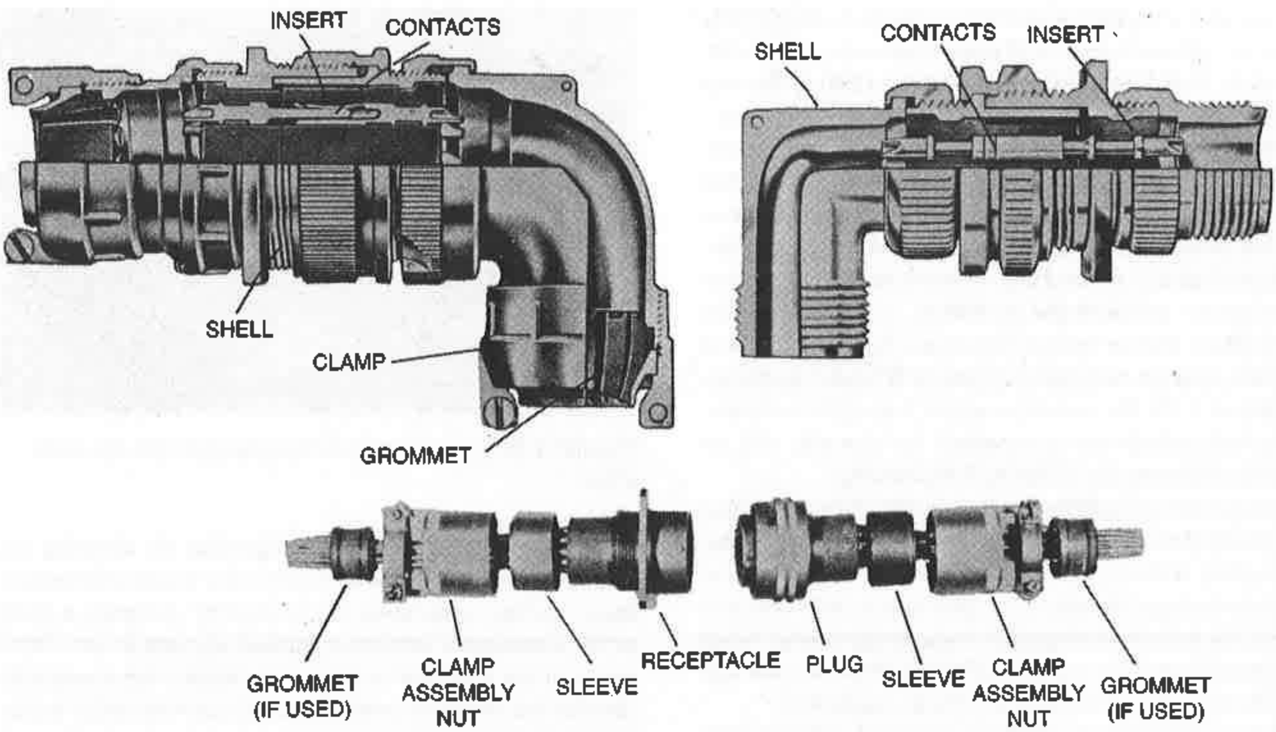


FIGURE 4-32 Bendix MS-type connectors. (*Bendix Corporation.*)

a small-pointed soldering iron or soldering gun. The solder should be of the rosin-core wire type and should be applied to the pocket as it is heated with the soldering iron. As soon as the solder flows smoothly into the pocket and penetrates the wire, the soldering iron should be removed to avoid the possibility of burning the insulation of either the wire being soldered or the adjacent wires. Only enough solder should be applied to fill the pocket, and all small drops of solder should be removed from between the pins. After each pin is soldered, a plastic sleeve insulator should be pushed down over the soldered joint and metal pin to prevent the possibility of short-circuiting. The insulating sleeves should be tied, clamped, or of the heat-shrink type to prevent them from slipping off the pins.

As mentioned earlier, crimp type solderless contacts are used in a variety of connectors.

Due to their proven reliability, the crimped-type connections are typically found on modern aircraft. Soldered-type connectors are found on older aircraft. The process of crimping the wire to the connector relies on a mechanical tool used to compress the pin around the stripped portion of the wire. Some of the characteristics of soldered and crimp-type connectors are as follows:

Soldered Connections

a. The flux used for soldering is corrosive and can weaken the connection over time.

b. Errors such as too much heat, too much solder, not enough heat, and lack of connection cleanliness are difficult to eliminate.

c. Gold-plated contacts can be destroyed by the soldering process.

d. Solder wicking into the wire strands can create additional stress in the wire.

Crimped Connections

a. The use of the appropriate tools helps to eliminate the chance of human errors.

b. No corrosive fluxes are used during crimping.

c. Gold-plated contacts are completely compatible with the crimping process.

d. The connection is easily inspected prior to pin installation.

e. Field repair can be performed more easily and with less error than repair of soldered connections.

When preparing a wire for installation into a pin or socket, the technician must first remove the proper length of insulation from the end of the wire. During this process it is very important not to damage the conductor through broken or nicked strands beyond acceptable limits. The proper length of insulation to remove depends on the conductor size and the type of pin or socket to be used. The manufacturer's installation data should be consulted for strip length specifications. A properly stripped wire for both a solder connection and a crimp-type connection is shown in Fig. 4-33.

There are three basic procedures that must be performed to install a wire for all crimp-type connectors. (1) The wire must be stripped, (2) the wire must be crimped to the pin or

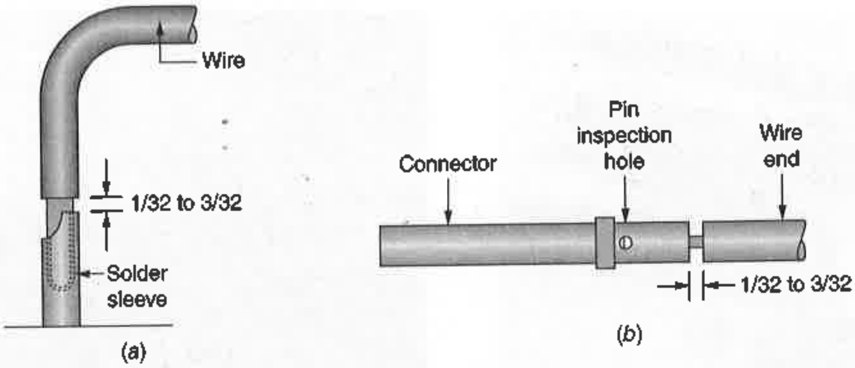


FIGURE 4-33 Wire strip lengths: (*a*) In the case of a solder pot connection, the wire should be long enough to reach to the bottom of a solder cup, with $\frac{1}{32}$ to $\frac{3}{32}$ in. of wire exposed beyond the cup; (*b*) The wire in a crimp connection should be visible in the inspection hole of the crimp contact, with $\frac{1}{32}$ to $\frac{3}{32}$ in. of wire exposed beyond the barrel. (*The Deutsch Co.*)

socket, and (3) the pin or socket must be installed in the connector housing. Each of these procedures should be followed by a visual inspection of the work performed, and defects must be eliminated. After this process has been successfully completed, the connector should be reassembled and installed in the aircraft. Figure 4-34 gives detailed instructions for the installation of a contact into a typical connector assembly.

Wire installation instructions are as follows:

Step 1 Install the pin or socket into the crimp tool with the wire barrel facing up. During this process be sure to use the correct tool and any necessary adapters and/or the appropriate setting for the pin or socket desired.

Step 2 Remove the correct length of insulation from the wire, using appropriate methods.

Step 3 Install the stripped portion of the wire into the connector barrel, and compress the connector by squeezing the tool handles together. The tool will release the contact when the crimping process has been completed. If the contact will not release, the crimp cycle has not been completed and the contact must be compressed further.

Step 4 Inspect the finished crimp through the inspection hole in the contact. The wire must be visible; if it is not, the crimp must be redone using a new contact.

Step 5 Install the contact into the connector housing, using the appropriate tool. During this process it is very important to ensure that the contact is installed completely and reaches a firm stop inside the connector housing. Often a small click is heard as the contacts reach their stopping point.

There are two methods commonly used to install a contact into a connector housing: **front release** and **rear release**. The front-release contact is held in place by a relatively complex combination of retainers molded into the connector housing.

A special tool is used to install a front-release contact in the front of the connector housing. A rear-release contact is installed in the rear of the connector housing and is secured with two or more small lines as shown in Fig. 4-35. The rear-release method provides better front-end support for the contact; therefore, the contact is less likely to bend during reassembly of the connector.

Contact Removal. To remove a contact from a connector assembly, the technician must first remove any outer-shell components to expose the wire and contact to be removed. A special removal tool is slid gently into the connector housing; it releases the locking tabs holding the contact in place. In many cases a double-ended tool is used for both contact installation and removal. This helps to eliminate confusion when repairing defective connections. To remove a rear-release contact, simply slide the tool over the wire and onto the contact. Once the tool has reached the end of its travel, the locking labs have been depressed and the contact can be removed. A similar procedure is used for the removal of front-release contacts; however, extra care must be taken not to damage front-release components. Figure 4-36 shows the removal of front- and rear-release pins.

Potting. The process of encapsulating electric wires and components in a plastic or similar material is called **potting**. Potting is typically used for the purpose of reducing vibration stress or inhibiting moisture transfer. The process is sometimes recommended for certain components and should be accomplished as directed by the appropriate instructions.

With the invention of a variety of environmentally sealed connectors, potting is used only in limited situations and typically found on older aircraft.

Light-Duty Connectors. Recently, many connectors using nylon or plastic housing have been employed on aircraft. These connectors are used in applications where a high stress resistance or waterproofing is not required.

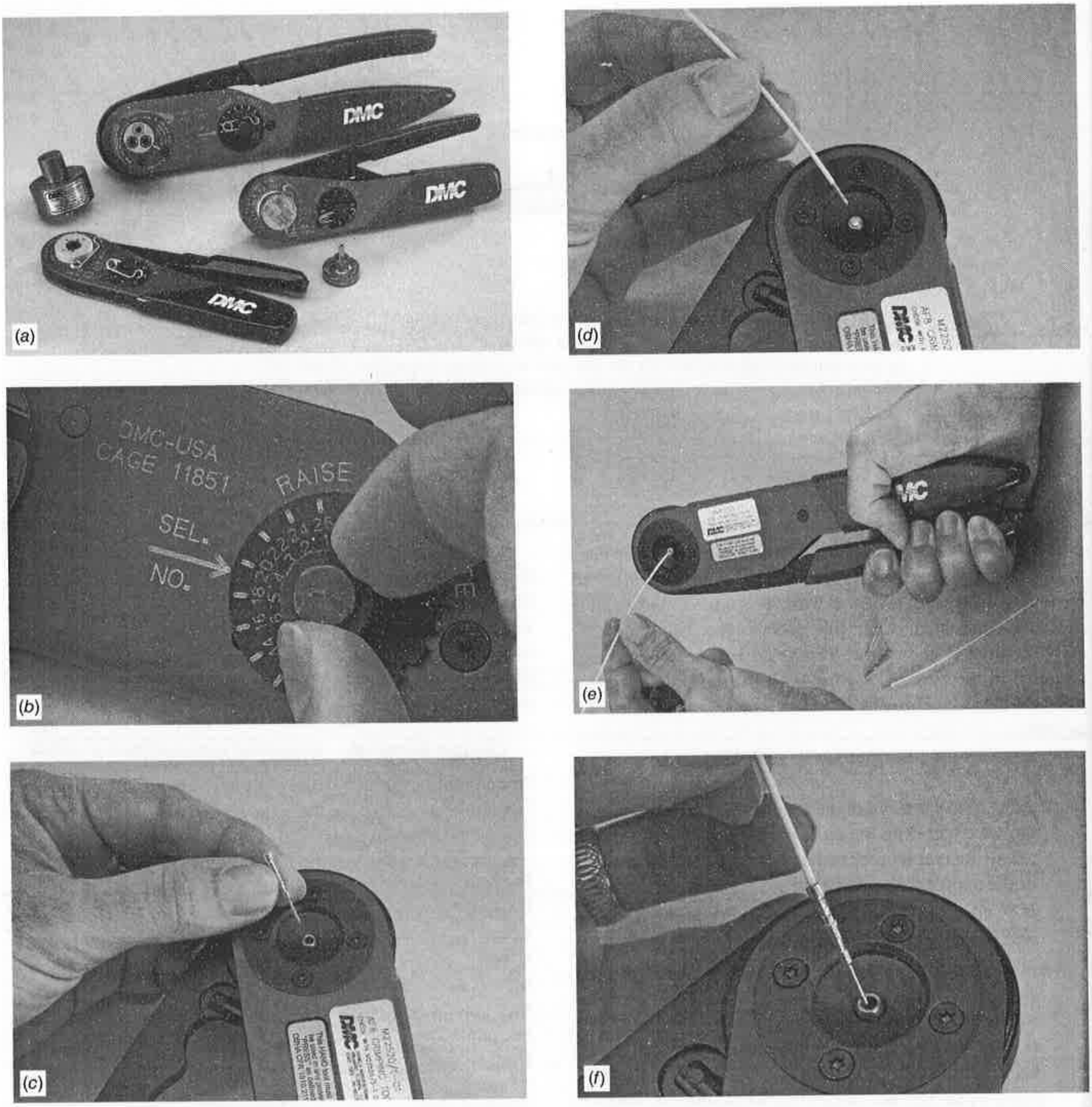
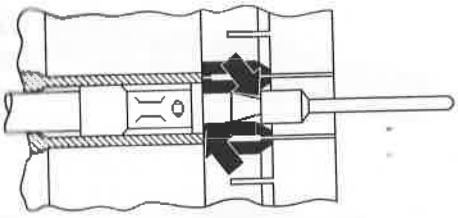


FIGURE 4-34 Common steps used during the crimping process. (*a*) Select the correct crimping tool and adaptors for the wire and pin being crimped. (*b*) Adjust the tool for the proper wire size. (*c*) Insert the pin or socket into the tool. (*d*) Insert properly stripped wire into the pin/socket. (*e*) Completely compress (squeeze) handles until tool automatically releases. (*f*) Remove wire and pin/socket assembly and visually inspect. See also color insert. (*Daniels Manufacturing Corporation.*)

Several manufacturers produce these connectors; therefore, it is vital to ensure complete compatibility prior to installing pins, sockets, or connectors. Figure 4-37 shows a variety of light-duty connectors. Typically these connectors are limited to use in light aircraft, in areas not critical to flight safety.

The housings of light-duly connectors are produced by molding a nylon or plastic material into a single unit. Two mating housings produce one connector. The connectors may be designed to fasten to an electrical unit or installed on the end of a wire or a wire bundle. The pins and sockets are connected to their respective wires by means of a special crimping tool designed by the connector manufacturer. Pins and sockets are installed by pushing them into the housing until they are locked in place. To remove a pin or socket from its housing, a special tool is needed to depress the locking tabs that hold the pin or socket in the housing. Once the tabs are depressed, the connection may be easily removed. Various housings and pins are shown in Fig. 4-38. There are several variations of each connector available; be sure to choose any replacement using current manufacturer's data.



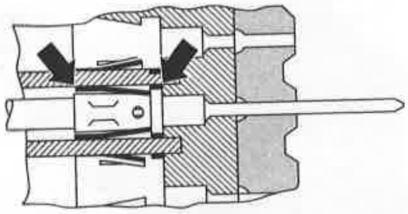
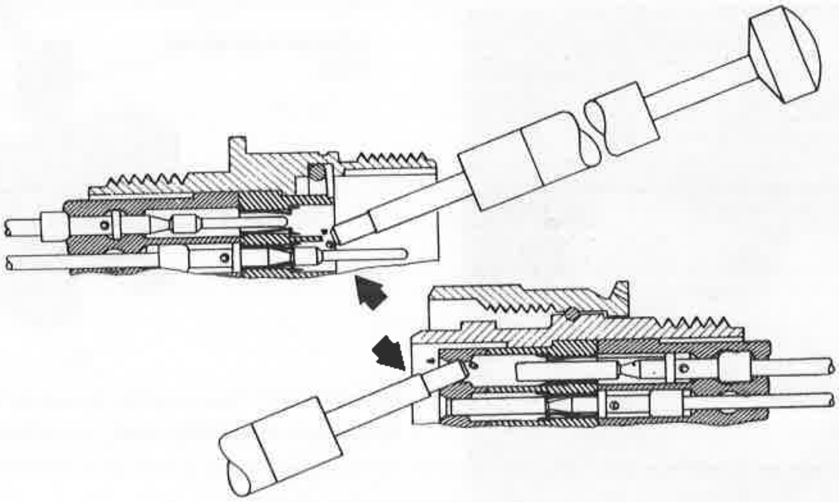


FIGURE 4-35 Pin retention systems. (*The Deutsch Co.*)

Terminal Blocks

Another type of quick connect/disconnect system used for individual wires is known as the **terminal block**. This system is typically found on large aircraft in areas not critical to flight safety, such as passenger entertainment or reading light systems. Terminal blocks are typically made up of individual modules that connect two or more wires. The modules are designed to fit into a mounting track. The track is then mounted to the aircraft's structure. Tracks come in various lengths to accommodate one or several modules. As seen in Fig. 4-39, the wire is attached to a special crimped-on pin; the pin then fits into the module. To insert the pin, simply apply light pressure using the installation tool. To remove the wire and pin. simply slide the removal tool into the module alongside the pin. This will relax the retaining spring and release the wire.



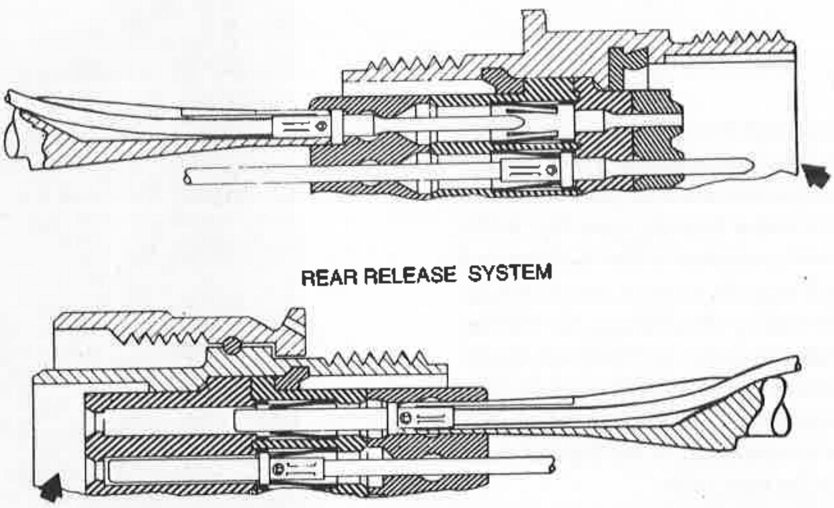


FIGURE 4-36 Removing contact pins. Releasing the retention system from the rear assures that the intermating seal on either the socket or the pin insert is not damaged by the contact removal tool. (*The Deutsch Co.*)

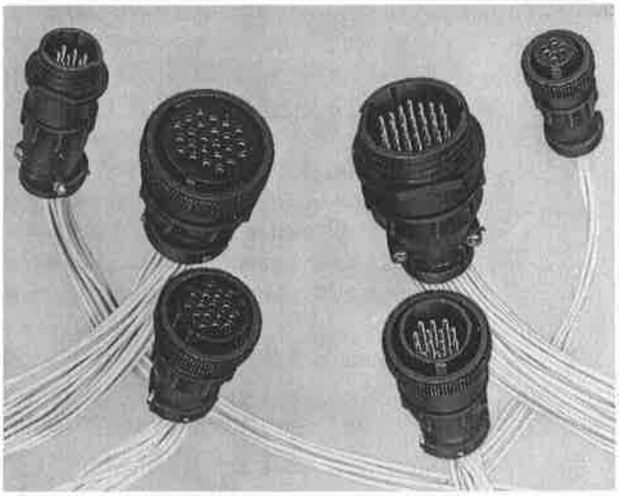


FIGURE 4-37 Typical light-duty connectors. (*AMP Products Corporation*)

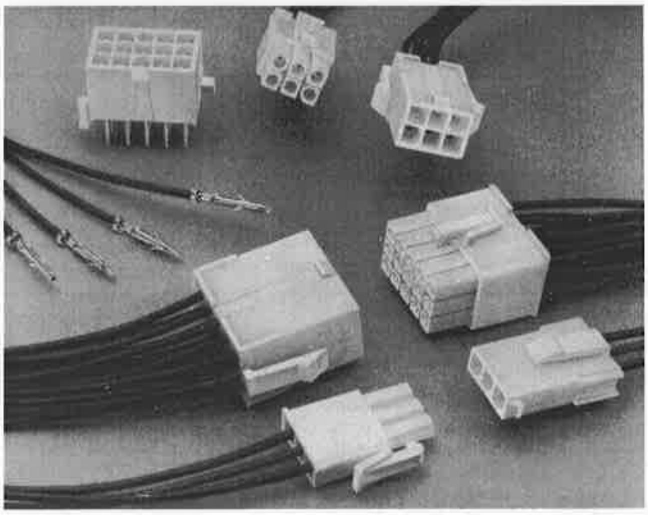


FIGURE 4-38 Various pins and housings of typical connectors. (*AMP Products Corporation.*)

D-Sub connectors

Another commonly used connector found on modern aircraft is commonly known as the **D-sub connector**. These connectors contain two or more parallel rows of pins or sockets surrounded by a D-shaped metal housing (see Fig. 4-40). One big advantage of D-sub connectors is that the backshell design provides mechanical support, ensures correct orientation, and can easily shield against electromagnetic interference. In order for the D-sub connectors to shield the electrical contacts from interference, the backshell must be constructed of metal and connected to a ground. In most cases, the backshell would also be connected to the braided metal shielding which surrounds the wire cable.

Like all connectors, the D-sub is made of two outer housings: the plug and the receptacle, each containing a series of either pins or sockets. The housings may be mounted directly to an LRU or to the end of a cable. A backshell should be

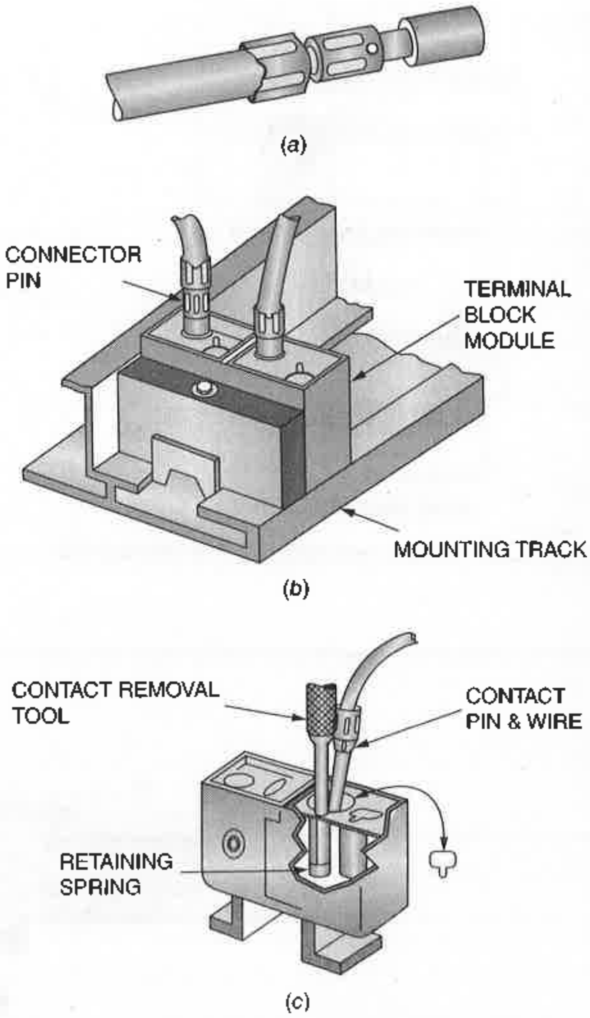


FIGURE 4-39 Terminal block module: (*a*) connector pin; (*b*) module installed on track; (*c*) contact removed.

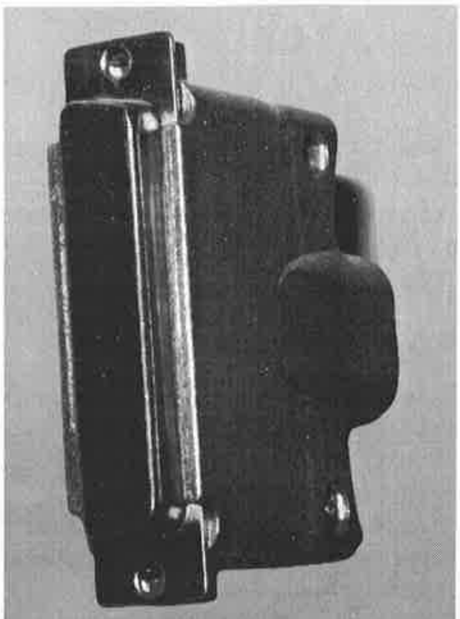


FIGURE 4-40 D-sub connector with shielded back shell.

installed to surround the wire side of all housings connected to a cable. Common D-sub connectors contain 9, 15, 25, 37, or 50 pins or sockets. Most D-sub connectors found on aircraft should conform to the MIL-DTL-24308 standard.

BONDING AND SHIELDING

Bonding

Bonding is the process of electrically connecting the various metallic parts of an aircraft to form one single electric connection. That is, there will be a very low resistance path from any one part of the structure to any other part. This is often referred to as the aircraft ground and connects all electrical circuits to the negative voltage of the battery or alternator. When the metal structure of the aircraft is used as an electrical ground (negative connection), the aircraft is said to use a single wire electrical system. Bonding also helps to reduce radio interference; to decrease the probability of lightning damage to such aircraft elements as control hinges; and to prevent the buildup of static charges between parts of the structure. Through bonding, the risk of fire due to static discharge is reduced.

A **bonding jumper** is a short length of metal braid or metal strip used to connect independent parts of the aircraft for bonding purposes. The bonding jumper wire will typically have a terminal at each end for attaching to the structure. These jumpers should be as short as practicable and installed in such a manner that the resistance of each connection does not exceed 0.003 Ω. They should also be installed in locations that provide reasonably easy access for inspection and maintenance. Care must be taken so that bonding jumpers do not interfere with the operation of any movable parts of the aircraft and so that the normal movement of such parts does not result in damage to the bonding jumpers.

When bonding jumpers are installed, it is important that all insulating coatings, such as anodizing, paint, oxides, and grease, be removed so that clean, bare metal surfaces come into contact. After the bonding is secured, it is good practice to coat the junctions with a sealing coating to prevent the entrance of moisture, which could produce corrosion. Electrolytic corrosion may occur quickly at a bonding connection if adequate precautions are not taken. Aluminum-alloy jumpers are recommended in most cases, but copper jumpers are used to bond together parts made of stainless steel, cadmium-plated steel, copper, brass, and bronze. Where contact between dissimilar metals cannot be avoided, the choice of jumper and hardware should be such that corrosion is minimized and the part likely to corrode is the jumper or hardware.

A guide to the selection of metals that can be joined without the danger of corrosion is given in the following grouping of metals. Metals in any one group may be joined with a minimum likelihood of corrosion.

Group 1. Magnesium alloys

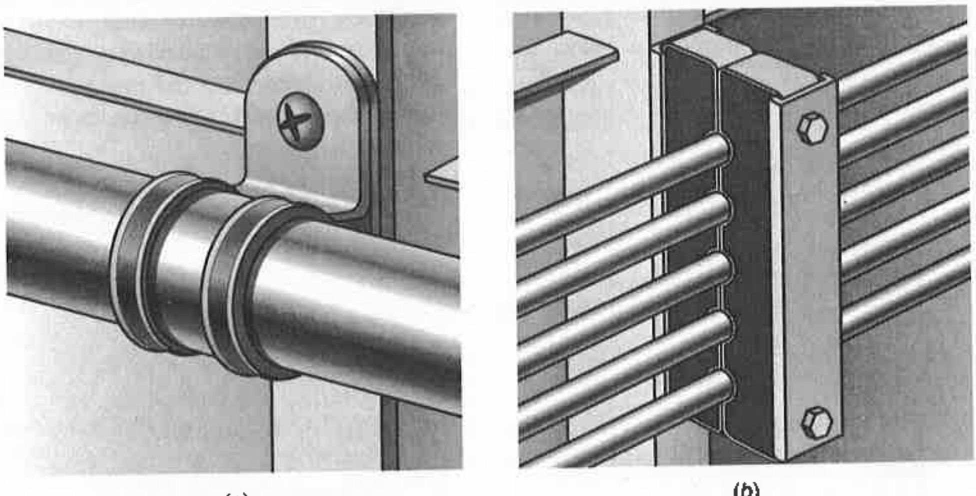
Group 2. Zinc, cadmium, lead, tin, steel

Group 3. Copper and its alloy, nickel and its alloys, chromium, stainless steel

Group 4. All aluminum alloys

The screws, washers, nuts, bolts, or other fasteners used for securing bonding jumpers must be of a material that is compatible with the metals being joined. For example, where aluminum jumpers are attached to aluminum-alloy structures, the fasteners should be made of aluminum.

The use of solder to attach bonding jumpers should be avoided for the same reasons that it is not recommended for electric wire connections. Tubular members should be bonded by means of clamps or clamp blocks as illustrated in Fig. 4-41. In this installation a thin aluminum strip lines both inner surfaces of the clamp block, and the ends of the metal strips are carried around the ends of the clamp block so that they make contact with the aircraft structure. Bonding braid may be connected between electrically separate parts of a structure as shown in Fig. 4-42. Each terminal of the bonding braid is securely attached to the sheet metal structure by means of



(a) (b)

FIGURE 4-41 Bonding for tubular members: (a) clamps and (b) clamp blocks.

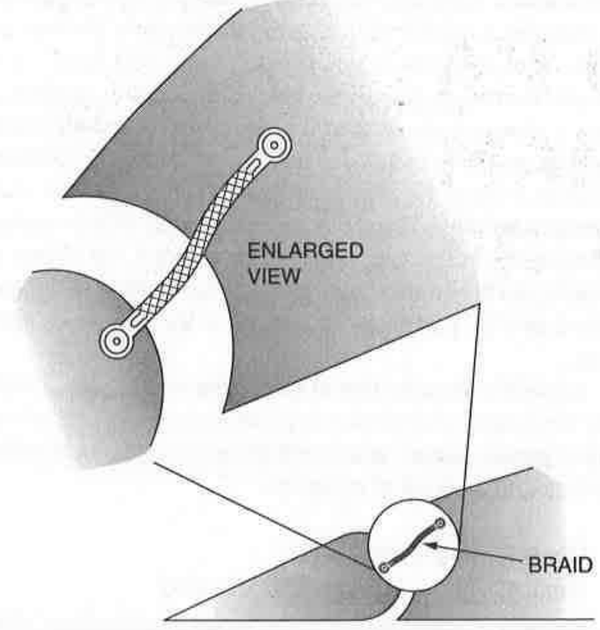


FIGURE 4-42 Installation of bonding braid.

machine screws and nuts. A typical attachment of a bonding jumper to an aluminum alloy structure is shown in Fig. 4-43.

When a bonding jumper is installed in a location where it will be required to carry a **ground load** for electric equipment, care must be taken to assure that the jumper has sufficient capacity to carry the load. This could occur when an electronic unit is mounted on shock mountings. If the equipment is grounded through the case, the ground current must be carried through the mounting structure and then through a bonding braid lo the main structure. A bonding braid too small to carry the load could overload and melt, thus creating a fire hazard and also causing the equipment to fail.

Shielding

With the increased number of highly sophisticated and extremely sensitive electronic devices found on modern aircraft, it has become very important to ensure proper shielding for many electric circuits. **Shielding** is the process of applying a metallic covering to wiring and equipment to eliminate interference caused by stray electromagnetic energy. Shielded wire (or cable) is typically connected to the aircraft's ground at both ends of the wire, or at connectors in the cable. The word *shielding* is also applied to the process of enclosing wires or electric units with metal.

As noted above, the purpose of shielding is to reduce the adverse effects of **electromagnetic interference (EMI)**. EMI is caused when electromagnetic fields (radio waves) induce unwanted voltages in a wire or component. The induced voltage can cause system inaccuracies or even failure, hence putting the aircraft and passengers at risk. Most people have experienced the adverse effects of EMI. For example, while listening to the radio, if nearby lightning strikes occur, the audio of the radio may crack, or crackle. This is caused by the electromagnetic interference caused by the current flow of the lightning. Shielding helps to eliminate EMI by protecting the primary conductor with an outer conductor, called the *shield* (see Fig. 4-44). The electromagnetic energy that would normally reach the primary conductor is induced in the shield and sent directly to the aircraft's electrical ground. In effect, the outer conductor (shields) blocks out EMI. Shielding is used anytime an LRU or related wiring must be protected from the effects of a high-frequency (HF) high-energy electromagnetic fields generated by the airborne or ground equipment. Shielding also eliminates the ability of any primary conductor or electrical unit to generate its own interference. Protecting one unit from the interference of another is called **electromagnetic compatibility.**

Shielding of a wire is typically done by surrounding the primary conductor(s) with a finely braided copper wire, as shown in Fig. 4-44. This technique provides adequate protection for most circuits; however, some very sensitive equipment may require the use of a second shield, or two braided conductors. In some cases, a thin metallic foil is wrapped around the primary conductor and used for the shield. Unfortunately, this technique increases the wire's rigidity. Another type of EMI shield is made of a composition of ferrite and polymers. Cable with this shield is lighter in weight and has good vibration resistance.

Another form of electromagnetic energy which can cause system failure is known as high-intensity radiated fields (HIRF). HIRF is caused by radio frequency energy of strength sufficient to adversely affect either a living organism or the performance of an electronic device. A microwave oven is an example of a device producing HIRF. In the case of the microwave, the HIRF energy is contained by a metal surrounding, and the oven creates no hazard.

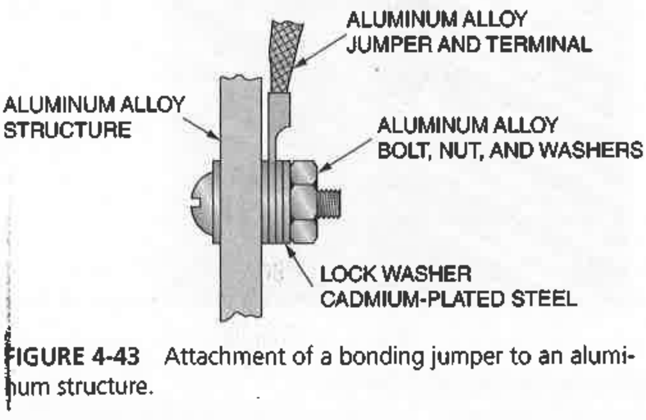


FIGURE 4-43 Attachment of a bonding jumper to an aluminum structure.

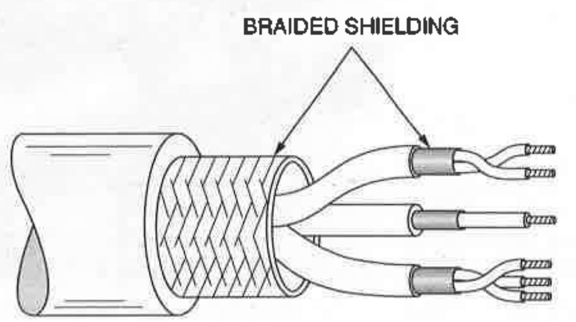


FIGURE 4-44 Shielded cable.

For aircraft, the potential dangers from HIRF can be caused by high-power, high-frequency transmitters. For example, if an aircraft flies too close to a high-power antenna, any sensitive electronic equipment on the aircraft may be adversely affected. The dangers of HIRF have existed ever since large scale radio, television, and radar signals have transmitted from earth-bound antennas. However, it was not until aircraft began to use sensitive electronic equipment that HIRF became a problem. As more sensitive computerized and digital electronics are installed on modern aircraft, additional HIRF protections must be in place.

The easiest way to protect against the dangers of HIRF is the installation of adequate shielding on all sensitive electronics. Modern aircraft use shielded cable and surround most electronic LRUs in metal housings. For example, a typical autoflight computer will contain all circuitry in a standard-size metal container, will use shielded cable for all sensitive wiring, and will be subject to rigorous HIRF testing prior to certification and installation on any aircraft.

WIRE IDENTIFICATION

To facilitate installation and maintenance, all wiring should be indelibly marked with **wire identification numbers**. Any consistent numbering system is considered adequate if the numbers are placed at each end of each section of wire and also at intervals along the wire. To accomplish this marking during aircraft assembly, the wire is usually run through a numbering machine, which stamps the numbers along the wire at specified intervals. The identification numbers and letters should clearly show the circuit in which the wire is installed, the particular wire in the circuit, the wire gage, and other pertinent information. Care must be taken when marking coaxial cable with a machine. If too much pressure is applied to the cable, it may be flattened, and this will change the electrical characteristics of the cable. Other specialty wires such as data bus cable can be damaged during the wire making process. Always consult appropriate technical data prior to making any wire.

Electric wires or cables may be identified by both numbers and letters, especially on large aircraft. For example, on a typical transport category aircraft the following letter system may be used to identify specific circuits:

(*Note*: This is an abbreviated list and most large aircraft wire numbering systems will contain greater detail.)

AC power	X
Deicing and anti-icing	D
Engine control	K
Engine instrument	E
Flight control surfaces	C
Central instrument systems	F
Fuel and oil	Q
Heating and ventilating	H
Ignition	J
Lighting	L
Miscellaneous electrical	M
Power (DC)	P
Radio navigation and communication	R
Warning emergency devices	W

Numbers used along with the letters for identification also have a specific purpose. In the identification number 2P281C-20, there are two letters and three separate numbers. The number 2 indicates that the wire is associated with the No. 2 engine, and the letter *P* means that the wire is a part of the electric power system. The number *281* is the basic wire number and remains unchanged between the electric units of any particular system regardless of the number of junctions the wire may have. The letter *C* identifies the particular section of wire in the circuit, and the number *20* indicates the gage of the wire. Figure 4-45 shows three sections of wire just described. Here, it can be seen that the basic wire number remains constant and only the second letter (A, B, or C) will change. The letter *A* designates the first wire segment in the circuit, the letter *B* indicates the second wire segment of the circuit, and the letter *C* indicates the third segment of the circuit. The individual segments of wire are created when the circuit must travel through an electrical connector.

On large, complex aircraft, the wire-numbering system may also include a **wire bundle code** to identify which bundle contains a specific wire. This system helps the technician to find the desired wire quickly without searching individual bundles. The above system is only an example of a typical wiring code; many different systems have been devised by manufacturers. It is therefore very important to be familiar with the wiring code of the aircraft currently being serviced. Most manufacturers include a wire code explanation in the maintenance manual for each aircraft.

Identification markings are often stamped directly on the insulation of the wire or cable. During aircraft construction, individual wires are marked using a wire marking machine. The wires are then assembled into one or more bundles to form what is typically called a **wire harness**. The entire wire harness is then installed as the various components of the aircraft are assembled. A typical large aircraft will contain many individual wiring harnesses that will contain multiple wire bundles. Many aircraft maintenance facilities that perform major retrofits or large electrical installations will also use a wire marking machine during the manufacture of a wire harness.

Wire markings are placed 3 in. [7.6 cm] from any termination point on a wire or cable and then consecutively every 15 in. [38.1 cm] along the wire. Once again at the opposite end of the wire, an identification marking must be within

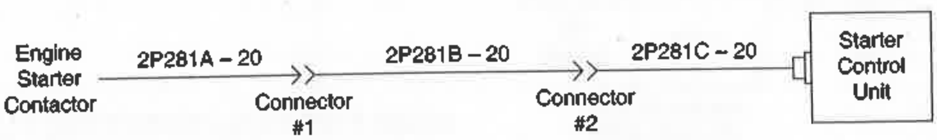


FIGURE 4-45 Three segments of the same wire A, B & C.

3 in. of the wire end. Wires that are 3 to 7 in. long should be marked at the midpoint of the wire.

Many older wire marking machines use a heat process to stamp letters and numbers on the outer insulation of a wire. In some cases this type of wire marking has led to deterioration of the wire insulation due to the excess heat during the number stamping process. There are specific guidelines for the use of hot-stamp wire marking machines, and the technician must follow them carefully during any wire marking. Other wire-marking techniques, which are less damaging to the wire insulation have been developed and have replaced many of the hot-stamp machines.

Specially designed inkjet and laser printers are now available for wire marking and are considered to be much safer because, if used correctly, they do not stress the wire insulation during the marking process. These modern wire marking machines are now used in most aircraft applications. Keep in mind, each type of wire and machine has specific characteristics that determine how the wire can be labeled. Always check the capability between the wire to be marked and the equipment used for wire marking.

If the outer coating or surface of a wire sheath is such that it cannot be easily marked, sleeving or tubing can be marked and placed over the wire. High-temperature wires, shielded wiring, multiconductor cable, and thermocouple wires usually require special sleeves to carry identification marks. Metallic sleeves or bands must not be used on electric wires.

Wire harnesses are often identified by number to indicate the particular section installed in a system. These harnesses are identified by means of a marked sleeve or pressure-sensitive tape. Methods of marking wires and harnesses are shown in Fig. 4-46.

The use of heat shrink tubing for marking wire has become common in many aircraft maintenance facilities due to the low cost of the equipment and ease of installation. Typically, if only a few wires are being installed in an aircraft this method of wire marking is preferred. For larger installations, laser printers are typically used. Figure 4-47 shows a portable heat shrink tubing marker. The desired wire number is first printed onto a heat shrink tube. One or more printed tubes are then slid over the wire end as needed. The last step to complete the wire marking would be to shrink the tubing using a low-temperature heat gun.

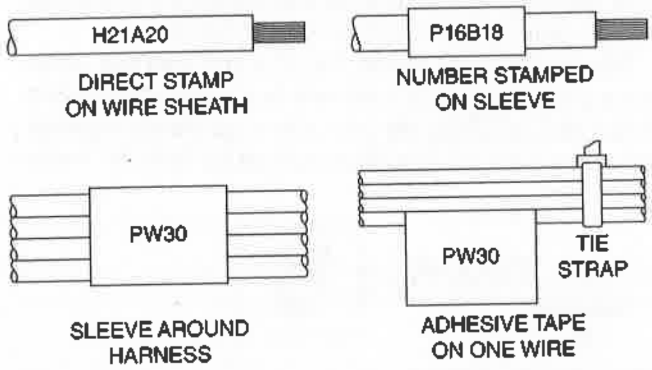


FIGURE 4-46 Methods of marking wires and harnesses.

FIGURE 4-47 Wire marking machine for heat shrink tubing.

When wires are installed in an aircraft for an additional circuit or when existing wires are replaced, the technician should always add lables with the appropriate code. The original wire-marking identification is to be retained whenever possible. The installation of wires with correct labels will facilitate any future maintenance or service activities.

Wiring and Schematic Diagrams

During the design, manufacture, and repair of electrical systems, it is imperative to understand the various current paths and types of wire being used in each system. For this purpose electrical **diagrams**, or **schematics**, are included in the maintenance and installation data for the aircraft's electrical systems. The schematics use various symbols to represent different types of wire and connections within a circuit. A schematic can be thought of as a "road map" that helps technicians to find their way around an electric circuit. In many cases wire identification numbers are also included on the electrical schematic.

If two wires are shown to intersect on a schematic, it does not always mean that they are electrically connected. On a wiring diagram there are two common ways to show electric wires that intersect. Two wires that intersect on the schematic and *do not* connect in the actual circuit are shown in Fig. 4-48*a*. Two wires that intersect on the wiring diagram and *do* form an electrical connection are shown in Fig. 4-48*b*.

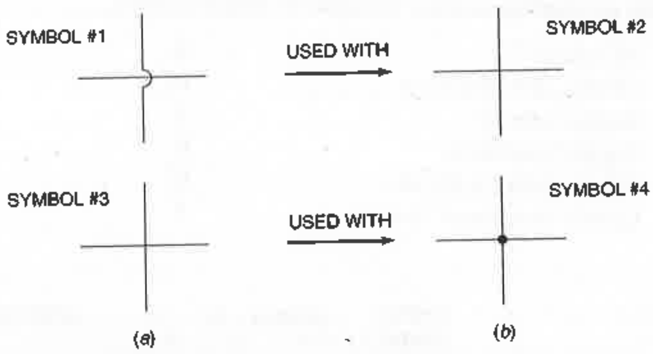


FIGURE 4-48 Wiring diagram symbols for electric wire. (*a*) Wires without an electrical connection; (*b*) wires with an electrical connection.

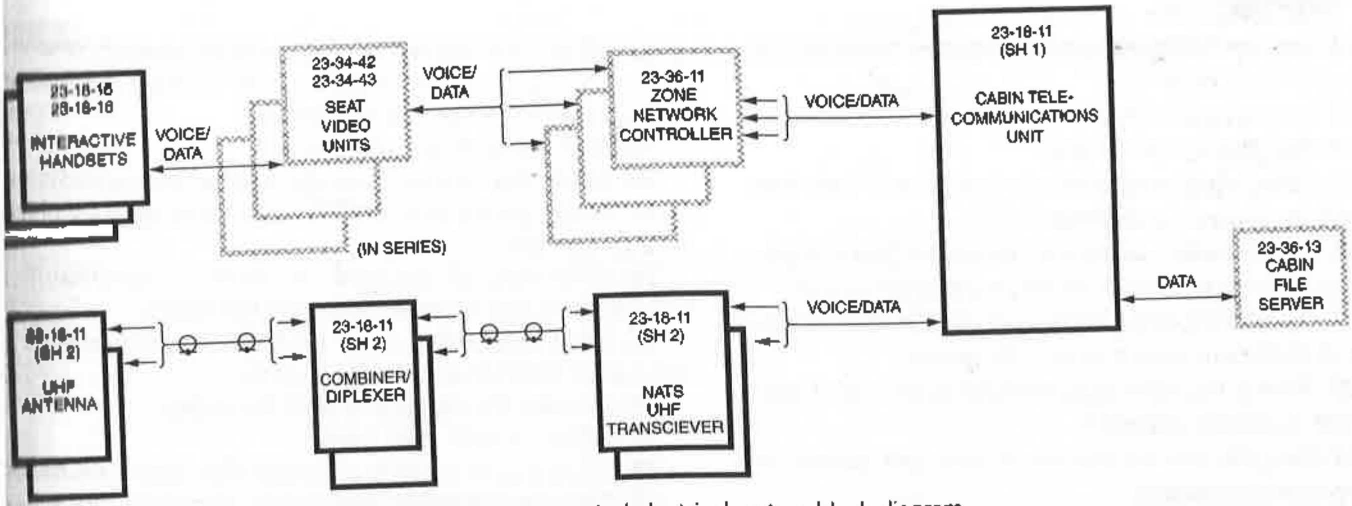


FIGURE 4-49 A typical electrical system block diagram.

To eliminate confusion, symbols 1 and 2 are always used together on a specific schematic and symbols 3 and 4 are used together. To further your understanding of wiring schematics, review the set of schematic symbols found in the Appendix of this text.

For most schematics a single wire is represented by a solid black line. Shielded cable is typically shown with a dotted line surrounding a solid line; this represents one conductor inside another. An electrical ground symbol means the wire is terminated at the metal structure of the airframe. On composite aircraft, the ground symbol may mean that the wire is terminated at a central location of the aircraft, which is then connected to the negative terminal of the battery. Symbols for plugs, wire connections, and other items can vary from the examples shown in the Appendix, so be sure to refer to the manufacturer's data prior to maintenance on any electrical system. Refer to Chap. 13, "Design and Maintenance of Aircraft Electrical Systems," for more information on schematics.

Electrical diagrams are another common means to display the layout of electrical circuits. **Diagrams** are typically more general in nature than electrical **schematics**; that is, diagrams offer a broad overview of a system and schematics provide specific detail. One common type of diagram is known as a **block diagram.** The term **block** indicates the general nature of a block diagram. As seen in Fig. 4-49, a typical block diagram shows the major components of an electrical system and eliminates details such as wire numbers or pin connections which are typically included in a wiring schematic. Although most aircraft manufactures follow specific rules for developing electrical diagrams and schematics, many individuals often use the terms interchangeably. Both, a diagram and a schematic offer technicians' valuable information concerning electrical components and systems. Whenever performing aircraft maintenance, always become completely familiar with all electrical diagrams and schematics for the system being maintained. As with general practice, this text will use the terms diagram and schematic interchangeably unless otherwise stated at the time.

REVIEW QUESTIONS

1. What properties make aircraft wire special?
2. Why is aircraft wire stranded?
3. What types of materials are used for wire insulation?
4. Describe shielded wire or cable.
5. What is the maximum allowable temperature for silver-coated copper wire?
6. What is the maximum allowable temperature for aluminum wire?
7. What is a coaxial cable?
8. How is the cross-sectional area of a wire indicated?
9. Describe the method used to determine a wire size using a wire gage tool.
10. What voltage drop is allowed for a 115-V system in a continuously operating circuit?
11. What size of copper wire should be used in a 28-V circuit for a 10-A continuous load when the wire is in a conduit and the distance from the bus to the load is 20 ft [6.1 m]?
12. What is the minimum bend radius for a wire bundle?
13. What can be done to protect wire and wire bundles from abrasion?
14. Describe a satisfactory method for wire-bundle lacing.
15. Describe an approved clamp for wire bundles.
16. Describe how wire bundles should be routed in an aircraft.
17. Describe electrical conduit.
18. When it is impractical to separate an electric wire from a line carrying flammable fluids; where should the wire be located with respect to the fluid line?
19. Describe typical terminals used with aircraft electric wire or cable.
20. Describe the use of wire strippers.
21. Why is it important to use specific types of crimping tools when installing wire terminals?

22. Why are soldered terminals not recommended for aircraft electric systems?

23. How may aircraft wires be spliced?

24. Describe a terminal strip.

25. What is the maximum number of terminals that should be attached to a single stud?

26. When electric wires pass through holes in bulkheads, what protection must be provided and why?

27. Discuss the precautions necessary in the installation of aluminum wire in an aircraft system.

28. What is the advantage provided by the use of connectors in electric systems?

29. Describe the installation of pins and sockets in crimp-type connectors.

30. Explain the purposes of bonding in an aircraft.

31. What is the maximum resistance permitted for a bonding connection?

32. Describe the procedure for installing a bonding jumper.

33. What is the requirement for a bonding jumper that must carry a ground load for a unit of electric equipment?

34. What is the purpose of shielding?

35. How is shielding accomplished?

36. Explain how electric wires are identified in a system.

37. Where should wire identification marks be placed on a wire or bundle?

38. What methods are used for attaching identification numbers and letters to wires and harnesses?

39. What precautions must be taken for any wires installed in SWAMP areas of the aircraft?

40. Describe the purpose of *data bus cable*.

41. What is a *fiber optic cable*?

42. What aircraft are likely to contain fiber optic cable?

43. Describe the safety precautions necessary when working with fiber optic cable.

44. Describe how some wire splice connectors are designed to be moisture resistant.

45. What is a D-sub connector?

46. Describe the purpose of a block diagram.

Alternating Current 5

INTRODUCTION

A thorough understanding of alternating current is becoming increasingly important to aviation maintenance technicians, aircraft engineers, electronic or avionics specialists, as well as pilots. Modern aircraft utilize alternating current for a variety of systems during both flight and ground operations.

The trend in aircraft design has been to increase the number of onboard electrical systems and the use of alternating current (ac).

Large transport category aircraft employ ac power systems, which typically supply more than one voltage. For example, both 26 and 115 V ac are commonly used on aircraft; and the Boeing 787 aircraft employ ac generators which produce 235 V ac.

The advances in modern electronics have made it possible for even light, single-engine aircraft to maintain small ac power systems. Most of the electrical systems found on large aircraft operate on ac, although a direct current (dc) system is also used. The dc emergency system must be maintained because technology has yet to produce an ac storage battery, and a battery may be the sole power source during emergency situations. In the future, however, one might find aircraft powered totally by ac systems, including emergency backups.

Some of the units operated by alternating current in airplanes are instruments, fluorescent lights, radio equipment, electric motors, navigation equipment, and automatic pilots. This list does not include all the devices that are or may be operated by alternating current, nor is it intended to indicate that all types of the above-named devices require alternating current.

DC electrical power on transport category aircraft is used for specific systems, as well as emergency hookup. In many cases a component or system may operate on dc internally yet receive ac from the power distribution systems. The component would then convert the ac power into dc power for internal use.

A good knowledge of the principles of alternating current is essential for the understanding of various electric devices. This is especially true with regard to ac electric motors, alternators, and transformers. This chapter explains the nature of alternating current and many of its characteristics and uses.

DEFINITION AND CHARACTERISTICS

Alternating current is defined as current that periodically changes direction and continuously changes in magnitude. (Remember, current is defined as the movement of electrons.) The current starts at zero and builds up to a maximum in one direction, then falls back to zero, builds up to a maximum in the opposite direction, and returns to zero. In like manner, the voltage attains a maximum in one direction, drops to zero, rises to a maximum in the opposite direction, and then returns to zero. Voltage (electrical pressure) does not actually flow; therefore, when voltage changes direction, the positive and negative values simply reverse. That is, the voltage polarity of the circuit reverses.

It is difficult for some students to visualize the nature of alternating current, but there are many common devices that can be used to illustrate this principle. First, consider reciprocating (moving back and forth) devices such as a carpenter's saw, a connecting rod in a piston engine, or the pendulum in a clock. Each of these devices performs useful work with a reciprocating motion. Figure 5-1 shows a hydraulic analogy

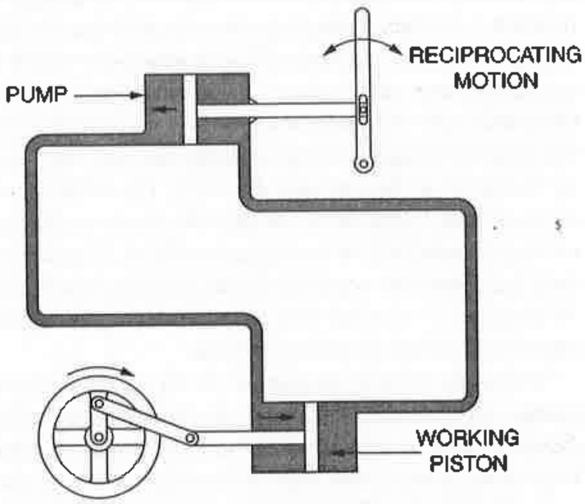


FIGURE 5-1 Hydraulic analogy of alternating current.

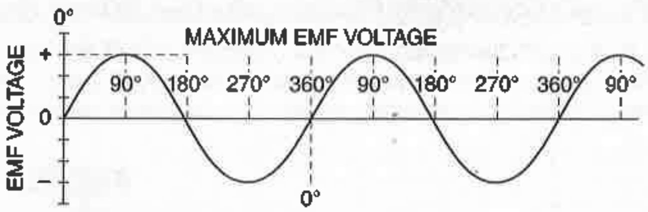


FIGURE 5-2 A sine curve.

of an ac circuit performing work. The pump forces the fluid back and forth in the pipes and causes the working piston to move back and forth. This piston is connected to a crankshaft, which converts the reciprocating motion of the piston into the rotary motion of the flywheel.

Values of alternating current and voltage are indicated by a **sine curve or sine wave.** In Fig. 5-2, this curve represents a definite voltage or current value for a certain degree of rotation through the alternating cycle. One cycle begins at 0° and ends at 360°. The value of the alternating current is zero at 0°, maximum in one direction at 90°, zero at 180°. maximum in the opposite direction at 270°, and zero at 360°, as shown in the sine curve. The values of 360° and 0° along the horizontal axis of the sine wave are virtually identical. At 360° (0°), one cycle ends and the next cycle begins.

For practical purposes, the values of an alternating current can be considered to follow the sine curve. This can be understood by considering the generation of alternating current by a simple generator (see Fig. 5-3). A single loop of wire is placed so that it can be rotated in a magnetic field. As the loop is turned, the sides of the loop cut through the lines of force, and an electromagnetic force (emf) is induced in the sides of the loop. At position 1 the conductor moves parallel to the flux lines as the loop rotates in a clockwise direction. The voltage increases as the loop moves from position 1 to position 2. At position 2 the induced voltage is at a maximum value. This occurs because the loop is moving perpendicular to the flux lines. As the conductor moves beyond position 2, the voltage decreases. The voltage once again reaches zero at position 3. One-half of a revolution has been completed at position 3. As the conductor passes this position, the induced voltage reverses. This reversal occurs because side B of the conductor loop now moves down and side A moves up. Originally, side A moved down and side B moved up; hence, the induced voltage reverses polarity because the flux lines are being cut in the opposite direction. The negative voltage increases until position 4 and then decreases as the conductor loop travels back to its original position. At position 5 the loop has made one complete cycle, and the process repeats. At position 5 it can be seen that the rotating loop has produced a sine wave of voltage-values.

When the current is carried to an external circuit by means of slip rings, it travels in one direction while the loop moves from 0 to 180°, and in the other direction while the loop moves from 180 to 360°. When it is horizontal, the loop is in either the 0 or 180° position, and no voltage is induced. When the loop is in a vertical position, the maximum voltage is induced because at this time the sides are cutting the greatest number of lines of force.

It has been found that the instantaneous value of the voltage induced in a loop as it rotates in a magnetic field is proportional to the sine of the angle through which the loop has rotated from 0°. Hence, we use the sine curve to represent the values from 0 to 360°. The value of either the voltage or the amperage can be represented in this manner.

As illustrated in Fig. 5-3, the sine wave is above the horizontal axis as current travels in one direction and below the horizontal axis as current travels in the other direction. Often the values above the curve are considered positive and values below the curve, negative. The assignment of positive and negative is completely arbitrary; however, they do represent a change in the direction of current flow. This concept of changing direction can also be applied to the voltage of an ac circuit.

RMS, or Effective, Values

In order to determine the amount of power available from an alternating current, we must arrive at its effective value. It is obvious that effective value does not equal maximum value, because maximum value is attained only twice in the cycle. Even though the current during one half-cycle is equal and opposite in direction to that during the other half-cycle, the currents do not cancel each other; work is done whether the current is moving in one direction or the other. Therefore, the effective value must lie somewhere between the zero value and the maximum value.

The effective value of an alternating current is calculated by comparing it with direct current. The comparison is based on the amount of heat produced by each current under identical conditions. Since the heat produced by a current is proportional to the square of the current ($P = I^2R$), it is necessary to find the square root of the mean square of a number of instantaneous values. The resultant value is called **the root-mean-square (rms)** current. In other words, all the instantaneous values of the sine wave are squared, the results are added together, and the mean is determined. The square root of the mean is equal to the effective voltage. For all general-purpose applications, the effective voltage or current can be determined using the following equations:

$$E_{eff} = 0.707 \times E_{max}$$

$$I_{eff} = 0.707 \times I_{max}$$

Conversely,

$$E_{max} = 1.414 \times E_{eff}$$

$$I_{max} = 1.414 \times I_{eff}$$

In all practical applications of alternating current, the values of voltage, or current, are stated according to their effective values rather than the maximum values. For example, when the voltage is given as 110 V, the maximum value of the voltage is 1.414 × 110 V = 155.6 V. Keeping this in mind, technicians should always make certain that any instrument

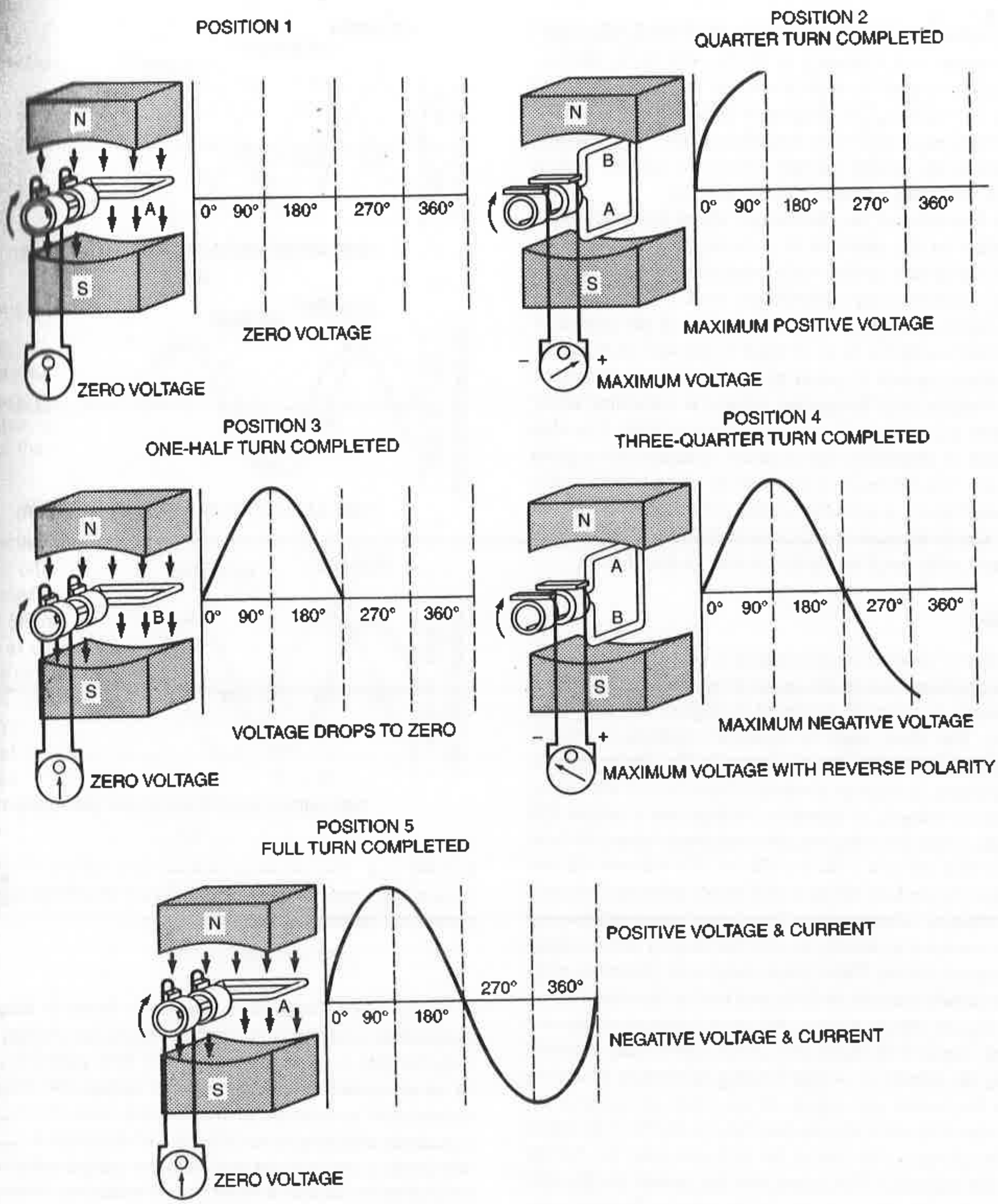


FIGURE 5-3 A simple ac generator.

or equipment connected to an ac electrical circuit is rated for the appropriate voltage and current ratings.

Frequency

It has been explained that one cycle of alternating current covers a period in which the current value increases from zero to maximum in one direction, returns to zero, increases to maximum in the opposite direction, and then returns to zero. The number of cycles occurring per second is the **frequency** of the current and is measured in a unit called the **hertz**, named for Heinrich Rudolph Hertz, a German physicist of the late nineteenth century who made a number of important discoveries and valuable contributions to electrical science. One hertz (Hz) is equal to 1 cycle per second [1 cps]. The terms **kilohertz**, **megahertz**, and **gigahertz** are often used when describing radio frequencies and computer processor speeds. One kilohertz is equal to 1000 Hz, and one megahertz is equal to 1 000 000 Hz, and one gigahertz is equal to 1 000 000 000 Hz.

City lighting and power systems in the United States generally operate at a frequency of 60 Hz, 100 Hz in Europe. Alternating currents in airplane circuits usually have a frequency of 400 Hz. This frequency is commonly used for modern aircraft as well as for a number of other applications.

Some of the newest aircraft operate ac systems with a variable frequency between 360 and 800 Hz.

The frequency of an alternating current has a considerable effect on the operation of a circuit, for many units of electric equipment operate only on current of a certain frequency. Wherever such equipment is used, it is important to make sure it is designed for the frequency of the current in the circuit in which it is to be used. Units such as synchronous motors operate at speeds proportional to the frequency of the current, even though the voltage is somewhat lower or higher than the rated voltage of the machine. It is also important to remember that a circuit designed for a given frequency may be easily overloaded by using a current of a different frequency, even though the voltage may remain the same. This is because of effects of inductive and capacitive reactance, which will be explained later in this chapter.

Phase

The phase of an alternating current or a voltage is the angular distance between two points on an ac wave form. The angular distance is typically measured in degrees of rotation, or degrees. The phase angle in electrical equations is usually represented by the Greek letter theta (θ). The **phase angle** is the difference in degrees of rotation between two alternating currents or voltages, or between a voltage and a current. For example, when one voltage reaches maximum value 120° later than another, there is a phase angle of 120° between the two voltages. Figure 5-4*a* shows a 120° phase difference between three different voltage curves. This type of phase relationship is very common in aircraft circuits that employ a three-phase ac electrical system. Three-phase systems are known as **polyphase circuits** and will be discussed later in this chapter.

In most ac circuits a phase shift exists between voltage and current. Figure 5-4*b* shows sine curves representing a current lagging the voltage, or voltage leading the current. In circuits where the current and voltage do not reach maximum at the same time, they are said to be *out of phase*. In Fig. 5-4*b*, notice that the current wave crosses the zero axis after the voltage wave has crossed it. This means that the current reaches zero at the same time, after voltage. In like manner, the peak value of current occurs after the peak value of voltage. For this reason we know that the current is lagging the voltage by several degrees.

Current is said to be "lagging" because it reaches all respective values sometime after voltage. The lag time is traditionally measured in degrees. In Fig. 5-4c, it will be seen that the voltage is approximately 90° out of phase with the current. That is, the voltage follows the current by approximately 90°.

Capacitance in AC Circuits

Capacitance can be defined as the ability to store an electric charge. Most capacitance in a circuit is created by a device called a **capacitor**. Capacitor theory is discussed in detail in Chap. 6; that section should be studied carefully to gain a full understanding of how capacitors react in an ac circuit. In short, capacitors oppose the change of current flow in a circuit. In an ac circuit, since the current is constantly changing in magnitude and direction, a capacitor will create a constant opposition to the applied current. This opposition to current is similar to a resistance; however, it also creates a phase shift within the circuit. (Resistance creates no phase shift.)

When a capacitor is connected in series in an ac circuit, it appears that the alternating current is passing through the capacitor. In reality, electrons are stored first on one side of the capacitor and then on the other, thus permitting the alternating current to flow back and forth in the circuit without actually passing through the capacitor.

A hydraulic analogy can be used to explain the operation of a capacitor in a circuit (see Fig. 5-5*a*). The capacitor is represented by a chamber separated into two sections by an elastic diaphragm. The ac generator is represented by the piston-type pump. As the piston moves in one direction, it

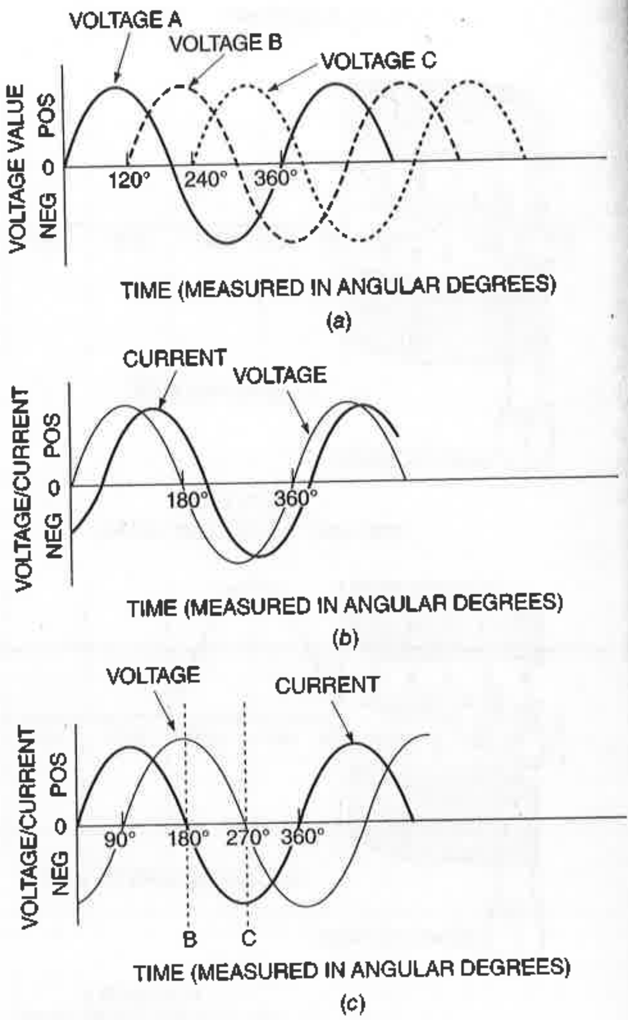


FIGURE 5-4 Out-of-phase voltage and current curves: (*a*) voltage curves of a three-phase circuit; (*b*) voltage leads current; (*c*) current leads voltage.

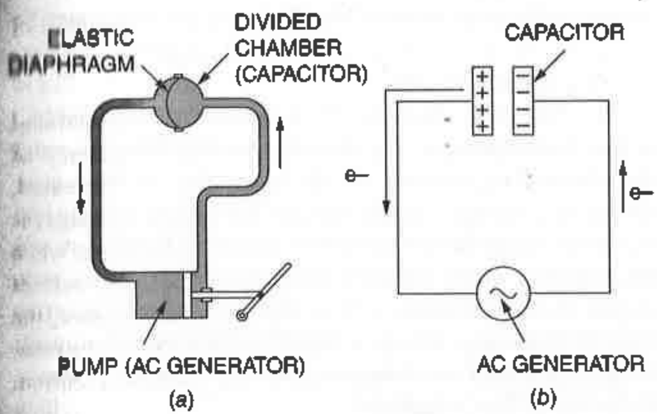


FIGURE 5-5 Hydraulic analogy of a capacitor. (*a*) The hydraulic pump forces fluid into the right side of the divided chamber; (*b*) the ac generator forces electrons into the right side of the capacitor.

forces fluid into one section of the chamber and draws it out of the other section. The fluid flow represents the flow of electrons in an electric circuit. Thus it can be seen that there is an alternating flow of fluid in the lines and that work is done as the fluid moves back and forth, first filling one side of the chamber and then the other.

As seen in Fig. 5-5*b*, the operation of a capacitor in an ac circuit is for all practical purposes identical to the operation of the chamber just described. The electrons build up on one plate of the capacitor, and this negative charge forces the electrons to flow away from the other plate. As the ac current reverses direction, the capacitor is charged with the polarity reversed. With each ac cycle, as voltage from the source begins to drop, the current starts to flow out of one plate of the capacitor and into the other; and this cycle repeats as long as the current is flowing.

This constant charging and discharging of the capacitor creates an electrostatic field and dielectric stress within the capacitor. A **dielectric** is an insulating material used to separate the plates of a capacitor. The dielectric stress is similar to the stress of the elastic diaphragm of the hydraulic circuit (Fig. 5-5*a*). The dielectric stress creates a force that opposes the applied current. In other words, the capacitor will create a current flow in the opposite direction of the applied current. This current flow has two effects on the circuit: (1) it opposes, or "resists," the applied current, and (2) it creates a **phase shift** between voltage and current.

The phase shift in capacitive circuits causes the current to lead the voltage. This phase shift causes current to reach its maximum and minimum values before the voltage of the circuit. If it were possible to have a circuit with only capacitance and no resistance, the current would lead the voltage by 90° (Fig. 5-4*c*). Studying Fig. 5-4*c*, it can be seen that as the voltage rises, the current begins to drop because of the dielectric stress in the capacitor. This, of course, means that opposition to the flow of current is developing. By the time the voltage has reached its maximum value, the capacitor is completely charged; hence no current can flow. At this point *B* the current has a value of zero. As the voltage begins to drop, the current flows out of the capacitor in the opposite direction because the potential of the capacitor is higher than the potential on the applied voltage. By the time the voltage has dropped to zero, the current is flowing at a maximum rate because there is no opposition. This point on the curve is represented by the letter *C*.

It must be remembered that the above action takes place only when there is no resistance in the circuit. Since this is impossible, a circuit in which the current leads the voltage by as much as 90° does not exist. However, the study of such a circuit gives the student a clear understanding of the effect of capacitance. In an ac circuit where both capacitance and resistance are present, the phase shift will be between 0 and 90°.

The effects of capacitance in ac circuits are most pronounced at higher frequencies. Modern electronic circuits often produce frequencies of many millions of cycles per second (Hz). For this reason special types of electronic and electric devices and equipment have been designed to reduce the effects of capacitance where these effects are detrimental to the operation of the circuit.

Capacitive Reactance

If capacitance is considered the *ability* to oppose changes in current flow, then **capacitive reactance** is the *actual* opposition to current flow in a given ac circuit. Since capacitive reactance opposes the flow of current in ac circuits, it is measured in ohms. It should be noted that capacitive reactance also creates a phase shift in the circuit and therefore cannot be thought of as resistance. Capacitive reactance is represented by X_C and is a function of both the circuit's ac frequency and the total capacitance.

The capacitive reactance in a circuit is inversely proportional to the capacitance and the ac frequency. This is because a large-capacity capacitor will take a greater charge than a low-capacity capacitor; hence, it will allow more current to flow in the circuit. If the frequency increases, the capacitor charges and discharges more times per second; hence, the change in current flow becomes more rapid. From the following equation for capacitive reactance, it can be seen that reactance will decrease as capacitance or frequency increases.

The formula for capacitive reactance is

$$X_C = \frac{1}{2\pi f C}$$

where X_C = capacitive reactance, Ω
f = frequency, Hz
C = capacitance, F

To determine the capacitive reactance in a circuit in which the frequency is 60 Hz and the capacitance is 100 μF, substitute the known values in the formula. Then

$$X_C = \frac{1}{2\pi \times 60 \times 100 / 1000000}$$

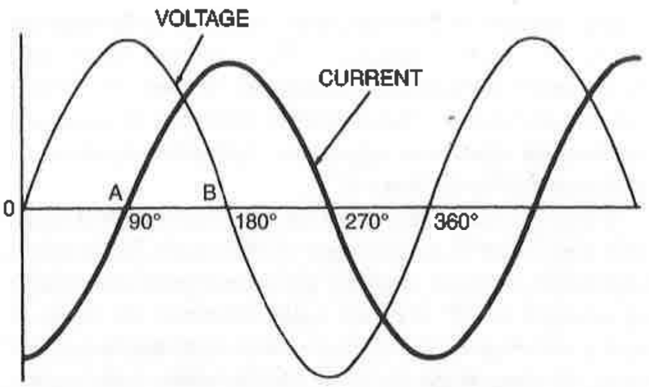


FIGURE 5-6 Current lagging voltage.

Remember that 1 μF is one-millionth of a farad; hence, 100 μF is equal to 100/1 000 000 F. Therefore,

$$X_C = \frac{1}{6.283 \times 0.006} = \frac{1}{0.037698} = 26.5\ \Omega$$

Inductance in AC Circuits

The effect of **inductance** in ac circuits is exactly opposite to that of capacitance. Capacitance causes the current to lead the voltage, and inductance causes the current to lag. Figure 5-6 shows the voltage and current curves for a purely inductive circuit. In order to completely understand the effects of inductive reactance, one should first study the section discussing the inductance coil in Chap. 6.

According to **Lenz's Law**, whenever a current change takes place in an inductance coil, an emf (voltage) is induced that opposes the change in current. The induced voltage will then be maximum when the rate of current change is the greatest. Since the current change is most rapid in an ac circuit when the current is passing through the zero point, the induced voltage will be maximum at this same time, marked *A* in Fig. 5-6. When the current reaches maximum, there is momentarily no current change, and hence the induced voltage is zero at point *B*. Remember, to induce a voltage in any circuit, there must be a current change; thus a "moving" magnetic field is created around the inductor coil. So at point *B*, where there is no rapid current change, there will be no induced voltage. This effect causes the current to lag the voltage by 90° in a purely inductive circuit. But since a purely inductive circuit is impossible because there is always resistance present, the current lag of 90° is purely theoretical. In an ac circuit where both resistance and inductance are present, the current will lag the voltage somewhere between 0 and 90°.

Inductive Reactance

The effect of inductance in an ac circuit is called **inductive reactance** and is measured in ohms because it "resists" the flow of current in the circuit. **Inductive reactance (X_L) *is the actual* opposition to current flow created by inductors in an ac circuit.** Inductance *L* is the ability of a coil to oppose changes in current flow. The inductive reactance of any given circuit is a function of the ac frequency and the inductance of that circuit.

The inductive reactance in a circuit is proportional to the inductance of the circuit and the frequency of the alternating current. As the inductance is increased, the induced voltage (which opposes the applied voltage) is increased; hence the current flow is reduced. Likewise, when the frequency of the circuit is increased, the rate of current change in the inductance coil is also increased; hence, the induced (opposing) voltage is higher and the inductive reactance is increased. As inductive reactance increases, current in the circuit flow is reduced.

We can clearly see that the effects of capacitance and inductance are opposite, since inductive reactance increases as the frequency increases and capacitive reactance decreases as the frequency increases. The formula for inductive reactance is

$$X_L = 2\pi f L$$

where X_L = inductive reactance, Ω
f = frequency, Hz
L = inductance, H

Let us assume that an inductance coil of 7 H is connected in a 60-Hz circuit and it is necessary to find the inductive reactance. By substituting the known values in the formula,

$$X_L = 2 \times 3.1416 \times 60 \times 7 = 2638.94\ \Omega$$

Combining Resistance, Capacitance, and Inductance

In practical applications found on a typical aircraft, there are various components that have resistance, capacitance, and inductance. In that case the circuit is known as an **RCL** circuit. A circuit containing only resistance is called a **resistive circuit (R)**. Other circuits are known as **resistive inductive (RL)**, and **resistive capacitive (RC)**. Each name describes the types of elements that are contained in the circuit. For example, an RC circuit contains both resistive units and capacitive units. For any circuit that is not purely resistive, the total opposition to current flow is called *impedance*. As noted earlier, all circuits contain some resistance, inductance, and capacitance; however, in some cases the inductance and capacitance effects are considered negligible.

And of course, there is no inductive or capacitive reactance in a dc circuit. In a dc circuit frequency (F) is equal to 0; therefore, X_L and X_C are also equal to zero.

IMPEDANCE

In the study of Ohm's law for dc circuits, it was found that the current in a circuit was equal to the voltage divided by the resistance. In an ac circuit it is necessary to consider capacitive reactance and inductive reactance before the net current in such a circuit can be determined. The combination of resistance, capacitive reactance, and inductive reactance is called **impedance**, and the formula symbol is Z.

It might appear that we could add the capacitive reactance, inductive reactance, and resistance to find the impedance, but this is not true. Remember that capacitive reactance and inductive reactance have opposite effects in an ac circuit. For this reason, to find the total reactance we use the difference in the reactances. If we consider inductive reactance as positive, because inductance causes the voltage to lead the current, and capacitive reactance as negative, because it causes the voltage to lag, then we can add the two algebraically; that is,

$$X_L + (-X_C) = X_t \quad \text{or total reactance}$$

Now it might appear that we could add this result to the resistance to find the impedance, but again we must consider the effect of resistance in the circuit. We know that resistance in a circuit does not cause the current to lead or lag, and for this reason its effect is 90° ahead of inductance and 90° behind capacitance. Therefore, it is necessary to add resistance and reactance vectorially.

A vector is a quantity having both magnitude and direction. Vectors are often represented graphically by a line pointing in a given direction. Vectors may be used to represent a given force. The strength of the force is indicated by the length of the line representing the vector. The values for X_L, X_C, and R can be represented using a vector diagram as illustrated in Fig. 5-7*a*. Resistance is always shown on the horizontal axis, inductive reactance on the vertical axis pointing up, and capacitive reactance on the vertical axis pointing down. As illustrated, it is easy to see that the effects of X_L and X_C cancel each other, and the effects of resistance are 90° from either reactance. As demonstrated in Fig. 5-7*b*, using vector addition, the three vectors X_L, X_C, and R can be combined into one resultant vector called *impedance* (Z). The length of the impedance vector can be determined graphically or algebraically. The Pythagorean theorem, $A^2 + B^2 = C^2$, can easily be applied to solve for Z; that is,

$$X_t^2 + R^2 = Z^2$$

or

$$Z = \sqrt{R^2 + X_t^2}$$

Substituting for X_t,

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

This formula is typically used to solve for Z or an unknown R or X value. It should be noted that this formula can be applied to determine the impedance in *series* circuits only. That is, the total values of resistance, capacitance, and inductance must be in series with each other, as shown in Fig. 5-8. The equations for parallel circuits will be discussed later.

After the impedance is found in an ac circuit, the other values can be found by Ohm's law for alternating current. In this formula we merely substitute the symbol Z, meaning impedance, for the normal symbol R, meaning resistance. The formula then reads

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

Sample Problem. If a series ac circuit contains an inductor with inductive reactance X_L equal to 12 Ω, a capacitive reactance X_C of 18 Ω, a resistance R of 5 Ω, and an applied voltage of 120 V, what is the current flow through that circuit?

Solution. In an ac circuit, $I = E/Z$; therefore, the value for Z must be determined.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$
$$= \sqrt{5^2 + (12-18)^2}$$
$$= \sqrt{25+36}$$
$$= 7.8\Omega$$

Note: Always subtract X_C from X_L, then square the result; $X_L - X_C$ may produce a negative number. This negative number will become positive when it is squared.

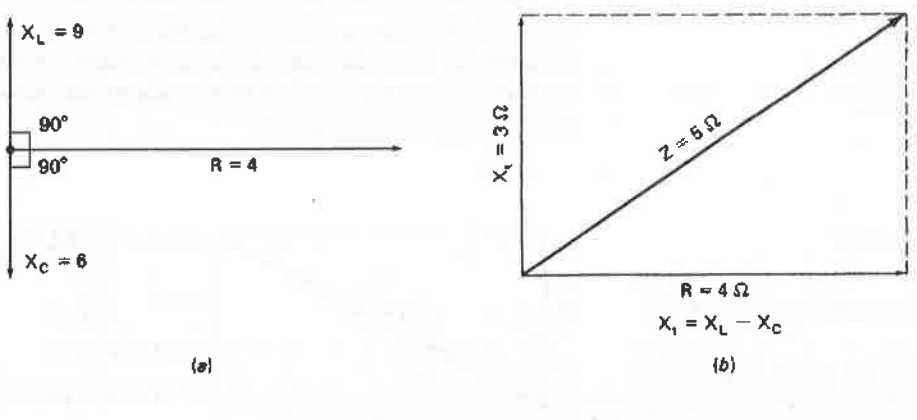


FIGURE 5-7 Vector diagrams of resistance, reactance, and impedance.

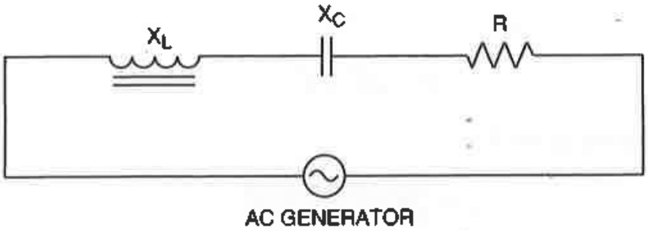


FIGURE 5-8 A simple series ac circuit.

To find I, use $I = E/Z$:

$$I = \frac{120V}{7.8\Omega}$$

$$= 15.4 \text{ A}$$

Current will lead voltage in this circuit because X_C is larger than X_L and therefore has a greater effect on the phase shift.

Phase Angle

As stated earlier, a *phase angle* is the angular distance between current and voltage in an ac circuit. The phase angle is designated by the Greek letter theta (θ). To better understand the phase shift created in an ac circuit, study the vector diagrams in Fig. 5-9. As illustrated, θ is always measured between the horizontal line and the resultant Z vector. For a simple R, C, or L circuit, the resultant vector equals the R, C, or L vector. For a pure resistive (R) circuit, the phase shift is 0°. For a pure inductive (L) or capacitive (C) circuit, the phase shift angle is always 90°. Voltage leads current in the inductive circuit, and current leads voltage in the capacitive circuit.

To determine the exact value of a phase shift angle, the trigonometry function of sine, cosine, or tangent is used. Figure 5-10 demonstrates the calculations to find θ in an RL circuit. The sine of θ is employed in this case to find the angle's value. The sine of θ is determined to be 0.446; a calculator is then used to determine the actual angle of 26.5°. If the tangent was used to find θ, the calculations would be as follows:

$$\tan\theta = \frac{\text{opposite side}}{\text{adjacent side}}$$

$$\tan\theta = \frac{10}{20} = 0.5$$

$$\theta = \tan^{-1} 0.5 = 26.5°$$

The cosine function could be used in a similar manner to find the angle θ.

The value of the phase angle has great importance when an ac circuit is designed. A small phase angle means the resistance vector is large compared with the reactance vectors. A large phase angle occurs when the inductive or capacitive reactance vector is much larger than the resistance vector. If this situation occurs, the ac circuit becomes very inefficient and may overload the power source.

The ratio of resistance compared to inductive or capacitive resistance becomes critical during the design of ac electrical systems. If a technician makes major modifications to an ac electrical system, it is important to ensure the phase angle remains within specifications.

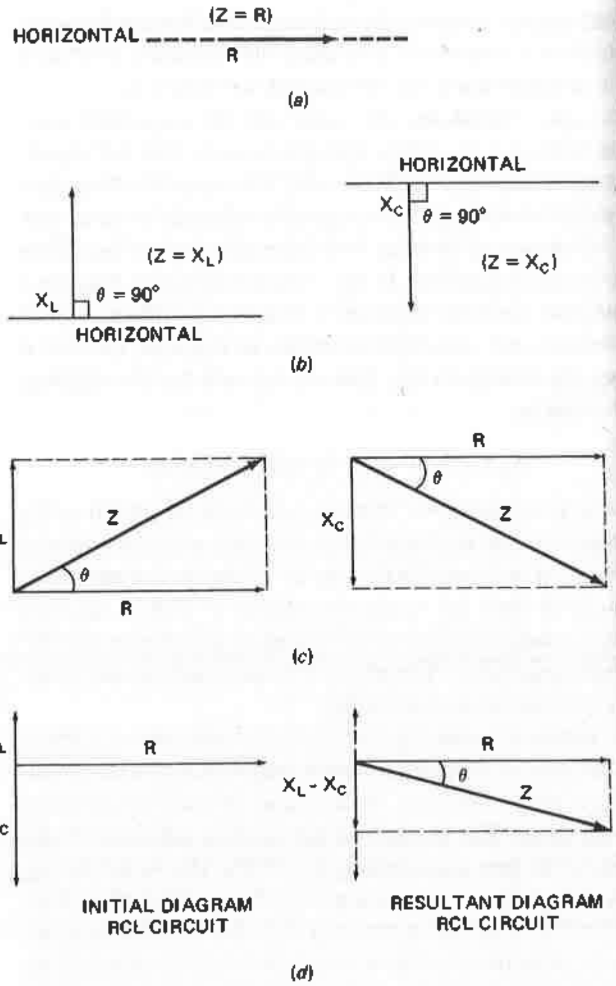


FIGURE 5-9 Various phase shift angles: (*a*) Pure resistive (R) circuit; θ = 0°. (*b*) Pure inductive (L) or pure capacitive (C) circuit; θ = 90°. (*c*) Resistive inductive (RL) or resistive capacitive (RC) circuit; θ is greater than 0° but less than 90°. (*d*) Resistive capacitive inductive (RCL) circuit; θ is greater than 0° but less than 90°.

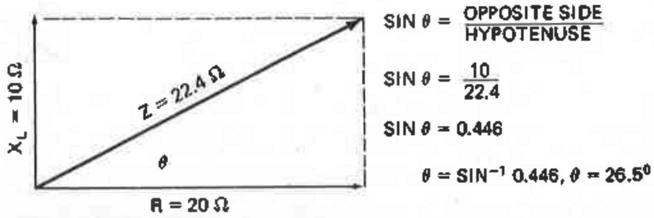


FIGURE 5-10 Phase angle calculations.

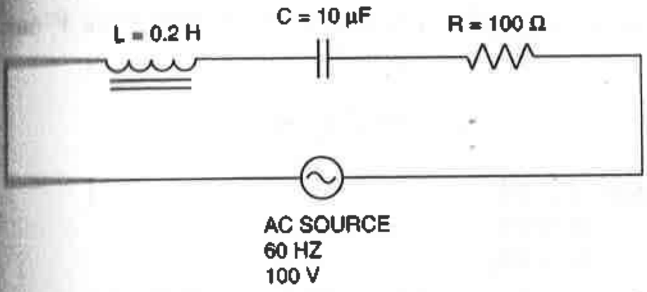


FIGURE 5-11 The sample series ac circuit for sample problem.

Sample Problem. In a series ac circuit (see Fig. 5-11), determine the total impedance Z, the total current flow I_t, and the phase angle θ.

Step 1. Find the inductive and capacitive reactance. (*Note:* Remember to convert microfarads to farads.)

Find Inductive reactance
$$\begin{cases} X_L = 2\pi f L \\ \quad = 2\pi 60(0.2) \\ \quad = 75.4\,\Omega \end{cases}$$

Find capacitive reactance
$$\begin{cases} X_C = \dfrac{1}{2\pi f C} \\ \quad = \dfrac{1}{2\pi 60(0.00001)} \\ \quad = \dfrac{1}{0.0038} \\ \quad = 265.26\,\Omega \end{cases}$$

The inductive reactance is 75.4 Ω; rounding gives 75 Ω. The capacitive reactance is 265.26 Ω; rounding gives 265 Ω.

Step 2. Find the circuit's impedance.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$
$$= \sqrt{100^2 + (75.4 - 265.26)^2}$$
$$= \sqrt{46046}$$
$$= 214.58\,\Omega$$

The impedance is 214.58 Ω; rounding gives 214 Ω.

Step 3. Determine the phase shift angle (Fig. 5-12). (*Note:* Current will lead the voltage, since X_C is larger than X_L.)

$$\sin\theta = \frac{190}{214}$$
$$\sin\theta = 0.8879$$
$$\theta = 62.6°$$

The phase shift angle is 62.6°.

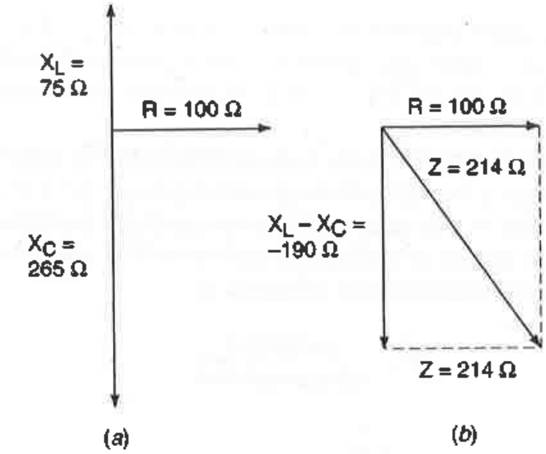


FIGURE 5-12 Vector diagram of the series ac circuit for sample problem.

Step 4. Find the total current flow.

$$I_t = \frac{E_t}{Z}$$
$$= \frac{100\,V}{214\,\Omega}$$
$$= 0.74\text{ A}$$

The total current flow equals 0.47 A.

Power Factor Calculations for AC Circuits

There are typically two types of power used to describe the work performed by an ac circuit. **True power** is the power consumed by the resistance of an ac circuit. **Apparent power** is the power consumed by the entire ac circuit. Thus apparent power takes into consideration the power consumed because of the resistance and the inductive and capacitive reactances. True power considers only resistance. Just as impedance is found vectorially, so is apparent power, as illustrated in Fig. 5-13. Reactive power Q is placed on the vertical axis. **Reactive power** is a function of the total reactance of a circuit. True power P is placed on the horizontal axis, and its magnitude is found by $P = I^2R$. Apparent power U is the resultant vector and can be found using

$$U = \sqrt{P^2 + Q^2}$$

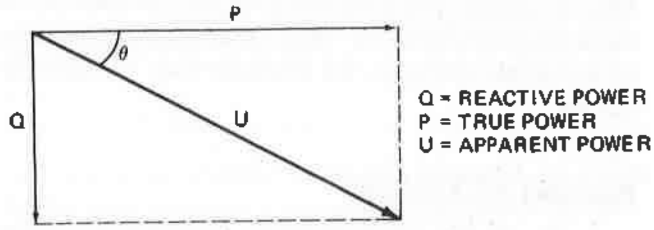


FIGURE 5-13 Apparent power vector diagram.

To distinguish between the types of power, true power is measured in **watts (W)**, apparent power is measured in **volt-amps (VA)** and reactive power is measured in **volt-amps-reactive (VAR).**

Power factor (PF) is the ratio of true power to apparent power; a circuit's efficiency will determine the power factor. That is, the more inductive or capacitive reactance, the lower the circuit's efficiency and the smaller the power factor. Power factor can be calculated by

$$\text{PF} = \frac{\text{true power}}{\text{apparent power}}$$

$$= \frac{P}{U}$$

Since power factor is a ratio, it has no units of measure. If $P = 130$ W and $U = 140$ VA, the power factor can be calculated as follows:

$$\text{PF} = \frac{P}{U}$$

$$= \frac{130}{140}$$

$$= 0.928$$

A power factor of 1.0 indicates a purely resistive circuit. A power factor of zero indicates a purely reactive circuit.

Power factor can also be calculated by using the cosine of the phase shift angle. That is,

$$\text{PF} = \text{cosine } \theta$$

Therefore, if the power factor is known, the phase shift angle (not direction) is also known. The greater the reactance in a circuit for a given resistance, the larger the phase shift angle, the lower the power factor, and the lower the circuit's efficiency. Once you understand this relationship, it is easy to see why large quantities of inductive or capacitive reactance create inefficiencies and are undesirable in an ac circuit.

Most aircraft ac alternators contain critical specifications for both apparent power and a power factor range. Apparent power is used because it describes the power used by the entire circuit—that is, both resistance and reactive power. Apparent power would be measured in **kilovolt-amps (kVA)**, and the power factor would be given as a range. For example, a particular aircraft alternator may be rated as follows: apparent power maximum of 200 kVA and a power factor range of 0.90 to 1.0. These specifications must never be exceeded; otherwise, the alternator may be internally damaged.

Parallel AC Circuits

As mentioned earlier, the calculations used to find impedance for parallel circuits are different from those used with series circuits. The letter Z is still used to represent impedance; however, for parallel circuits $Z_t = 1/Y$. To solve for Y, one must use the following equation:

$$Y = \sqrt{G^2 + (B_L - B_C)^2}$$

where $G = 1/R$
$B_L = 1/X_L$
$B_C = 1/X_C$

Here we can see that G, B_L, and B_C are simply the inverse of the resistance R, the inductive reactance X_L, and the capacitive reactance X_C for a given circuit. G, B_L, and B_C have no practical value in electrical terms; however, they must be used as an interim step whenever the total impedance of a parallel circuit is determined. Once you have calculated these values, the equation

$$Y = \sqrt{G^2 + (B_L - B_C)^2}$$

can be used to find Y. The value for Y must then be inverted to find Z, as shown next.

$$Z = \frac{1}{Y}$$

For parallel ac circuits, voltage leads current if B_L is greater than B_C. Voltage will lag current if B_C is greater than B_L (Fig. 5-14*a*). The phase shift angle (θ) is determined by the angle between the resultant vector Y and the horizontal vector G as seen in Fig. 5-14*b*.

As seen in the following example, the calculation of impedance Z for parallel circuits is relatively easy if you always remember to invert the values for R, X_L, and X_C before calculating for Y. Then simply invert Y to find total impedance Z.

Sample Parallel Problem. To find the total impedance and the phase shift angle for the circuit in Fig. 5-15, take the following steps:

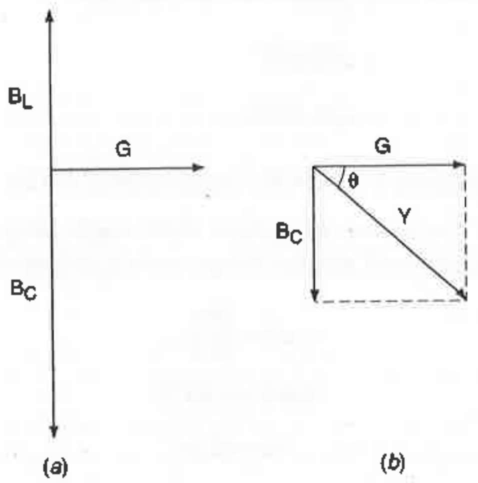


FIGURE 5-14 Vector diagrams of parallel ac circuits; θ is measured between the horizontal and resultant vectors.

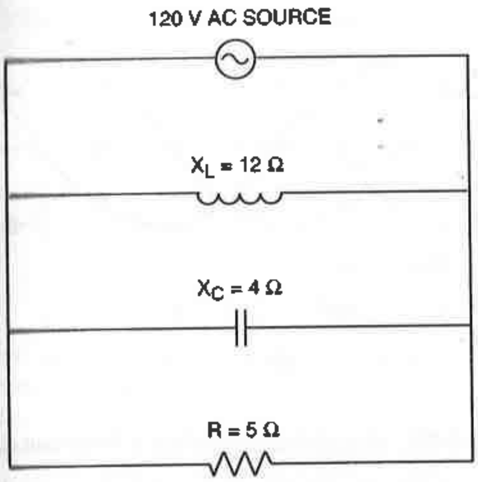


FIGURE 5-15 Circuit for the sample parallel problem.

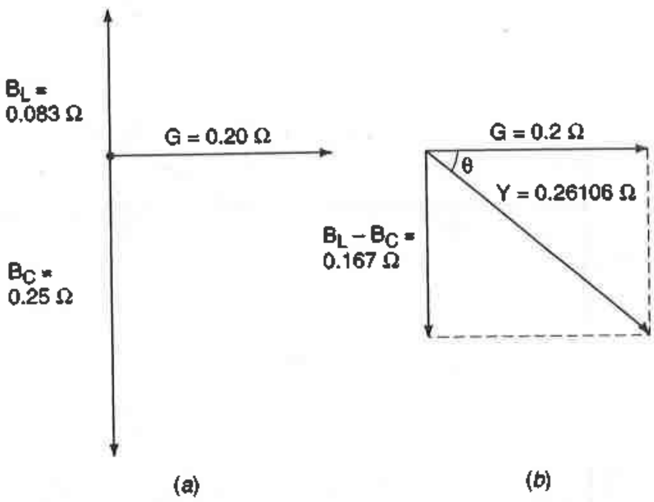


FIGURE 5-16 Vector diagrams of the parallel ac circuit.

Step 1. Convert R, X_L, and X_C to G, B_L, and B_C.

$$G = \frac{1}{R} \qquad G = \frac{1}{5} \qquad G = 0.20\,\Omega$$

$$B_L = \frac{1}{X_L} \qquad B_L = \frac{1}{12} \qquad B_L = 0.083\,\Omega$$

$$B_C = \frac{1}{X_C} \qquad B_C = \frac{1}{4} \qquad B_C = 0.25\,\Omega$$

Step 2. Solve for Y.

$$Z = \sqrt{G^2 + (B_L - B_C)^2}$$

$$= \sqrt{0.02^2 + (0.083 - 0.25)^2}$$

$$= \sqrt{0.0283}$$

$$= 0.2606\,\Omega$$

Step 3. Invert Y to determine Z.

$$Z = \frac{1}{Y}$$

$$= \frac{1}{0.2606}$$

$$= 3.84\,\Omega$$

The total impedance Z is equal to 3.84 Ω.

Step 4. Calculate the phase shift angle for the vector diagram in Fig. 5-16.

$$\sin\theta = \frac{\text{opposite side}}{\text{hypotenuse}}$$

$$\sin\theta = \frac{0.167}{0.2606}$$

$$\sin\theta = 0.641$$

$$\theta = 39.8°$$

This circuit has a phase shift angle of 39.8°, and voltage lags current.

To determine the total current for the circuit, divide the total voltage by the total impedance as shown below.

$$I_t = \frac{E_t}{Z}$$

$$= \frac{120\,V}{3.84\,\Omega}$$

$$= 31.25\text{ A}$$

Total current is 31.25 A.

Vector Addition of Voltage and Current

In a series **dc** circuit, total voltage is equal to the sum of the individual voltage drops. In a series **ac** circuit, however, the voltage total is equal to the voltage drops summed vectorially. That is, the voltage drops created by the resistances are summed, the voltage drops across the capacitances are summed, and the voltage drops across the inductances are also summed. These three totals are then added vectorially, with resistance voltage drops placed on the horizontal axis, inductive voltage drops placed vertically pointing up, and capacitive voltage drops placed vertically pointing down. This is illustrated in Fig. 5-17*a*. The total voltage drop is then calculated using the equation

$$E_t = \sqrt{E_R^2 + (E_{X_L} - E_{X_C})^2}$$

The total current in a parallel dc circuit can be found by summing the current flows through each individual path. Total current in a parallel ac circuit is found by adding currents vectorially. The vector diagrams in Fig. 5-17*b* demonstrate the summation of ac current flows. The equation

$$I_t = \sqrt{I_R^2 + (I_{X_L} - I_{X_C})^2}$$

is used to find I, where I_t is the total current in the ac circuit, I_R is the sum of the resistive current flows, I_{X_L} is the sum of

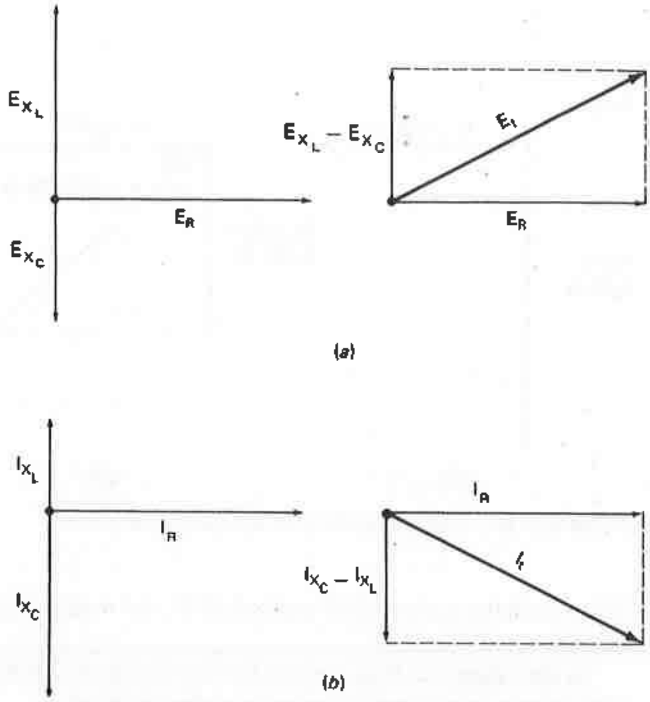


FIGURE 5-17 Vector addition in an ac circuit: (a) voltage; (b) current.

the inductive currents, and I_{X_C} is the sum of the capacitive currents.

The following is a sample problem: If a parallel ac circuit contains two inductors carrying 2 A each, a capacitor carrying 1 A, and three resistors carrying 1.5 A, 0.5 A, and 3 A, what is the circuit's total current flow?

First, add the individual current flows for resistance, inductance, and capacitance.

$$I_R = 1.5\text{ A} + 0.5\text{ A} + 3.0\text{ A}$$
$$= 5\text{ A}_{\text{Resistive}}$$
$$I_{X_L} = 2\text{ A} + 2\text{ A}$$
$$= 4\text{ A}_{\text{Inductive}}$$
$$I_{X_C} = 1\text{ A}_{\text{Capacitive}}$$

To find I_t, use

$$I_t = \sqrt{I_R^2 + (I_{X_L} - I_{X_C})^2}$$
$$= \sqrt{(5\text{ A})^2 + (4\text{ A} - 1\text{ A})^2}$$
$$= \sqrt{34\text{ A}}$$
$$= 5.8\text{ A}_{\text{Total}}$$

POLYPHASE AC CIRCUITS

A **polyphase** ac circuit consists of two or more circuits that are usually interconnected and so energized that the currents through the separate circuits and voltages have exactly equal

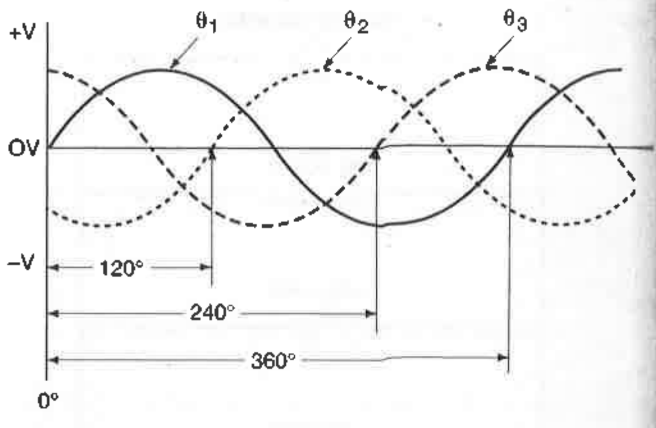


FIGURE 5-18 A typical sine wave for a three-phase circuit.

frequencies but differ in phase. A difference in phase means that the voltages do not reach peak positive or peak negative values at the same time. Also, the corresponding values of current are usually separated by an equal number of degrees. For example, in a **three-phase** ac system, no. 1 phase will reach a peak voltage 120° before the no. 2 phase, the no. 2 phase will reach the maximum positive voltage 120° before no. 3 phase. Thus the three phases are separated by an angle of 120° (Fig. 5-18).

Modern, large, transport-category aircraft of all types employ a **three-phase** ac electrical system. This system is considerably more efficient than a comparable single-phase ac system or a dc electrical system. Because of the great electric power requirements on large aircraft, a dc power system would add hundreds of pounds of weight in comparison with a three-phase ac system. The three-phase system found on these aircraft uses a polyphase ac generator that produces three ac voltages 120° apart.

Figure 5-19 is the diagram of a delta-connected alternator stator. This alternator, which also can be called an ac generator, supplies three separate voltages spaced 120° apart. It is called a **delta-connected** alternator because the diagram is in the form of the Greek letter delta (Δ). With a delta connection, the voltage produced across all three phases will be equal; in this example 110 V ac.

Another method for connecting the phase windings of a three-phase system is illustrated in Fig. 5-20. This is known as a **Y connection**. An alternator of this type can have three

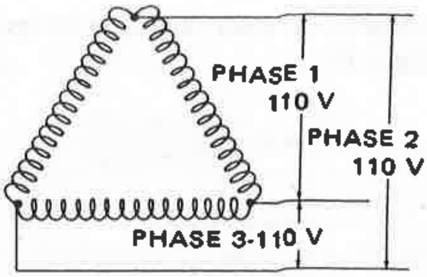


FIGURE 5-19 Schematic diagram of a delta alternator stator winding.

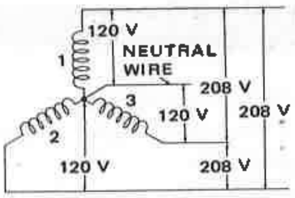


FIGURE 5-20 Schematic diagram of a Y-wound alternator stator.

or four terminals. When there are three terminals, the voltages between any two of the terminals are equal but 120° apart in phase. To operate single-phase equipment, any two of the terminals are used. When the alternator has four terminals, the fourth is common to all windings and is called the **neutral wire**. This makes it possible to obtain two different voltages from the same alternator. In the ac power system of a transport-category aircraft, the neutral wire is typically grounded, and the three phase connections, which may be A, B, and C or 1, 2, and 3, are distributed to the power system of the airplane. In all cases, the separate phase terminals must be properly identified and insulated from each other.

The voltage between any two of the three phase windings of the Y system is equal to the vectorial sum of the voltages of two of the phase windings. For example, if the voltage across one winding is 120 V, the voltage between two of the three phase terminals is 1.73 times 120, or 208 V. An arrangement of this kind is convenient because the 120-V circuit may be used for operating lights and other small loads and the three-phase 208-V circuit used to operate larger power equipment such as electric motors. On an airplane in which the neutral wire is grounded, a single-wire system can be used for all single-phase 120-V circuits. The 208-V three-phase power can be directed to a three-phase motor or some other device requiring this type of power. Where direct current must be obtained for certain power needs, the three-phase current can be directed through a three-phase, full-wave rectifier. Rectifiers are explained in Chap. 6.

Single-phase equipment and such items as lights are operated by connecting one terminal of the load to one of the three-phase conductors and the other terminal to the metal structure of the airplane (ground). Thus the single-phase circuits make use of the voltage from one phase winding, and three-phase equipment is connected to the three separate phase windings. The voltage from ground to any one of the phase terminals is 120 V (single-phase voltage); the voltage from one phase terminal to another phase terminal is 208 V; and the voltage for the three-phase system is 208 V.

ALTERNATING CURRENT AND THE AIRPLANE

You might be wondering, why use alternating current to power aircraft electrical systems? Simply stated, ac power is much more flexible than dc power. Alternating current is produced by all aircraft generators and alternators. This power must be converted to dc if such power is desired. Since converting ac to dc does require some power itself, it only makes sense to convert as little as possible and use mainly ac electrical systems.

There are three principal advantages in the use of alternating current for electric power systems. (1) The voltage of ac power can be changed easily by means of transformers. This makes it possible to transmit power at a high voltage with low current, thus reducing the size and weight of wire required. (2) Alternating current can be produced in a three-phase system, thus making it possible to use motors of less weight for the same amount of power developed. (3) AC generators are more efficient than dc generators and typically have fewer moving parts; hence, service and upkeep are greatly reduced.

A simple example will demonstrate the advantage of using high voltages for power transmission. We shall assume that we have a 1-hp [746-W] motor that must be driven at a distance of 100 ft [30.5 m] from the source of electric power. With a dc source of 10 V, the motor will require approximately 125 A, assuming that the motor is 60 percent efficient. Now when we consider the current-carrying capacity of copper wire, we find that a No. 1 gage wire is required to carry the current for the motor. One hundred feet of this wire weighs approximately 25 lb [11 kg]. If we substitute a 1-hp, 200-V ac motor for the 10-V dc motor, the current required is only about 5 or 6 A, depending on the efficiency of the motor. This will require a No. 18 gage wire which weighs about 1 lb [0.5 kg] for 100 ft. This comparison clearly demonstrates the advantage of higher voltages for power transmission. Using a high-voltage AC motor saves approximately 24 lb of wire.

On large transport-category aircraft, three-phase alternating current is produced by the engine-driven generator (alternator). Three-phase current is used to power most of the large motors found on this type of aircraft. Three-phase ac motors are much lighter and smaller than if they were produced as single-phase ac or a direct-current motor. Three-phase motors are typically used to power hydraulic pumps, equipment-cooling blower fans, and other systems that require large amounts of mechanical energy. Single-phase ac is also used to power light-duty motors, such as those used to operate a valve assembly. Single-phase ac is also used to power a variety of other systems, such as lighting.

Alternating current can be converted to different voltages much more easily than direct current. Through the principle of electromagnetic induction, ac voltage can easily be increased or decreased to virtually any desired level. A device called a **transformer** is used for this purpose. Most aircraft alternators produce power at 115 V and 400 cycles per second (Hz). However, various voltages are often desirable for specific electrical equipment. For example, fluorescent lamps operate on a relatively high voltage obtained from the output of a ballast transformer. If the same amount of light was to be produced using dc, a much greater amount of power would be consumed. Just as voltage can be increased, it can also be decreased to a relatively low level for charging a battery or operating other systems requiring only 28 V.

Even in large aircraft, some dc power is required for specific systems. Alternating current can easily be converted to dc when this becomes necessary. Usually, the dc power required is only a very small percentage of the total electric power consumed in the aircraft.

In some cases, light aircraft use ac power systems for the operation of certain equipment. Since light aircraft generate electric power using *dc* generators or alternators, they require an **inverter** to produce *ac*. An inverter is a device that changes dc voltage to ac voltage. An inverter is used only when a small amount of ac is required. Inverters can be designed to produce virtually any voltage value. Typically, 26- or 115-V inverters are used for light-aircraft systems.

Alternating-current systems do have certain disadvantages, such as the radiation of an electromagnetic field around each conductor. This field can interfere with communication or navigation systems if not properly controlled. For the most part, however, the advantages of ac far outweigh the disadvantages. For this reason, the majority of transport-category aircraft contain ac electrical systems.

State-of-the-Art AC Electrical Systems

The trend in aircraft design is to incorporate more electrical systems and reduce the number of hydraulic, pneumatic, and other mechanical systems. This design concept is often referred to as the **more electric airplane.** Both light and heavy aircraft use more electrical power than ever before. Today's light aircraft rely mainly on dc power and typically contain more than one battery for emergency power. Modern transport category aircraft, such as the Boeing 777, the Airbus A-380, and the Boeing 787 operate using vast amounts of electrical energy and therefore have multiple ac generators. For example, the twin-engine B-787 has six engine-driven generators. These generators produce 235 and 115 V alternating current, as well as 270 and 28 V direct current.

Due to the extreme power requirements and the use of multiple voltage values, the electrical systems found on modern transport category aircraft is extremely complex. These aircraft are often called **fly-by-wire** because they rely on electricity to move all flight controls. In general, the aircraft could not be controlled if all electrical systems fail. Now, more than ever before designers, engineers, and technicians must consider electrical systems as extremely critical and ensure proper operations of both ac and dc power. Electrical power distribution systems will be discussed in additional detail later in this text.

REVIEW QUESTIONS

1. Define *alternating current.*
2. What are the advantages of alternating current in large transport aircraft?
3. Explain how the sine wave describes the values of an alternating current.
4. What is meant by *rms,* or *effective, values* of alternating current?
5. What is the relationship between the frequency and the period of an ac wave?
6. Explain the term *frequency.*
7. What is meant by *phase* in speaking of alternating current?
8. Why does alternating current appear to flow through a capacitor?
9. What is the effect of capacitance in an ac circuit?
10. Define *capacitive reactance.*
11. Give the formula for capacitive reactance.
12. What is the capacitive reactance in a circuit when the capacitance is 1 μF and the frequency is 60 Hz?
13. What unit is normally used to indicate the capacitive reactance?
14. What unit is used to measure inductive reactance?
15. Give the formula for inductive reactance.
16. Compute the inductive reactance in a circuit where the frequency is 1000 kHz and the inductance is 20 mH.
17. Explain impedance.
18. Describe a vector diagram used to show the combination of 15-Ω inductive reactance, 10-Ω capacitive reactance, and 4-Ω resistance.
19. Compute the impedance in on ac circuit that has the following values: $f = 1400$ kHz, $L = 5$ mH, $C = 2$ μF, $R = 600\ \Omega$.
20. Define *phase angle.*
21. What is the symbol for phase angle?
22. Define *power factor.*
23. What are the formulas for true power and apparent power?
24. Define the relationships between power factor and phase angle.
25. How are individual current flows added in an ac circuit?
26. How are individual voltage drops added in an ac circuit?
27. What is a multiphase ac circuit?
28. What voltage and frequency alternating current is produced by most aircraft alternators?

Electrical Control Devices 6

INTRODUCTION

There are numerous means of controlling the voltage and current of any particular circuit. The use of switches, resistors, transistors, and other electrical devices has become commonplace in all modern aircraft. These devices are necessary in order to assure the correct operation and control of any electrical load. This chapter will discuss the theory of operation of and installation practices for the various electrical control devices used on modern aircraft.

SWITCHES

A **switch** can be defined as a device for closing or opening (making or breaking) an electric circuit. It usually consists of one or more pairs of contacts, made of metal or a metal alloy, through which an electric current can flow when the contacts are closed. Switches of many types have been designed for a wide variety of applications. The switches can be manually operated, electrically operated, or electronically operated. Switches operated by the pilot, or other human beings, are typically large enough for easy access. On the other hand, electronic switches are typically computer operated and are often extremely small. In many cases, thousands of electronic switches are contained in a single or integrated circuit. A manual switch is usually operated by either a lever or a push button. Electrically operated switches are generally called **relays or solenoids.** An electronically operated switch utilizes a transistor or integrated circuit to control the current flow through a circuit. The "switch" is turned on or off by means of an electric signal applied to the transistor or integrated circuit. The following discussion on switches will focus on manual switches, and electronic switching will be discussed later in this chapter.

To be suitable for continued use, a switch must have contacts that are capable of withstanding thousands of cycles of operation without appreciable deterioration due to arcing or wear. The contacts are usually made of special alloys that are resistant to burning or corrosion. The operating mechanism of a switch must be ruggedly constructed so it will not fail owing to wear or load stresses. For aircraft use, a switch must be of a type and design which can meet FAA approval standards, and be approved by the manufacturer of the aircraft.

The type of electrical load that a switch is required to control will determine to some extern the type and capacity of switch to be employed in a circuit. Some electric circuits will have a high surge of current when first connected, and then the current flow will decrease to the normal operating level. This is typical of circuits for incandescent lamps or electric motors. An incandescent lamp will draw a high current while the filament of the lamp is cold. The resistance of the filament increases severalfold as the temperature reaches maximum; hence the current is reduced at this time. The switch for an incandescent-lamp circuit must be able to carry the high starting current without damage.

An electric motor will draw a high current during starting because of the extra torque required for initial rotation. The countervoltage of the armature is also weak during initial motor starting. When the motor reaches normal operating speed, the countervoltage increases and opposes the applied voltage, substantially reducing current flow.

Inductive circuits, those which include electromagnetic coils of various types, have a momentary high voltage at the time the circuit is broken. This high voltage causes a strong arc to occur at the switch contacts.

It is apparent from the foregoing discussion that a switch must be able to carry a greater load than the nominal running load of the circuit in which it is installed. Accordingly, **derating factors** are applied in determining the capacity of a switch for a particular installation. The derating factor is a multiplier that is used to establish the capacity a switch should have in order to control a particular type of circuit. Derating a switch ensures that the electrical contacts of the switch will be large enough to handle any "extra" voltage/current when those contacts initially close or initially open. For example, if an incandescent-lamp circuit operates continuously at 5 A in a 24-V system, the capacity of the switch should be 40 A because the derating factor is 8. That is, the surge current for the lamp circuit can be almost eight times the steady operating current. Table 6-1 gives the derating factors for aircraft switches in various types of dc circuits. It should be noted that the voltage stated in this example is 24 V dc. This circuit operates at 24 V only when the aircraft generator or alternator is off line (not in use). The nominal voltage of a charged battery is approximately 24 V, which may vary slightly. When the aircraft's charging systems (generator or alternator) are supplying power, the electrical system voltage should be between 26 and 28 V.

TABLE 6-1 Derating factors.

Nominal system voltage	Type of load	Derating factor
24	Lamp	8
24	inductive	4
24	Resistive	2
24	Motor	3
12	Lamp	5
12	inductive	2
12	Resistive	1
12	Motor	2

It is important, therefore, that aircraft electrical components and systems be designed to operate in a range of voltages. This range must include the maximum charging system voltage (say 29 V) and the minimum battery voltage (say 22 V for a weak battery). For use of this text and for most of the industry, consider any system voltage to be in a range. For an aircraft with a 24-V battery, the typical voltage range would be approximately 22 to 29 V. For an aircraft with a 12-V battery, the typical voltage range would be approximately 10 to 15 V. Technicians and other industrial personnel will often speak of a 24-V system, or a 28-V system; always remember this is the same system simply operating in different configurations. Virtually all aircraft employ either a 12-V or 24-V battery and their systems voltages will be in the range stated above.

The installation of switches should be in accordance with a standard practice so the operator will always tend to move the switch lever in the correct direction for any particular operation. Switches should always be installed in panels so the lever will be moved up or forward to turn the circuit on. Switches that operate movable parts of the aircraft should be installed so the switch lever is moved in the same direction that the aircraft part will be moved. For example, the landing gear switch should be installed so the switch lever will be moved down to lower the landing gear and up to raise the gear. The same principle should apply for wing flap operation.

Switches are designed with varying numbers of contacts to make them suitable for controlling one or more electric circuits. The switch used to open and close a single circuit is called a single-pole single-throw (SPST) switch. A switch designed to turn two circuits on and off with a single lever is called a double-pole, two-pole, single-throw (DPST) switch. A switch designed to route current to either of two separate circuits is called a double-throw switch. Schematic diagrams of several different types of switches are shown in Fig. 6-1. Double-throw switches can be designed with or without a center OFF position. The switch's OFF position disconnects the pole from both throws. Switches with a center OFF position are shown in Fig. 6-2. A three-position switch (one containing a center OFF position) would be used when it is necessary to connect a wire to a choice of two circuits or disconnect it from both. A two-position switch would be used when the circuit must always be connected to either of the two throws. Two-position DPDT switches contain no OFF position. When installing any switch, be sure it is capable of controlling the circuit properly. The schematic symbols for a switch are not always consistent among manufacturers. As illustrated in Fig. 6-1, more than one type of symbol may be used to represent a given switch configuration.

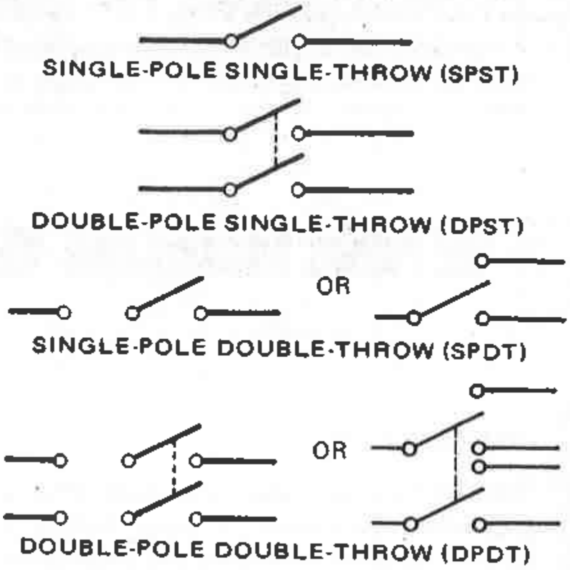


FIGURE 6-1 Schematic diagrams for different types of switches.

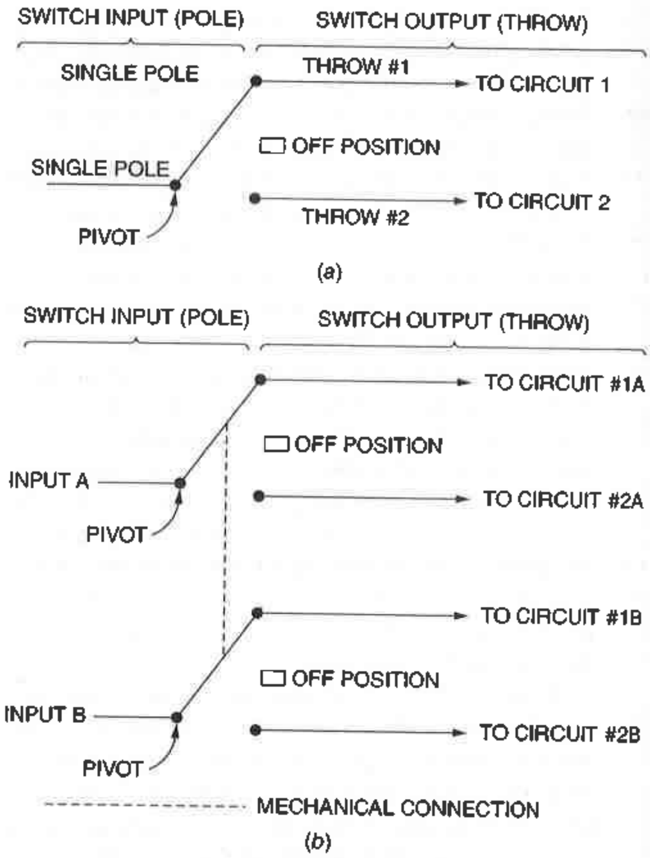


FIGURE 6-2 Three-position switch contains a center off position: (*a*) single-pole double-throw (SPDT), (*b*) double-pole double-throw (DPDT).

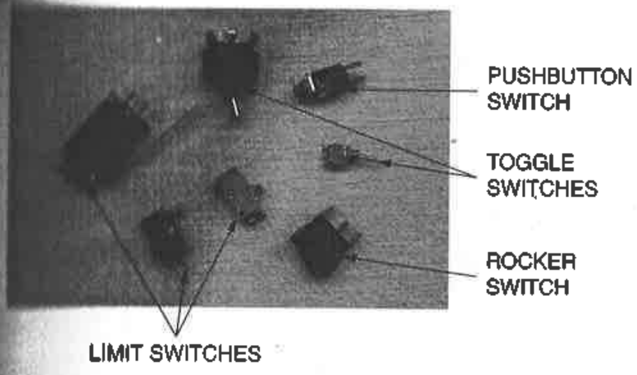


FIGURE 6-3 Common switch designs. See also color insert.

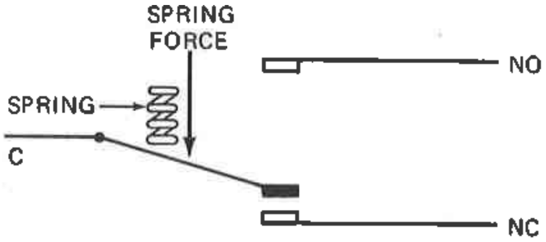


FIGURE 6-4 A schematic diagram of an SPDT microswitch.

Switches are available in several different configurations. Toggle, rotary, push button, rocker, and electromagnetic switches are examples each designed for a specific application. Figure 6-3 illustrates several switch types. Toggle or rocker switches are used to control most of the aircraft's electrical components. In situations where one contact must be connected to a choice of more than two circuits, a rotary switch is usually employed. Rotary switches are commonly found on radio control panels. A rotary switch would allow the pilot to make a selection of many different radio frequencies.

Limit switches require very little pressure applied to the actuator in order to move the switch's internal contacts. All limit switches are spring-loaded; therefore, once the external pressure is removed from the actuator, the electrical contacts will return to their normal position. The normal position of any spring-loaded switch is defined by the position of the contact points when there is no external force acting upon the switch actuator. Spring-loaded switches can be either **normally open** or **normally closed**. The contact points of a normally open switch are disconnected (open) until pressure is applied to the switch-actuating mechanism. If pressure is applied to the switch's actuator, the contact points connect (close). A normally closed switch contains closed contact points when there is no force applied to the switch actuator, and open points when a force is applied.

Limit switches are often called by other common names, such as **snap-action switch** or **micro switch**. The term **snap-action** comes from the fact that the actuator of the switch typically requires very little pressure or movement and the electrical switch contacts SNAP into place (either open or closed). The term **micro** switch is actually a trademarked name of limit switches made by the Honeywell Corporation. These switches are so popular that the trade name **Mirco-switch** has become a common name used to refer to many types of limit switches.

Limit switches are often SPDT or DPDT. This allows the switch to be used in several different configurations. As illustrated in Fig. 6-4, the pole of a limit switch is labeled "C" for common, and the throws are labeled "NC" for normally closed and "NO" for normally open. For example, a circuit that is needed to turn on a light when pressure is applied to the switch would be connected to the C and NO terminals. If the light must turn off when pressure is applied to the switch, the C and NC terminals would be used. Limit switches are used chiefly for detecting the position or limit of a moving component; hence the name "Limit switch." Landing gear, flaps, speed breaks, spoilers, and other moving components may all contain some type of limit switch in the electrical control circuit.

Electromagnetic switches, as discussed in Chap. 1, are called **relays** or **solenoids**. These switches use an electromagnet to move one or more sets of switch contacts. The power to engage the electromagnet is controlled through a separate switch or an electronic control unit typically located in a different part of the aircraft. In effect a relay or solenoid is used as a remote-switching device activated by another switch of some type. Relays and solenoids are spring-loaded switches; therefore, their contacts are designated as normally open, normally closed, and common, as seen in Fig. 6-5

Solenoids and relays may also be designated by their **duty cycle** (*continuous* or *intermittent*). A solenoid designed to operate for 2 min or less is considered intermittent-duty. A solenoid designed to be left in the activated position for longer than 2 min is a continuous-duty solenoid. If an intermittent-duty solenoid or relay is left in the activated position for too long, it will most likely overheat and fail.

Proximity sensors are a type of electronic switch with no moving contact points. They are used in conjunction with electronic circuitry to detect the position of various moving components on the aircraft, such as flaps and landing gear. On many high-tech aircraft, proximity sensors have replaced microswitches, since they are considered more reliable. Proximity sensors are discussed in Chap. 13.

Lighted push-button switches are found on many modern aircraft instrument panels. Each of these switches displays a lighted description *(legend)* of the circuit it controls (see Fig. 6-6). The flight crew can easily identify switches and determine the status of a circuit by the description on the front of the switch. Typically, the legends can be lit in two different configurations. This allows the aircraft designer to choose different colors for various operating modes of a circuit.

As shown in Fig. 6-7, these switches are constructed of two basic units: the switch assembly and the lighted push button. The switch assembly comes in one of various configurations such as momentary contact or continuous contact. The lighted push button contains up to four lightbulbs to provide redundancy for the legends. Newer versions of this lighted switch have replaced the light bulbs with the light-emitting diodes (LEDs). The LEDs are more efficient than

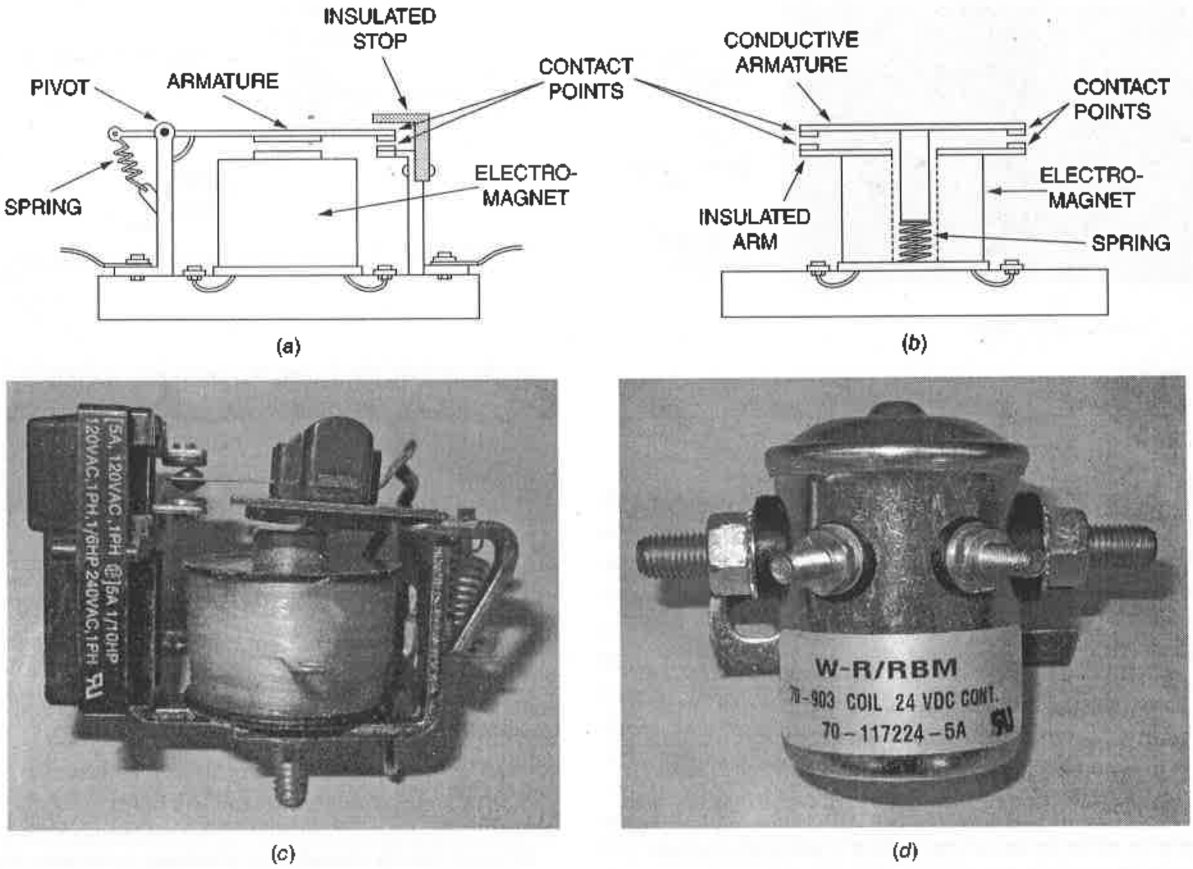


FIGURE 6-5 Electromagnetic switches: (*a*) relay diagram, (*b*) solenoid diagram, (*c*) relay photo, (*d*) solenoid photo.

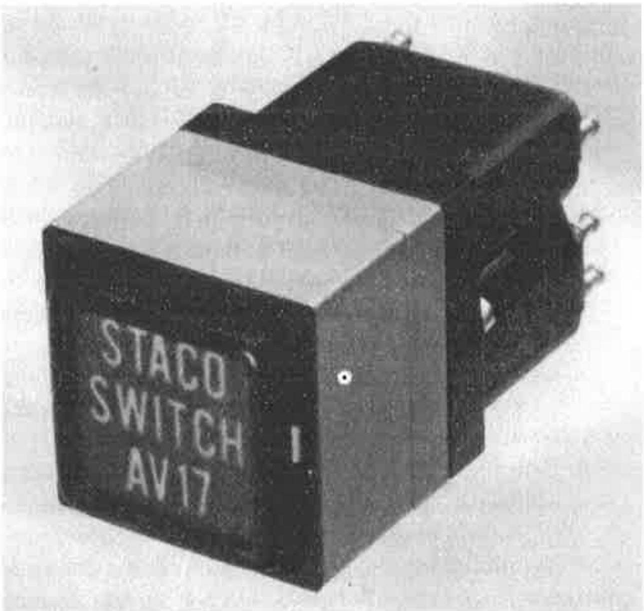


FIGURE 6-6 A typical lighted push-button switch. (*Staco-Switch, Aero Products Group.*)

conventional bulbs. This type of switch is typically designed to work in conjunction with computerized equipment; therefore, the contacts carry relatively small current flows. The electrical connections on the rear of the switch are typically soldered to their associated conductors.

CIRCUIT-PROTECTION DEVICES

A 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. 6-8. One might think of a short circuit as a problem that occurs when the current takes a "short-cut" back to the power source, hence causing an excel current flow. 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, emit smoke, or create a fire. 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.

Fuses

Fuses are one of many types of components that protect an electrical circuit. Fuses are a very simple and functional device; however, if a fuse fails it must be manually replaced.

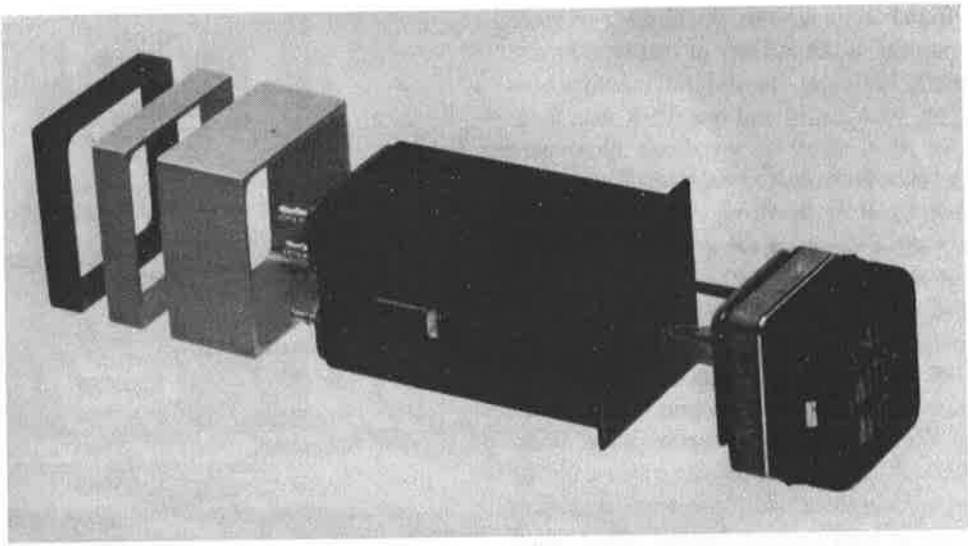


FIGURE 6-7 A lighted push-button switch assembly. *(StacoSwitch, Aero Products Group.)*

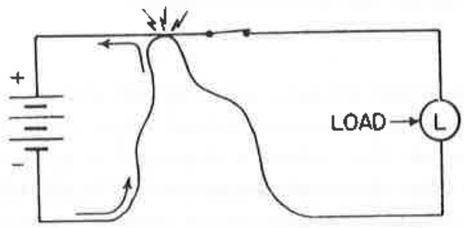


FIGURE 6-8 A schematic diagram of a short circuit

If it becomes necessary for a pilot to replace a fuse, his or her attention is drawn away from the duties of flight and this may pose a safety risk. For this reason, fuses have been replaced on most modern aircraft with a protective device which can be easily reset and does not require replacement. Many older aircraft were constructed with and still use fuses as well as some specialty equipment on modern aircraft. However, fuses are seldom found on modern aircraft.

A **fuse** is a strip of metal having a finely calibrated melting point. It is placed in a circuit in series with the load so that all load current must flow through the fuse. The metal strip is made of lead, lead and tin, tin and bismuth, or some other low-melting-temperature alloy.

When the current flowing through a fuse exceeds the capacity of the fuse, the metal strip melts and breaks the circuit. The strip must have low resistance, and yet it must melt at a comparatively low temperature. When the strip melts, it should not give off a vapor or gas or create other potential hazards; therefore, the fuse strip is typically enclosed in a sealed housing. The metal or alloy used must also be of a type that reduces the tendency toward arcing.

Fuses are generally enclosed in glass or some other heat-resistant insulating material to prevent an arc from causing damage to the electric equipment or other parts of the airplane. Fuses used in aircraft are classified mechanically as cartridge type, plug-in type, or clip type, although other specialty fuses may be used on some aircraft. All these types are easily inspected, removed, and replaced. Typical fuses are shown in Fig. 6-9.

During flight, spare fuses must be accessible to the pilot so that he or she can replace any fuses that may have accidentally failed. The FAA flight regulations stipulate that for

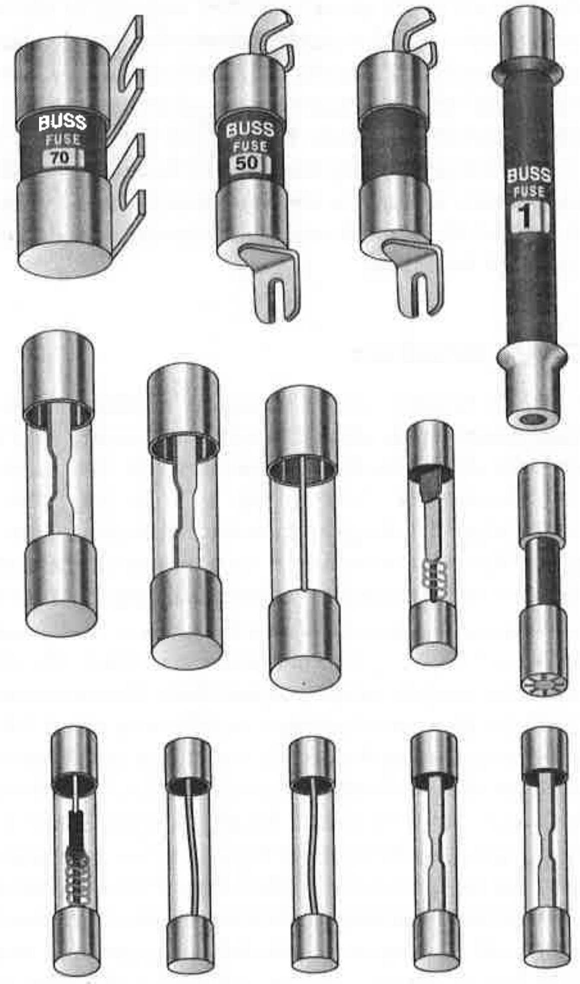


FIGURE 6-9 Typical fuses.

each type of fuse found on an aircraft, the number of spare fuses must be 50 percent of the number of that type or one (whichever is greater). Therefore, if an aircraft circuitry uses four 20-A fuses, five 10-A fuses, and one 30-A fuse there must be at least two 20-A, three 10-A and one 30-A spare fuses. These spare fuses are required only for flight under Federal Air Regulation part 91; however, during any aircraft inspection, it is advisable to ensure the proper number and location of spare fuses.

A **current limiter** is essentially a **slow-blow fuse.** That is, when the circuit becomes overloaded, there is a short delay before the metal link melts and disconnects the circuit. The fusable metal link is made of copper, which has a higher melting point than the alloys used in other types of fuses. The current limiter will carry more than its rated capacity and will also carry a heavy overload for a short time. It is designed to be used in heavy-power circuits where loads may occur of such short duration that they will not damage the circuit or equipment. The capacity of a current limiter for any circuit is so selected that the current limiter will always interrupt the circuit before an overload has had time to cause damage. Current limiters are shown in Fig. 6-10.

On many aircraft current limiters are used for protection of high-current circuits, such as alternator output power. For example, an aircraft that employs a 150-A alternator may have a current limiter designed to open at 151 A or greater. This circuit poses an extreme fire risk due to the high-current flow, and it is therefore critical to ensure that any over current situation is disconnected immediately. The current limiter will disconnect the circuit as needed; however, the current limiter cannot be replaced during flight. Most current limiters would typically be replaced by a technician, not the pilot. Typically a current limiter is located in an area of the aircraft where it can only be accessed while the aircraft is on the ground.

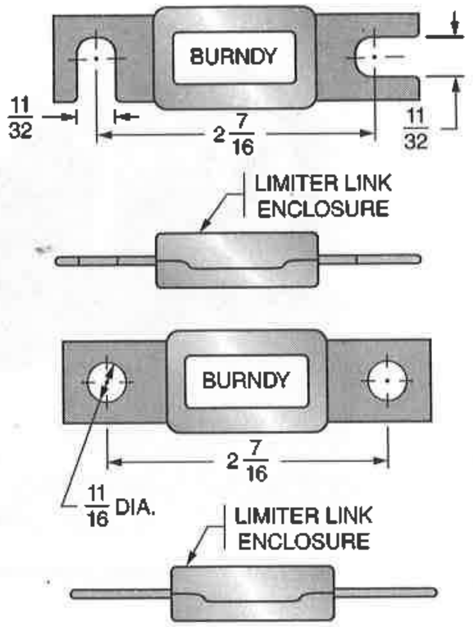


FIGURE 6-10 Typical current limiters.

Circuit Breakers

A circuit breaker serves a purpose similar to that of a fuse; however, the circuit breaker can usually be reset after the circuit fault has been removed. Typical aircraft circuit breakers are shown in Fig. 6-11. As shown here, circuit breakers are designed to control different current flow limits; this limit is indicated on the front of each circuit breaker. Circuit breakers are also available in different styles and shapes. A circuit breaker is basically a current control device, or switch, which automatically opens the circuit whenever current reaches a certain limit. The most common circuit breakers operate using a metallic strip which deforms with excess current flow. As the metal strip bends past a certain limit, the circuit breaker opens, or "trips," disconnecting the circuit. Since the circuit breaker is wired in series with the applied current, when the breaker opens, the circuit will no longer receive power. Unlike a fuse, if the overload situation has been eliminated, the circuit breaker can be reset and power will once again be restored. If the overload remains in the circuit, the unit must be designed so the pilot cannot manually override the circuit breaker.

Most circuit breakers are designed with a push-button control; this button moves outward whenever a circuit overload occurs. This button is depressed to reset the circuit breaker when the overload is removed. Circuits with a push-button breaker must also contain another means to turn on/off the circuit. Push-button-type breakers should not be used as an on/off switch. The unit shown on the right of Fig. 6-11 is designed with a lever or toggle; this type of circuit breaker is designed to be used as both a switch and circuit protection device. There are two common electrical symbols used to represent a circuit breaker; symbols used to represent a fuse, circuit breaker, and current limiter are shown in Fig. 6-12.

Requirements for Circuit-Protection Devices

Circuit breakers and fuses should in all cases protect the wire in the circuit from overload and should be located as close as possible to the power distribution bus. Remember that a bus is a metal strip to which a power supply is connected and from which other circuits receive power

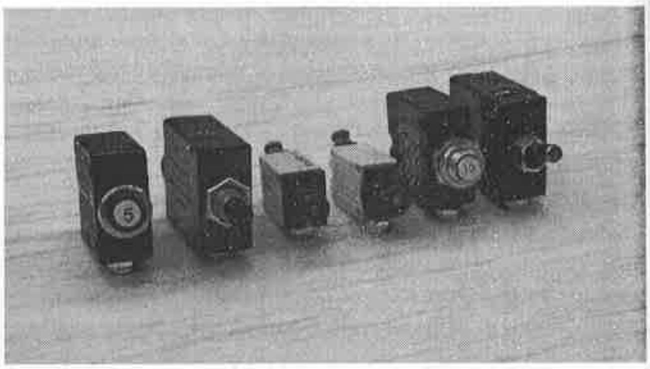


FIGURE 6-11 Typical circuit breakers.

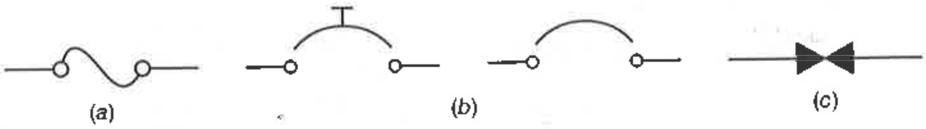


FIGURE 6-12 Common symbols for a circuit protection device: (a) fuse, (b) circuit breaker, (c) current limiter.

for operation. The bus bar is usually designed so the circuit breakers connect directly to the bar one adjacent to the next. The power distribution bus and circuit breakers are typically installed behind the instrument panel, and the push-button control of each circuit breaker is displayed to the pilot. A circuit breaker panel installed on a light twin-engine aircraft is shown in Fig. 6-13.

A circuit breaker or fuse should open the circuit before the wire becomes heated sufficiently to emit smoke or create damage. The time-current characteristic of the protective device should therefore be below that of the associated wire, with the result, of course, that the circuit protector will open the circuit before the wire is damaged. The term **time-current** refers to the product of multiplying the amount of current by the time during which it flows. In order to obtain maximum protection, the characteristics of the circuit protector should match as closely as possible those of the connected wire.

Table 6-2 is a guide to the selection of circuit-breaker and fuse ratings to protect copper cable. The conditions for the figures given in the table are as follows:

1. Wire bundles in 135°F [57.2°C] ambient temperature and altitudes up to 30000 ft [9144 m].
2. Wire bundles of 15 or more wires (cables), with wires carrying no more than 20 percent of the total current-carrying capacity of the bundle as given in specification MIL-W-5088 [Aeronautical Standards Group (ASG)].
3. Protectors in 75 to 85°C [23.9 to 29.4°C] ambient temperatures.
4. Copper wire specification MIL-W-5088 (ASG) or equivalent.

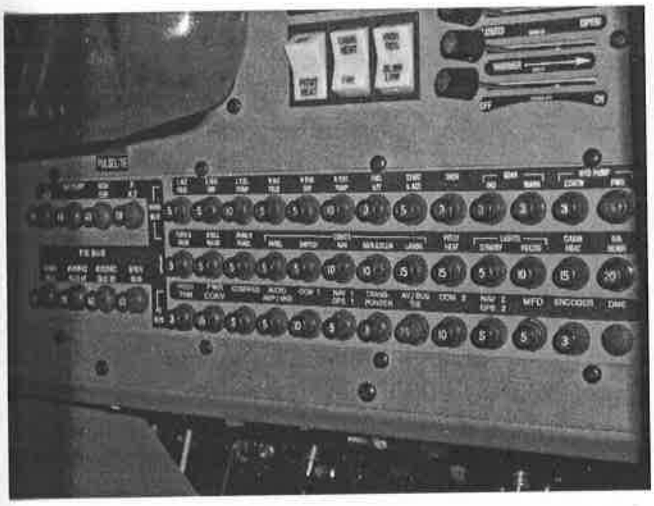


FIGURE 6-13 Circuit breaker panel from a twin-engine aircraft.

TABLE 6-2 Wire and cable protection chart.

Wire AN gage: copper	Circuit Breaker, A	Fuse, A
22	5	5
20	7.5	5
18	10	10
16	15	10
14	20	15
12	25(30)*	20
10	35(40)	30
8	50	50
6	80	70
4	100	70
2	125	100
1		150
0		150

*Figures in parentheses may be substituted where protectors of the indicated ratings are not available.

5. Circuit breakers to specification MIL-C-5809 or equivalent.
6. Fuses to specification MIL-F-15160 or equivalent.

If the actual conditions of an installation deviate materially from those stated for Table 6-2, a rating above or below the value recommended may be justified. For example, a wire run individually in the open air may possibly be protected by a circuit breaker of the next higher rating rather than that shown on the chart. In general, the chart is conservative for all ordinary aircraft electric installations. Always follow approved manufacturers, technical data whenever possible. This will help to ensure proper circuit protection.

All resettable circuit breakers should be designed to open the circuit regardless of the position of the operating control when an overload or circuit fault exists. Such circuit breakers are described as **trip-free**. One cannot manually override a trip-free circuit breaker if the circuit fault still exists. Automatic-reset circuit breakers, which reset themselves periodically, should not be used as aircraft circuit protectors.

RESISTORS

A resistor is a circuit element designed to insert resistance in the circuit. A resistor may be of low value (1-2 ohms) or of extremely high value (100000 ohms). The nature of resistance and its effect in electric circuits were discussed in

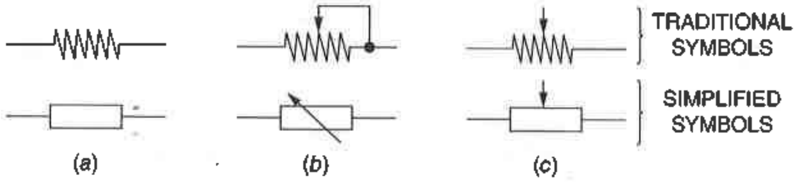


FIGURE 6-14 Common resistor symbols: (*a*) fixed value resistors, (*b*) variable resistor used as a rheostat, (*c*) variable resistor used as a potentiometer.

Chap. 1; the construction of resistors and their use in circuits is described briefly here.

Resistors in electronic circuits are made in a variety of sizes and shapes. They are generally classed as fixed, adjustable, or variable, depending on their construction and use. Figure 6-14 shows common resistor symbols. A typical fixed resistor is illustrated in Fig. 6-15. This type of resistor is constructed of a small rod of a carbon compound. The carbon rod is typically surrounded by an insulator material, and copper wire electrical connections are fixed to each end of the resistor. Of course the carbon rod must attach to the copper wire. The value of the resistance for each resistor is determined by the makeup and size of the carbon compound and may vary from only a few ohms up to several million ohms. The two important values associated with resistors are the value in **ohms** of resistance and the value in **watts**, which represents the capacity of the resistor to dissipate power. All resistors produce heat due to the power consumed by the resistor. It is critical that any resistor be capable of the correct power requirements.

The resistance value of small fixed resistors is indicated by a code color. The numerical values of the colors used in this coding are as follows:

Black	0	Yellow	4	Violet	7
Brown	1	Green	5	Gray	8
Red	2	Blue	6	White	9
Orange	3				

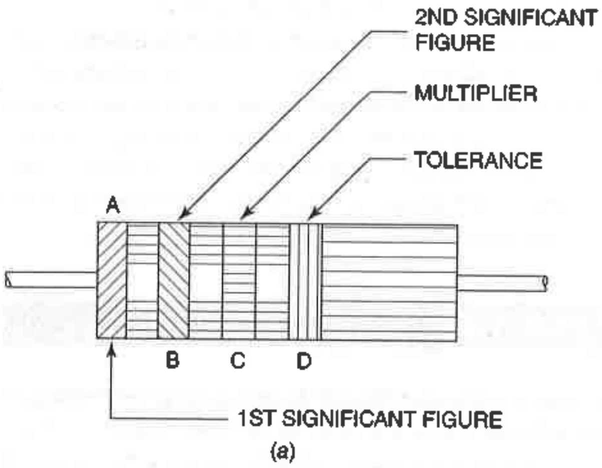
On most resistors there are four **color bands**. The band at the end of the resistor is called band A and represents the first digit of the resistance value. The next, band B, represents the second digit of the resistance value; the third, band C, represents the number of zeros to be placed after the first two digits; and the fourth, band D, indicates the degree of accuracy or tolerance of the resistor.

If a resistor's four bands are colored with green (band A), blue (band B), orange (band C), and silver (band D), then the value of the resistor is determined as follows: the green band indicates the figure 5 and the blue band the figure 6; the orange band shows that three zeros are to follow the 5 and 6. Therefore, the resistor has a value of 56 000 Ω. The silver, or D, band represents a tolerance of 10 percent. If this band were gold, the tolerance would be 5 percent.

Resistors required to carry a comparatively high current and dissipate high power are usually of the wire-wound ceramic type (see Fig. 6-16). A wire-wound resistor consists of a ceramic tube wound with fine wire, which is then covered with a ceramic coating or glaze. The terminals for the resistance wire extend out at each end of the resistor as shown. The value of the wire-wound resistor is usually printed on the ceramic coating.

Adjustable and Variable Resistors

An **adjustable resistor**, shown in Fig. 6-17, is the wire-wound type with a metal collar that can be moved along the resistance wire to vary the value of the resistance placed in the circuit. In order to change the resistance, the contact band must be loosened and moved to the desired position and then tightened so that it will not slip. In this



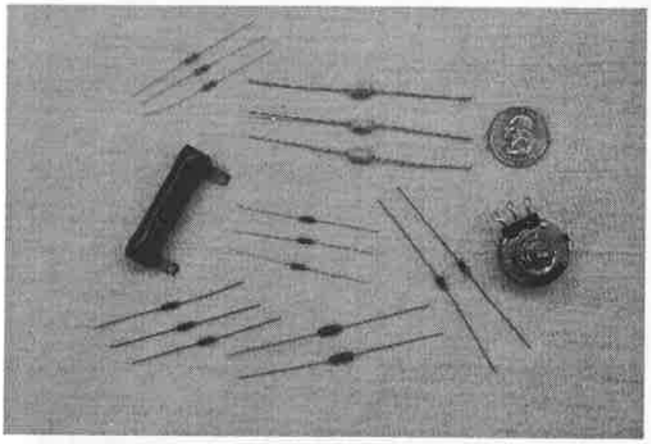


FIGURE 6-15 Typical resistors (*a*) color code, (*b*) common resistor types.

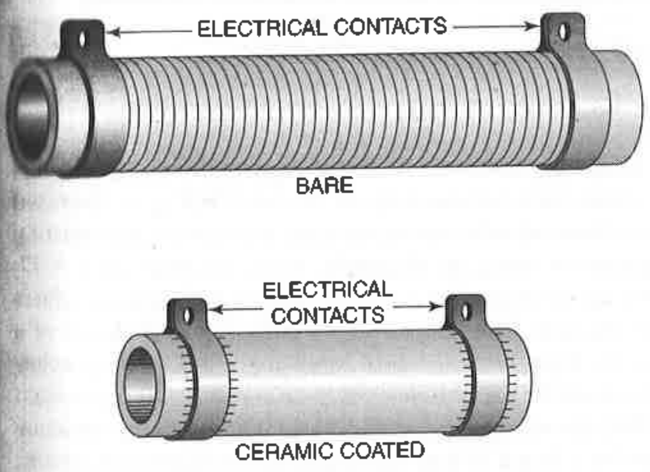


FIGURE 6-16 Wire-wound resistors.

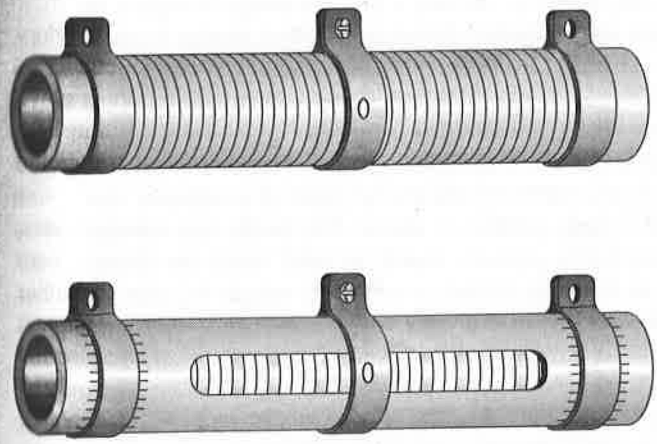


FIGURE 6-17 Adjustable resistors.

way the resistor becomes, for all practical purposes, a fixed resistor during operation.

A **variable resistor** is arranged so that it can be changed in value at any time by the operator of the electronic circuit. This change is usually accomplished by rotating a small adjustment knob or by turning a screw adjustment. Variable resistors are commonly known as **rheostats** or **potentiometers** (see Fig. 6-18). A rheostat is typically connected in a circuit merely to change the current flow and has a comparatively low resistance value (usually below 500 Ω). Its circuit connections are as shown in Fig. 6-19. Note that the rheostat has two terminals, one connected to the wire-wound resistor and the other connected to the sliding contact arm, which moves along the resistor. Potentiometers are typically found in electronic circuits which require very little power. Potentiometers are not subject to high current flows or high heat conditions and are therefore typically very reliable.

A potentiometer is connected with three terminals. One terminal is connected at each end of the resistor, and the third terminal is connected to the sliding contact arm. The value of the resistance of a potentiometer is comparatively high, and the resistor is normally made of a material such as a carbon or graphite compound. The purpose of a potentiometer is to vary the value of the voltage in a circuit.

A diagram of a potentiometer in a transistorized dimming circuit is shown in Fig. 6-20. The voltage applied between the base and emitter of the transistor is controlled by the potentiometer; subsequently, the voltage to the lamp is controlled by the transistor emitter-collector circuit. Transistors are discussed in greater detail later in this chapter.

It must be pointed out that the use of a resistor of any type must be very carefully considered. The capacity of a

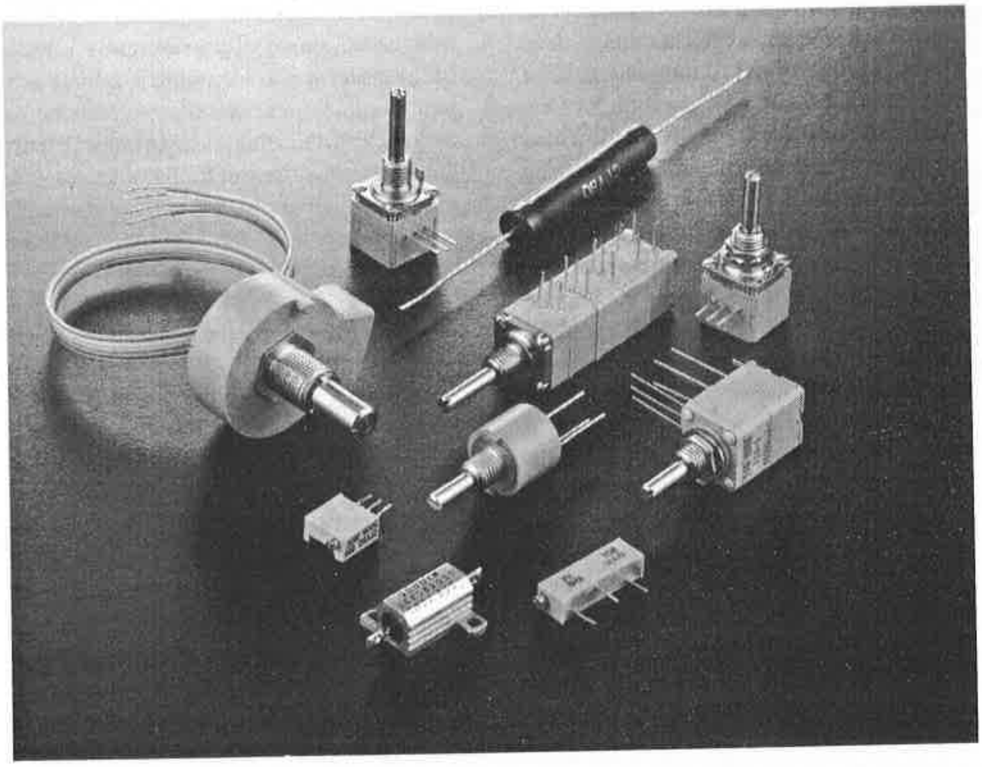


FIGURE 6-18 An assortment of variable resistors. (*Clarostat Mfg. Co.*)

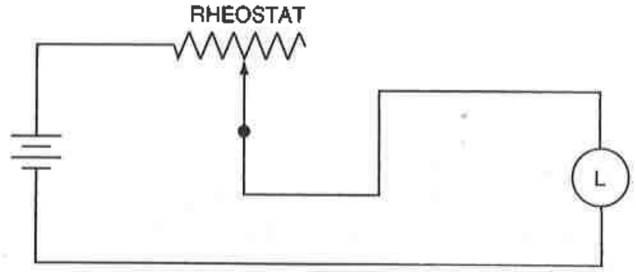


FIGURE 6-19 A rheostat circuit.

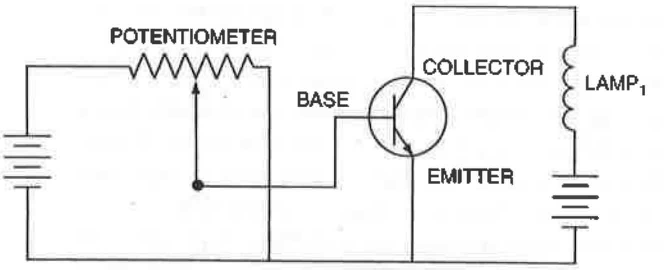


FIGURE 6-20 A potentiometer circuit.

fixed resistor, rheostat, or potentiometer must be such that the resistor can handle the current through the circuit without damage. It is always necessary to compute the current through the resistor by means of Ohm's law before placing the circuit in operation.

Voltage Dividers

Resistors are often arranged in such a manner as to create a **voltage divider** circuit. A voltage divider is simply two resistors placed in series with each other and in parallel with a voltage source. The voltage divider creates a voltage drop across each resistor that is proportional to the resistance of the individual resistor (see Fig. 6-21). When a high resistance load is placed across R_1 of the voltage divider, the load receives a voltage equal to (or close to) the original drop over R_1.

The actual voltage applied to the load is a function of the total parallel resistance of R_1 and R_{load}. In many cases, however, if the load resistance is large enough, the change in the voltage drop over R_1 is negligible with the addition of the load. The concept of a voltage divider circuit is the same as that used by a potentiometer circuit. In general, a potentiometer is a low power, adjustable voltage divider

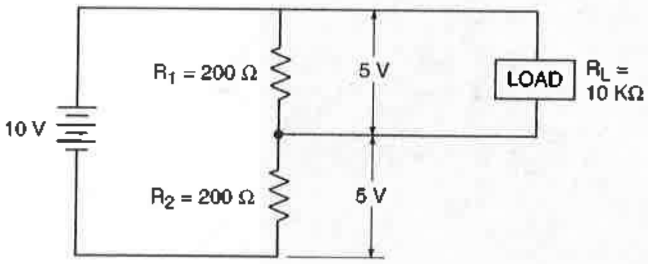


FIGURE 6-21 Example of a voltage divider circuit.

CAPACITORS

Capacitor Theory

A capacitor consists of two conductors that are capable of holding an electric charge and which are separated by an insulating medium. A simple capacitor, consisting of two metal plates separated by air, is shown in Fig. 6-22. The air, or some other insulating material, between the plates of a capacitor is called the **dielectric**. When the plates of a capacitor are connected to a voltage source, the capacitor becomes *charged*. This charge consists of an excess of electrons on the negative plate and a corresponding deficiency of electrons on the positive plate. If the capacitor is disconnected from the voltage source, the charge will remain in the capacitor for a length of time depending on the nature of the dielectric.

When a capacitor is charged, a static electric field develops across the dielectric, causing a positive charge to collect on one plate and a negative charge on the other. Energy is stored in the electrostatic field between the plates. The ability of a capacitor to store a static charge is known as **capacitance** and it is measured in units known as **farads**.

Unless there is a complete vacuum between the plates, the dielectric material between the plates of a capacitor consists of a large number of atoms. This holds true whether the dielectric is gaseous, liquid, or solid. Since the dielectric is an insulator, it takes a very high voltage to cause the free electrons to break away from the dielectric's atoms and move through the material. When the capacitor is charged, a voltage exists between the plates and acts upon the dielectric. During normal operation, the voltage is not great enough to cause the electrons in the dielectric to break away from their atoms; it does cause them to shift a small distance in their orbits. This shifting of the elections toward the positive plate of the capacitor creates what is known as a **dielectric stress**, which can be compared to a stretched rubber band. The dielectric stress is at least partially responsible for the force that causes a capacitor to dislodge.

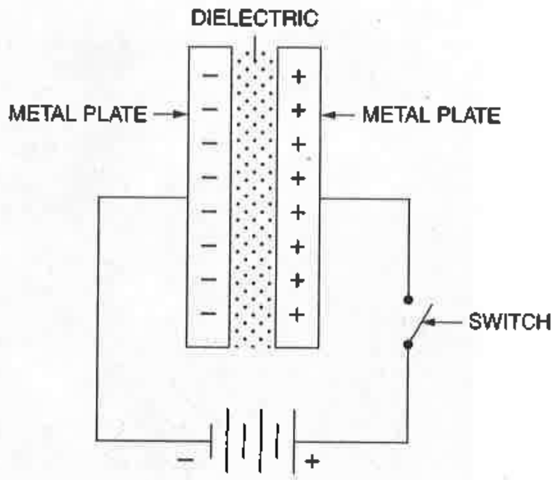


FIGURE 6-22 A simple capacitor circuit.

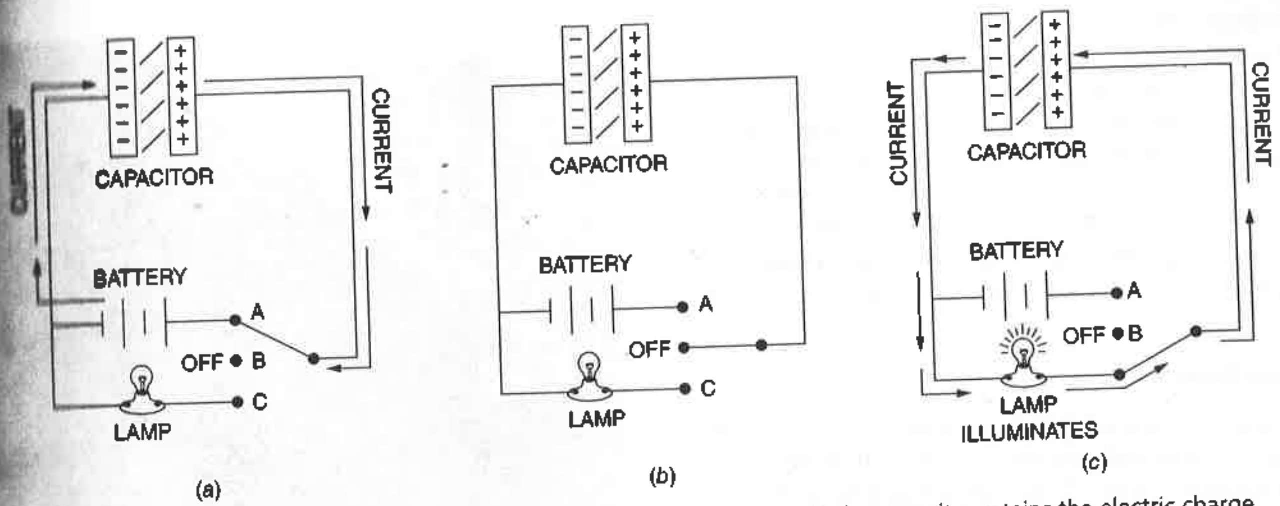


FIGURE 6-23 Capacitor operation: (a) the battery charges the capacitor, (b) the capacitor retains the electric charge, (c) the capacitor discharges into the lamp and the lamp illuminates.

Figure 6-23 shows the basic operation of a capacitor; refer to this diagram during the following discussion. If the switch is moved to position A, the capacitor is charged by the battery. The capacitor will retain this charge while connected to the battery or if the switch is moved to position B. When the switch is moved to position C, the capacitor discharges sending current through the lamp. The capacitor will continue to illuminate the lamp until the capacitor is discharged. In practice, most commonly used capacitors can only store a small amount of electrical energy and the lamp of this circuit would only illuminate for a short period, perhaps less than one second. It is obviously important to size any capacitor to specific circuit needs.

The construction of capacitors may vary widely, but all contain at least two electrical conductors separated by a dielectric (insulator). One common capacitor consists of two metal foils separated by a thin layer of insulating film. The foil becomes the conductor "plates" which can store an electric charge. Capacitors are widely used on aircraft as part of an electrical or electronic circuit. Capacitors are used for blocking direct current while allowing alternating current to pass, for smoothing the output voltage of power supplies, alternators and generators, and for resonant circuits that tune radios to particular frequencies.

The capacitance is greatest when there is a narrow separation between large areas of conductor (plates). In practice, the dielectric between the plates passes a small amount of leakage current and also has an electric field strength limit. If this limit is exceeded, the dielectric will breakdown and most likely destroy the ability for the capacitor to store a charge. This breakdown occurs when the capacitor is subjected to a voltage above the rated value of the capacitor.

A clear understanding of the operation of a capacitor can be had by studying the hydraulic analogy shown in Fig. 6-24. The capacitor is represented by a chamber separated into two equal sections by an elastic diaphragm representing the dielectric. These chambers are connected to a centrifugal pump by means of pipes. The pump represents the generator in an electric circuit, and the valve in one of the pipes represents a switch. When the pump rotates, it forces water into one of the chambers and causes the diaphragm to stretch. Water from the other chamber then flows out toward the pump. One of the chambers contains more water than the other, and the diaphragm, being stretched, maintains a pressure differential between the chambers. When the diaphragm pressure is equal to the pump pressure, the water will stop flowing, and the chamber will be "charged." If the valve is then closed, the diaphragm will maintain the differential of pressure between the sections of the chamber.

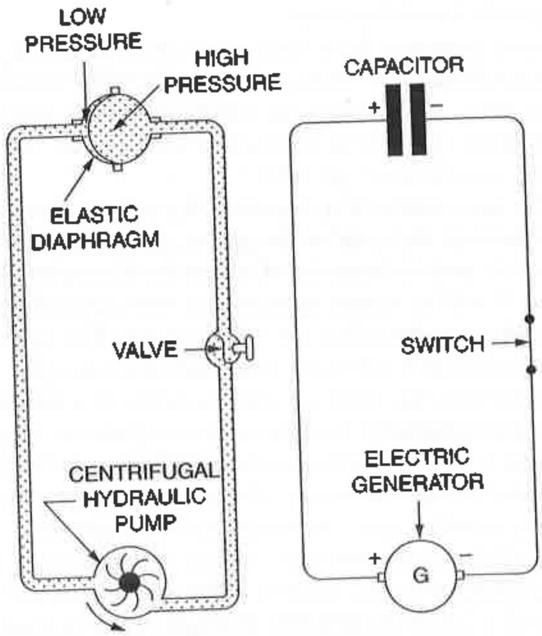


FIGURE 6-24 Hydraulic analogy of a capacitor.

In the corresponding electric circuit, when the generator is running, electrons are forced into one plate of the capacitor and withdrawn from the other plate. When the potential difference between the plates is equal to the voltage of the generator, the current flow will stop, and the capacitor will be charged. Now the switch can be opened, and the charge will remain in the capacitor.

Both the capacitor and the pressurized hydraulic chamber will continue to store potential energy until released. In the case of the capacitor, it could be discharged into another circuit, such as a resistor. In the case of the water, it could equalize pressure when the water was allowed to flow away from the high-pressure side of the elastic diaphragm.

Capacitance

The effect of a capacitor, that is, its ability to store an electric charge, is called **capacitance** (C). The unit of capacitance is the **farad** (F), which is the capacitance present when one volt will store one coulomb of electric energy in the capacitor. The farad is normally too large a unit for practical purposes, and so a smaller unit called the **microfarad** (μF) is generally used. One microfarad is one-millionth of a farad, and μ is the Greek letter mu.

Some capacitors have such small capacitance that even the microfarad is too large a unit for convenient expression of the value. In such cases the **picofarad** (pF) is used. One picofarad is equal to one-trillionth of a farad. This value can also be expressed as $1\ \text{pF} = 10^{-12}\ \text{F}$.

The capacitance of a capacitor depends on three principal factors: the area of the plates, the thickness of the dielectric, and the material of which the dielectric is composed. It will be readily apparent that two capacitors of the same physical dimension can differ considerably in capacitance because of a difference in the dielectric material.

To measure the dielectric characteristics of a material, a **dielectric constant** is used. Air is given a dielectric constant of 1 and is used as a reference for establishing the dielectric constants of other materials. Common dielectric materials include ceramics, glass, porcelain, and most plastics.

In addition to the dielectric constant of a material, its insulating quality must be considered. The insulating quality of a material is called its **dielectric strength** and is measured in terms of the voltage required to rupture (break down) a given thickness of the material. In selecting a capacitor for any purpose, it is important that the capacitance be correct and that the breakdown voltage of the capacitor be greater than the voltage to which the capacitor will be subjected when in use.

Types of Capacitors

There are two general types of capacitors: **fixed** and **variable**. The fixed capacitor is constructed with the plates and dielectric placed firmly together and covered with a protecting material such as plastic, ceramic material, or an insulated metal case. Because of the construction of a fixed capacitor, its capacitance cannot be changed.

Variable capacitors normally have fixed plates and movable plates arranged in such a manner that the dielectric effect between the plates can be changed by varying the distance between the plates or by moving one set of plates into or out of the other set. The construction of a typical variable tuning capacitor is shown in Fig. 6-25. Variable capacitors are used in radios and other electronic devices where it is necessary to change the capacitance to meet the requirements of a given circuit. The dielectric material in a variable capacitor is usually air.

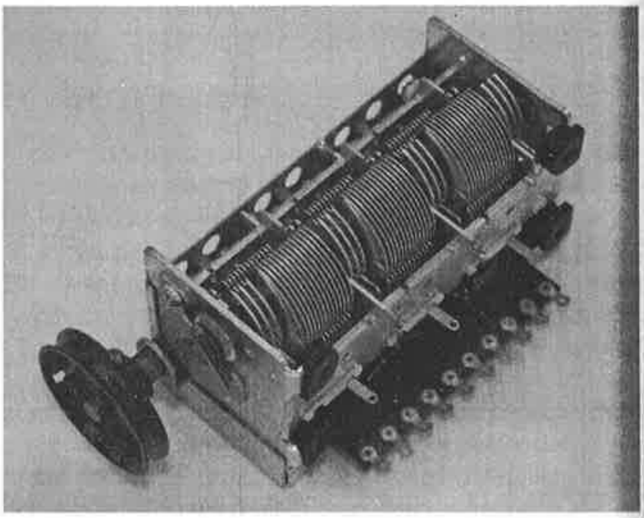


FIGURE 6-25 A variable capacitor.

Although the conducting elements of a capacitor are called plates, in a fixed capacitor they frequently consist of long strips of foil insulated with the plastic film and rolled together. The rolled plates are then covered with an insulating material and may be placed in a protective case. The leads from the plates may be brought out at one end or both ends of the case, depending on the design of the capacitor.

When a relatively high capacitance is desired in a small physical size, an **electrolytic** capacitor is used. In a capacitor of this type, the dielectric is a liquid or paste known as an *electrolyte*. The electrolyte forms an oxide on one of the plates, which effectively insulates it from the other plate. The dielectric constant of the electrolyte is much greater than that of the commonly used dry materials; hence, the capacitor has a considerably higher capacitance than the capacitors using dry materials. An electrolytic capacitor must be connected in a circuit with the correct polarity, because such a capacitor will allow current to flow through it in one direction. If the current flows through the plate of an electrolytic capacitor, the capacitance will be lost and the plates will decompose. Precautions must be taken to ensure that electrolytic capacitors are not connected in reverse and that they are not overloaded. Often these capacitors will overheat and burst if they are not connected and used properly. Incorrect use may thus create a safety hazard. Fixed capacitors of both the dry and the electrolytic types are manufactured in a wide variety of shapes, as shown in Fig. 6-26.

Multiple Capacitor Circuits

When capacitors are connected in parallel (Fig. 6-27), **the combined capacitance is equal to the sum of the capacitances.** The effect is the same as if one capacitor were used having a plate area equal to the total plate area of all the capacitors in the parallel circuit. Any multiple-plate

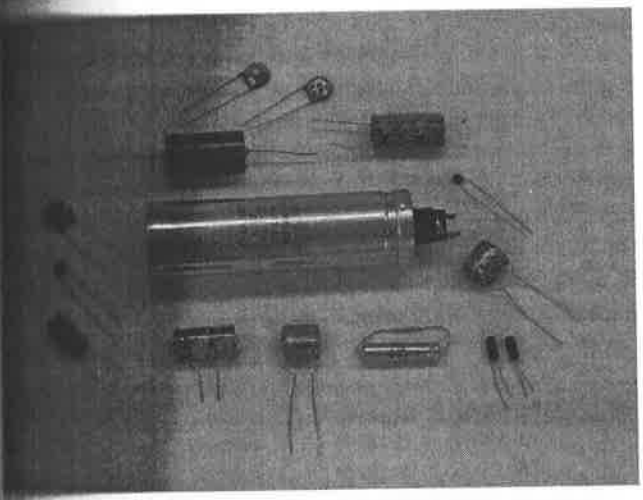


FIGURE 6-26 Capacitors.

capacitor is actually a group of capacitors connected in parallel. Since the capacitance varies directly as the area of the plates, it is apparent that two capacitors having the same plate area and connected in parallel have twice the capacitance of one, because the two capacitors have twice the plate area of the one.

The formula for capacitors connected in parallel is

$$C_t = C_1 + C_2 + C_3 \dots$$

For capacitors in series, the formula is similar to that used for resistances in parallel. **When capacitors are connected in series, the total capacitance is equal to the reciprocal of the sum of the reciprocals of the capacitances.** The formula is

$$C_t = \frac{1}{1/C_1 + 1/C_2 + 1/C_3 \cdots}$$

From the foregoing formula, it will be found that when capacitors are connected in series, the total capacitance decreases. The reason for this can be understood by observing a circuit where two capacitors of equal rating are connected in series (Fig. 6-27*b*). The two center plates will not contribute to the capacitance, because their charges are opposite and will neutralize each other. The effect is that of two outside plates acting through a dielectric that has twice the thickness of the dielectric of one of the capacitors. Therefore, the total capacitance of the two capacitors is equal to one-half the capacitance of one of the capacitors. Remember that the capacitance of a capacitor varies inversely as the thickness of the dielectric.

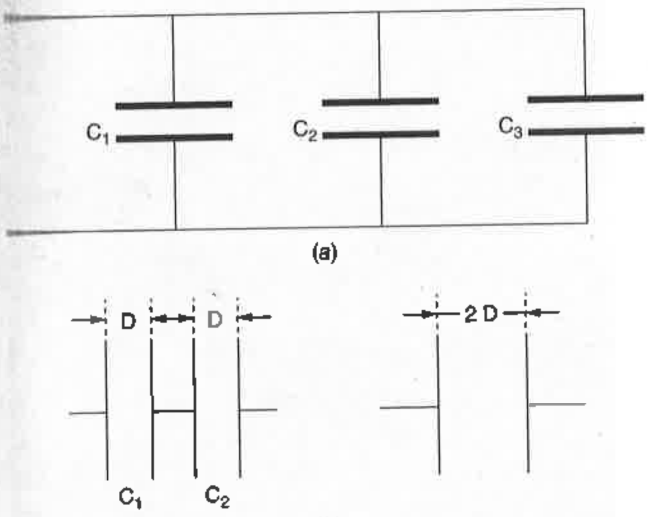


FIGURE 6-27 Capacitors connected (*a*) in parallel and (*b*) in series.

Time Constant

When a capacitor is connected to a voltage source, it takes a certain length of lime for the capacitor to become fully charged. If a high resistance is connected in series with the capacitor, the time for charging is increased. For any given circuit containing capacitance and resistance only, the time in seconds required to charge the capacitor to 63.2 percent of its full charge is called the **time constant** for that circuit. This same time constant applies when the capacitor is discharged through the same resistance and is the time required for the capacitor to lose 63.2 percent of its charge.

The charging and discharging of a capacitor in terms of time constants is illustrated in the graph of Fig. 6-28. It will be noted that it takes six time constants to charge the capacitor to 99.8 percent of full charge. The discharge curve is the exact reverse of the charge curve. When the capacitor is short-circuited, it will lose 63.2 percent of its charge in one time constant and almost 99.8 percent of its charge in six time constants.

To determine the length of a time constant in seconds for any particular capacitor-resistance circuit, it is necessary to multiply the capacitance (in microfarads) by the resistance (in megohms, or MΩ); that is,

$$T = CR$$

As an example of how the time constant can be used in determining the performance of a capacitor-resistance circuit, we shall assume that a 20-μF capacitor is connected in series

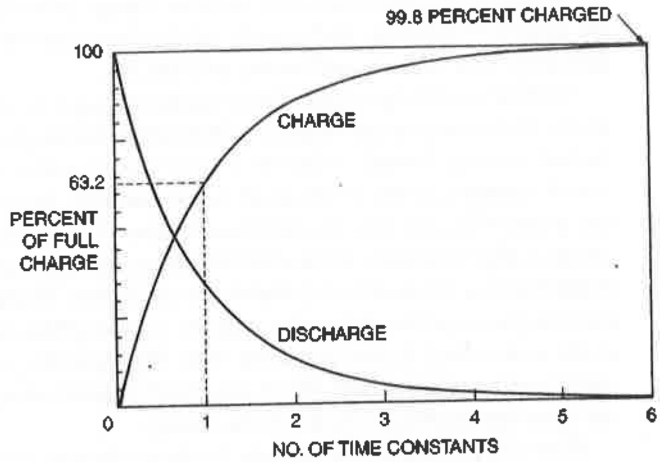


FIGURE 6-28 Curves showing the charging and discharging of a capacitor according to the time constant.

with a 10 000-Ω resistor and that 110 V is applied to the circuit at intervals of 0.5 s.

The time constant is equal to 20 × 0.01, or $T = 0.2$ s. (Note that 10 000 Ω is equal to 0.01 MΩ.) The time interval is given as 0.5 s; hence the number of time constants is 2.5. If we examine a time-constant chart or graph, we find that the voltage at 2.5 time constants will be approximately 92 percent of full voltage. Applying this to our problem shows us that 92 percent of 110 V is approximately 101 V. Thus we find that the capacitor in this problem will charge to approximately 101 V.

Effects and Uses of Capacitors in Electric Circuits

When a capacitor is connected in *series* in a dc circuit, no current can flow **through** the capacitor because of the insulating quality of the dielectric. (Current can only flow to the capacitor plates or away from the capacitor plates; never through the dielectric.) When a voltage is applied to such a circuit, there is a momentary flow of electrons into the negative plate of the capacitor and a corresponding flow out of the positive plate. As soon as the dielectric stress is equal to the applied voltage, the flow of electrons stops. If the voltage is removed, the charge remains in the capacitor until a path is provided through which the electrons can flow from the negative plate back to the positive plate.

When a capacitor is connected in *parallel* in a dc circuit, it opposes any change in the circuit voltage. As voltage from the source rises, current flows into the capacitor and thus slows the voltage rise in the rest of the circuit. If the voltage of the source remains at a higher level, the capacitor will charge to that level and will have no further effect on the circuit as long as the voltage remains constant. If the voltage from the source drops, the capacitor discharges into the circuit and holds the circuit voltage above that of the source for a short time. The property of capacitors to oppose changes in voltage is utilized in dc circuits to reduce or eliminate voltage pulsations. The voltage from a dc generator pulsates; that is, it varies slightly above and below the average value. When a capacitor of sufficient capacitance is connected in parallel with the generator output circuits, voltage pulsations are largely eliminated, and a more steady direct current is delivered. This is discussed further in Chap.10.

Another use for capacitors is to reduce the arcing at breaker points or switch contacts. When a switch opens and stops the current flowing through a circuit, a spark jumps across the switch's contact points. If this spark is uncontrolled, the contact points will soon become pitted and burned. This damage creates a high resistance at the switch contacts and can result in poor circuit efficiency or complete circuit failure. When a capacitor is connected in parallel with the contact points, the spark is absorbed by the capacitor; thus the capacitor prevents burning of the points. When the switch is again closed, the capacitor discharges back into the circuit.

Fluctuating voltages and currents in electric circuits cause the emanation of electromagnetic waves. These waves induce currents in radio and other sensitive circuits and interfere with their operation. Capacitors may be connected in the electric circuits at points where they will be most effective in absorbing the momentary fluctuations of voltage; in this way they reduce the emanation of electromagnetic waves.

In an ac circuit a capacitor is often used to block direct current but permit the flow of the alternating current. A capacitor can also be used in combination with an inductor and/or a resistor to allow certain ac frequencies to pass through the circuit; other frequencies are blocked. This technique is known *as filtering*.

INDUCTORS

Any electric conductor possesses the property of inductance; however, most **inductors** are specifically designed coils of wire. **Inductance is the ability of a conductor to induce a voltage into itself when a change in current is applied to the inductor**. An inductor can be a straight piece of wire or a coil. Figure 6-29 shows a variety of inductance coils.

The inductance of a single straight wire is usually negligible. However, if the wire is wound into a coil, the inductance value increases significantly. This is due to the relatively strong magnetic field produced by the current flowing through a coil of wire. It is the increase or decrease (a change) of this magnetic field that produces the coil's inductance. As discussed in Chap. 1, if there is relative motion between a conductor and a magnetic field, a voltage will be induced into that conductor. Figure 6-30 illustrates the formation of a magnetic field around an inductor coil with respect to time for a dc circuit. As illustrated, the magnetic field strength increases for a short time period, from point *A* to point *B*. This occurs at the instant current flow begins. Immediately after the switch opens, the current flow drops to zero. At this time, the magnetic field strength decreases as illustrated between points *C* and *D*. This increase and decrease of the magnetic field strength creates a relative motion between the

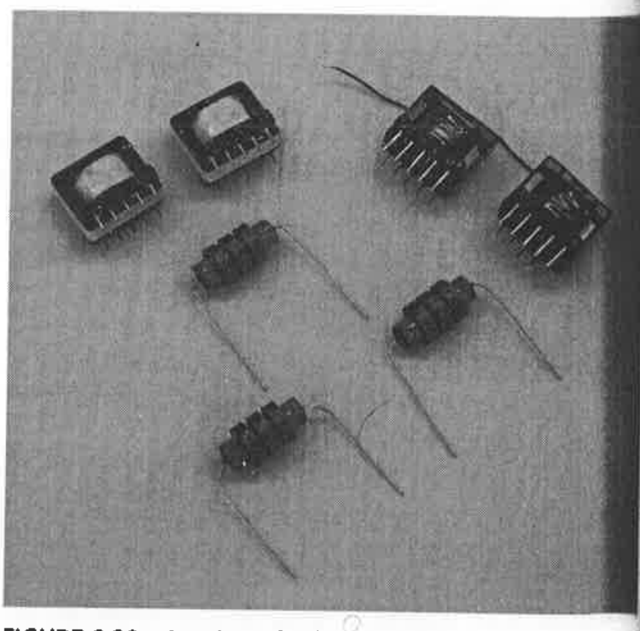


FIGURE 6-29 A variety of inductance coils.

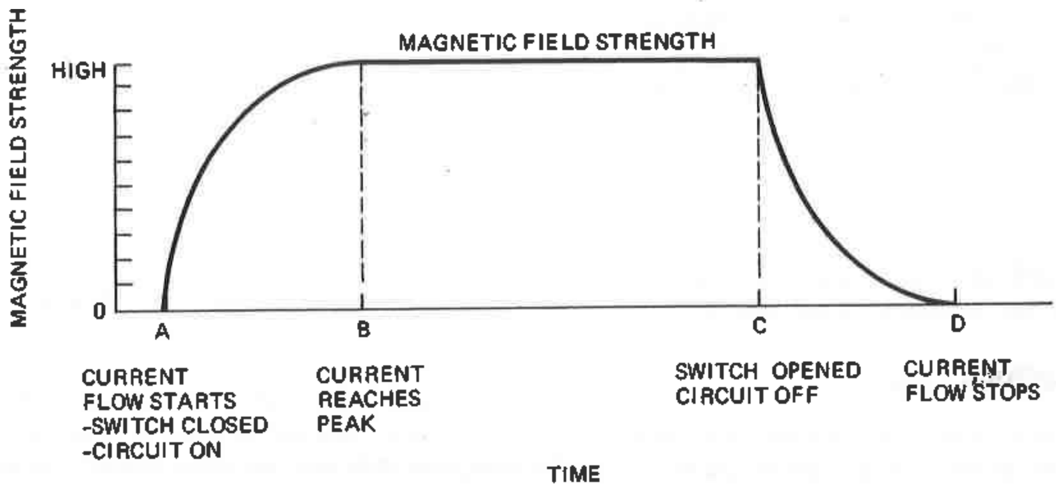


FIGURE 6-30 An inductance coil's magnetic field strength plotted with respect to time.

conductor and the magnetic field. That is, if the conductor is stationary and the magnetic field "grows" or "shrinks" around it, a voltage is induced into that conductor. This induced voltage is opposite in polarity to the source voltage. Since the induced voltage is opposite in polarity to the source voltage, it opposes the source voltage. This is illustrated in Fig. 6-31. The induced voltage is always much less than the source voltage; therefore, the induced voltage only weakens the source voltage. Current reacts in a similar manner. The induced current always opposes the applied current. The induced voltage exists only during changes in current flow (see Fig. 6-30). Therefore, inductance can be thought of as the ability to oppose changes in current flow.

Inductance can be compared to inertia of an object. Inertia tends to keep objects at rest and keep objects moving that already have motion, just as induced currents tend to keep electron flow zero if it is already zero and keep electrons flowing if they are already flowing. That is, induced currents tend to oppose changes in electron motion, just as inertia tends to oppose changes in an object's motion.

It was stated in Chap. 1 that the field strength of an electromagnet depends on the number of turns of wire in the coil, the current flowing in the coil, and the material in the core. Actually, an electromagnet and an inductance coil are essentially the same; hence, the effect of an inductance coil in a circuit also depends on the number of turns of wire in the coil, the current flowing in the coil, and the material used in the core. Inductance coils are made with soft-iron cores when a high inductive effect is desired. When a low inductive effect is desired, the inductance coil has no core; that is, the core is made of air.

The inductance of a coil is measured in a unit called the **henry** (H), named for Joseph Henry (1797–1878), an American physicist. **One henry is the inductance of a coil when a change of current of one ampere per second will induce an emf of one volt.** The symbol for inductance is the letter *L*. The henry is too large a unit for most applications, and so a smaller unit called the **millihenry** (mH) is used. One millihenry is one-thousandth of a henry.

As in the case with capacitance in a circuit with resistance, a time constant is applied in a circuit containing inductance in series with a resistance. In Fig. 6-28, the curves shown apply to an inductive circuit as well as a capacitive circuit. The curves for a circuit with inductance and resistance only are also shown in Fig. 6-32.

In the case of inductance, the maximum current flow in a circuit is delayed for a short time after the inductance coil is connected to a power source. The time constant is the time in seconds that is required for the current flow to reach 63.2 percent of maximum after the circuit is connected to the power source. The time constant for a decaying current is the time in seconds required for the current flow to fall to 36.8 percent of maximum. This is the same time as is required for the increase to 63.2 percent of maximum.

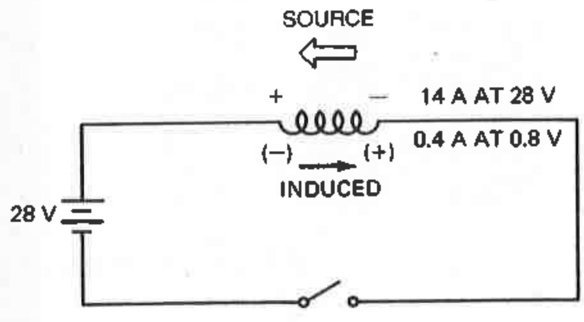


FIGURE 6-31 Relationships of applied voltage to induced voltage.

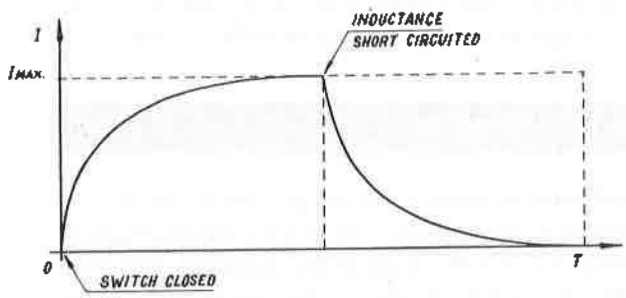


FIGURE 6-32 Curves showing the effects of inductance on the rise and fall of current.

To determine the time constant for a circuit containing only inductance and resistance, it is necessary to divide the inductance (L) in henrys by the resistance (R) in ohms. Hence,

$$T = \frac{L}{R}$$

If a 10-H inductance coil is connected in series with a 200-Ω resistance, the time constant is 10/200, or 0.05 s.

Multiple Inductor Circuits

In some cases two or more inductors are combined in a series or parallel arrangement. In either case the total inductance of the circuit changes owing to this combination. When inductors are wired in series with each other, the total inductance is increased. The resultant is the sum of the inductor values within the circuit, as shown by the following equation.

$$L_t = L_1 + L_2 + L_3 \ldots$$

When inductors are placed in parallel with respect to each other, the total inductance is decreased. The following equation is used to find the total inductance of two or more inductors in parallel.

$$L_t = \frac{1}{1/L_1 + 1/L_2 + 1/L_3 \cdots}$$

Uses of Inductors

As explained in Chap. 5, the opposition to current flow in an ac circuit created by an inductor is called **inductive reactance** and is measured in ohms. Since radio signals are transmitted using a rapidly changing (high-frequency) electromagnetic energy, inductors are often used in combination with capacitors to provide tuned circuit. These tuned circuits are most valuable in radio and television for filtering out unwanted frequencies and passing the desired frequencies.

In many electronic circuits it is desirable to use inductors that are variable in inductance. This means that devices must be provided that enable the operator to change the inductance of the inductance coil. A common method for changing the inductance is to use a powdered-iron core in the inductor and provide a means whereby this core can be moved in and out of the coil. An inductance coil that contains a movable core for tuning purposes is often called a *slug-tuned* inductor. Inductors of this type are often found in small radio receivers.

TRANSFORMERS

A **transformer** is a device used to increase or decrease the voltage in an ac circuit. In fact, one of the chief advantages of alternating current is that it can be transmitted at a high voltage with a low power loss; the voltage can then be reduced to any desired value by means of a transformer. We therefore frequently find transformers in ac systems.

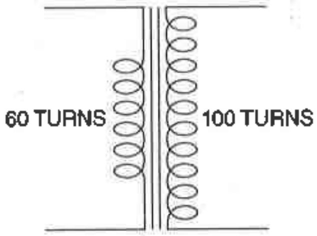


FIGURE 6-33 A schematic diagram of a transformer.

A schematic diagram of a transformer is shown in Fig. 6-33. It was explained in Chap. 1, in the section on electromagnetic induction, that every conductor of an electric current has a magnetic field. If alternating current is flowing in a conductor, the magnetic field around the conductor expands and collapses rapidly as the current changes in magnitude and direction. This rapidly changing magnetic field that surrounds all wires carrying alternating current makes the use of transformers possible.

A transformer consists of a **primary winding** and a **secondary winding** that typically surrounds a laminated soft-iron core or an annealed sheet steel core. The secondary coil may be wound on the primary coil or on a separate section of the same core. This is illustrated in Fig. 6-34. The laminated core reduces the effect of **eddy currents**, which otherwise would cause considerable heat and a loss of power.

The transformer theory of operation is similar to that of an induction coil. As an ac current flow is fed through the primary winding, a magnetic field expands and contracts around that winding. If another inductance coil, the secondary, is placed near the primary, it will receive an induced voltage from the constantly changing magnetic field of the primary. If the second coil is connected to a circuit, the induced voltage will produce a current flow. The greater the applied ac frequency (within limits), the better the voltage transformation between the primary and secondary. A relatively higher frequency ac, therefore, allows for the use of smaller transformers. Because of the inductive reactance of the primary and secondary coils, the induced voltage in

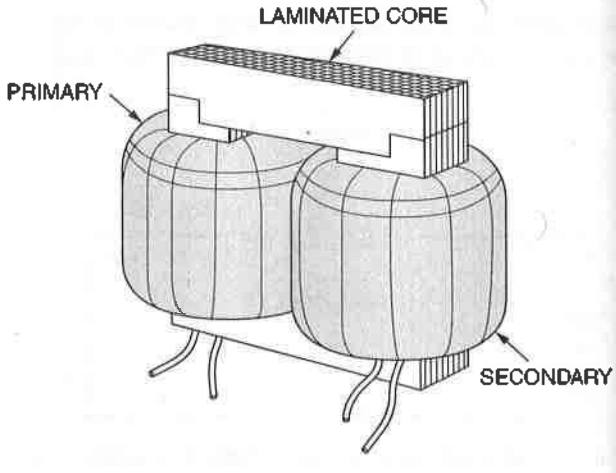


FIGURE 6-34 A transformer.

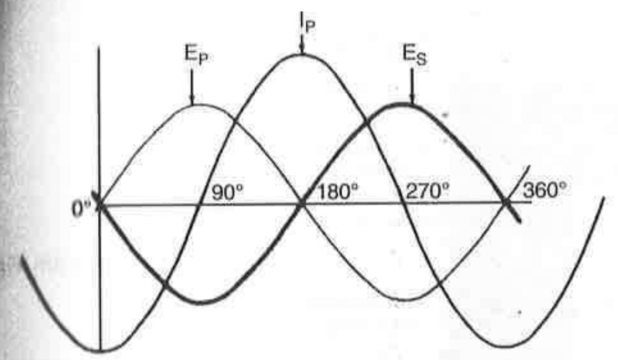


FIGURE 6-35 Voltage and current in the coils of a transformer.

the secondary is nearly 180° out of phase with the primary voltage. This is because the primary current is nearly 90° out of phase with the primary emf, owing to the inductance of the primary winding, and the emf of the second coil is 90° out of phase with that of the primary. In theory, the secondary emf of a circuit with no resistance would be exactly 180° out of phase with the emf of the primary, but since no circuit can be free of resistance, the secondary voltage will be slightly less than 180° out of phase with the primary voltage.

A study of Fig. 6-35 will help the student to understand the phase relationships in a transformer circuit. The curve E_p represents the emf applied to the primary coil of the transformer. I_p is the current in the primary, which lags behind the primary emf by almost 90° because of the inductance of the primary winding. Since the current change is greatest as the current reverses direction, a maximum emf (E_s) is induced in the secondary at this point. When the current reaches a maximum value at 180° on the curve, there is an instant when there is no current change; hence, at this point there is no induced emf in the secondary. As the current value decreases, the rate of change increases, and the secondary emf increases to oppose this change.

One of the most important features of a transformer is that the primary coil can be left connected to the line and will consume very little power unless the secondary circuit is closed. (**Line**, is a term used to describe an AC power source.) This is because of the inductive reactance of the primary winding. The primary current sets up a field that induces an opposing emf in the primary coil. This opposing emf is called **counter emf** and is almost equal to the emf applied to the coil; hence, only a very small current will flow in the coil when there is no load applied to the transformer secondary.

We can consider the field as a reservoir of power, and when the secondary circuit is closed, power is being drawn from the reservoir. Then current will flow in the primary circuit sufficient to maintain the field flux at a maximum value. If the secondary circuit is disconnected, no more power will be drawn from the field; hence, very little current will be necessary to maintain the field strength. From this we can see the current flow that enters the primary winding is directly related to the current that leaves the secondary winding.

Since the primary and secondary coils of a transformer are wound upon the same core, they are both affected by the same magnetic field. It will be remembered that the emf induced in a coil depends on the magnetic field strength and the number of turns in the coil. Since both the primary and secondary coils are being cut by the same magnetic field, the ratio of the primary emf to the secondary emf is proportional to the ratio of the number of turns of wire in the primary to the number of turns in the secondary. For example, if the primary coil has 100 turns of wire and the secondary has 200 turns, then the emf of the secondary will have twice the value of the emf in the primary. The formula for these values is

$$\frac{E_p}{E_s} = \frac{N_p}{N_s}$$

where E_p = voltage in primary
E_s = voltage induced in secondary
N_p = number of turns in primary winding
N_s = number of turns in secondary winding

It is obvious that the power output of a transformer cannot be greater than the power input. Since the power in a transformer is approximately equal to the voltage times the amperage, we can see that if the voltage in the secondary is higher than the voltage in the primary, then the amperage in the secondary must be lower than the amperage in the primary. In a transformer that is 100 percent efficient, the ratio of the amperage in the primary to the amperage in the secondary is inversely proportional to the ratio of the voltages. The formula for this relationship is

$$\frac{E_p}{E_s} = \frac{I_s}{I_p} \quad \text{or} \quad E_p I_p = E_s I_s$$

The equations for voltage, current, and number of turns in the primary and secondary for a transformer can be combined as follows:

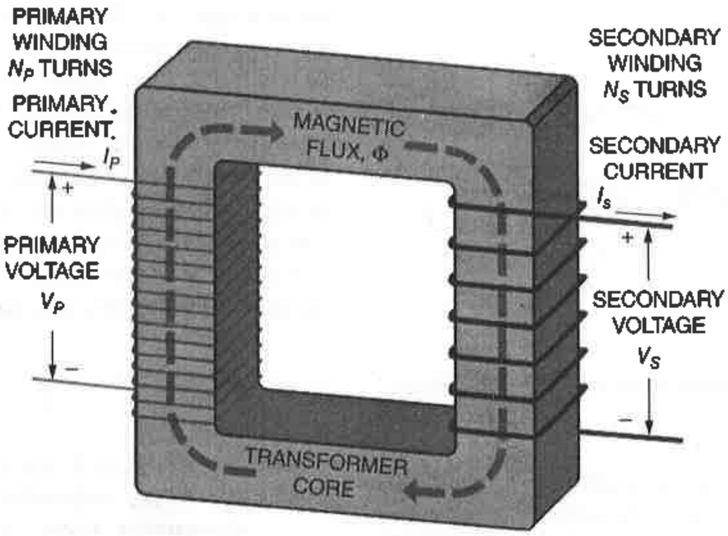
$$N_p/N_s = E_p/E_s = I_s/I_p$$

Or,

$$\frac{\text{TURNS}_{(p)}}{\text{TURNS}_{(s)}} = \frac{\text{Voltage}_{(p)}}{\text{Voltage}_{(s)}} = \frac{\text{Current}_{(s)}}{\text{Current}_{(p)}}$$

When the secondary of a transformer has more turns of wire than the primary and is used to increase voltage, the transformer is called a **step-up** transformer. When the transformer is used to reduce voltage, it is called a **step-down** transformer. In many cases the same transformer can be used as either a step-up or a step-down transformer. The coil connected to the input voltage is called the primary, and the coil connected to the load is called the secondary. Another way to consider the input and output values of a transformer is remember that power in to a transformer always equals the power out of the transformer. For now, let's assume that the transformer is 100 percent efficient and there is no loss during the transformer action. In this case,

$$\text{Power}_{\text{(primary)}} = \text{Power}_{\text{(secondary)}}$$



TRANSFORMER SPECIFICATIONS:

N_P = 1000 TURNS

V_P = 120 VOLTS

I_P = 10 AMPS

N_S = 500 TURNS

V_S = 60 VOLTS

I_S = 20 AMPS

POWER $_{(PRIMARY)}$ = POWER $_{(SECONDARY)}$

VOLTAGE $_{(P)}$ × CURRENT $_{(P)}$ = VOLTAGE $_{(S)}$ × CURRENT $_{(S)}$

OR 1200 W $_{(PRIMARY)}$ = 1200 W $_{(SECONDARY)}$

120 V $_{(P)}$ × 10 A $_{(P)}$ = 60 V $_{(S)}$ × 20 A $_{(S)}$

FIGURE 6-36 Transformer specifications.

and since Power = voltage × current ($P = E \times I$) we can substitute as follows:

$$E_{(primary)} \times I_{(primary)} = E_{(secondary)} \times I_{(secondary)}$$

or

$$\text{Voltage}_{(p)} \times \text{Current}_{(p)} = \text{Voltage}_{(s)} \times \text{Current}_{(s)}$$

Since both sides of the equation must be equal, it can be seen that if the transformer's secondary voltage is increased, the maximum current available in the secondary must decrease compared to the primary. Figure 6-36 shows an example of how to determine the output of a typical transformer. In this example, a 100 percent efficient step down transformer is used to simplify calculations. Most transformers are between 90 and 98 percent efficient; with larger transformers having higher efficiencies. Most of the power lost by transformers is changed into heat and noise; transformers get warm and often buzz or hum.

If it becomes necessary to use more than one transformer in a circuit, with the transformers connected either in series or in parallel, it is most important that they be properly *phased.* Figure 6-37 illustrates a simplified circuit for two

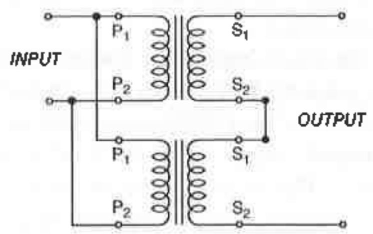


FIGURE 6-37 Transformers connected in series.

transformers connected in series. Note that the primary terminals P_1 of the first transformer and P_1 of the second transformer are connected to the same line of the power supply and that the P_2 terminals of the transformers are likewise connected to the same line of the power supply. With the primary circuits connected in this manner, the secondary terminals S_1 will be positive at the same time and negative at the same time. Therefore, to connect the two secondary circuits in series to obtain maximum voltage, S_2 of one transformer should be connected to S_1 of the other transformer and the opposite terminals S_1 and S_2 then used as output terminals. With this arrangement the voltages are additive, and the total output will be 220 V if the individual secondary windings

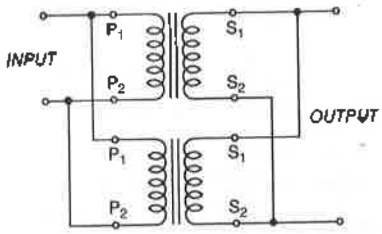


FIGURE 6-38 Transformers connected in parallel.

produce 110 V each. If the two secondary windings in this series were connected so that S_2 of one transformer was connected to S_2 of the other, then there would be no output from the two S_1 terminals, because the voltages would be working in opposite directions.

In Fig. 6-38, transformers are shown connected in parallel. The primary windings are connected in the same manner as those in the circuit of Fig. 6-37. To connect the secondary windings in parallel, the two terminals S_1 and the two terminals S_2 are connected to the same line. The output between these lines will then have the same voltage as each individual winding, and the available amperage will be additive. If the connection for one of the secondary windings is reversed, a short circuit will be created between the two secondary windings, and the transformers will be burned out, or the circuit breaker in the power supply will be opened.

DIODES AND RECTIFIERS

A **rectifier** is a device that allows current to flow in one direction but will oppose, or stop, current flow in the opposite direction. A rectifier can be compared to a check valve in a hydraulic system. A check valve is a one-way gate for fluids; rectifiers are one-way gates for electrons.

There are several types of solid-state rectifiers currently in use. The term **solid-state** refers to a device in which a solid material is used to control electric currents through the manipulation of electrons. Solid-state devices have proved to be a very reliable and efficient means of electron control for a wide range of applications.

Diodes

To understand the operating principles of a diode, one must first understand semiconductor theory. We shall, therefore, give a brief description of the structure of semiconductor materials and the electronic activity within a diode. Semiconductors are also known as solid-state devices because they are solid and contain no loose or moving parts.

The principal semiconductor materials used for rectifiers are **silicon** and **germanium**. It was explained in Chap. 1 that a semiconductor element has four electrons in the outer orbit, or shell, of each atom. Silicon has a total of 14 electrons in the atom, 4 of these being in the outer shell. Germanium atoms have 32 electrons, with 4 in the outer shell. In the pure state, neither of these materials will conduct an electric current easily.

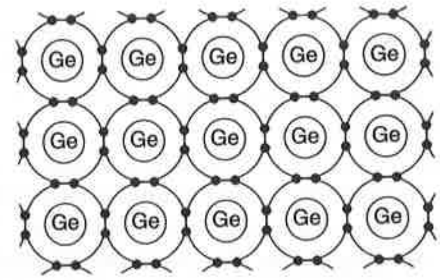


FIGURE 6-39 Germanium valence bonds.

This is because the atoms have a strong **valence bond** formed as the electrons in the outer shell of each atom pair with the electrons in adjacent atoms. This is shown in Fig. 6-39. The illustration is a two-dimensional concept of the **crystal lattice** for germanium. Actually, the electrons are in spherical shells rather than rings, and they rotate about the nuclei of the atoms. However, they still form energy bonds in the outer shells, and they are not easily moved from one atom to another. The only way this can happen is when a very high voltage is applied across the material and the valence bonds are broken. It can be stated that pure germanium and silicon do not have free electrons to serve as current carriers.

To make germanium or silicon capable of carrying a current, a small amount of another element (impurity) is added. This is called **doping**. The element **antimony**, having the chemical symbol Sb, has five electrons in the outer shell of each atom. When this material is added to germanium, the germanium becomes conductive. The reason for this is that the fifth electron from the Sb atom cannot bond with the germanium electrons and is left free in the material. This is shown in Fig. 6-40. Remember that the germanium atoms have four electrons in the outer shell of each atom; hence, only four of the Sb electrons can become paired in the valence bonds.

When germanium is treated with antimony, the resulting material is called ***n*-type** germanium because it contains extra electrons, which constitute negative charges. It must be remembered, however, that the material is still electrically neutral because the total number of electrons in the material is balanced by the same number of protons. The Sb atom has 51 protons, and their positive charge balances the negative

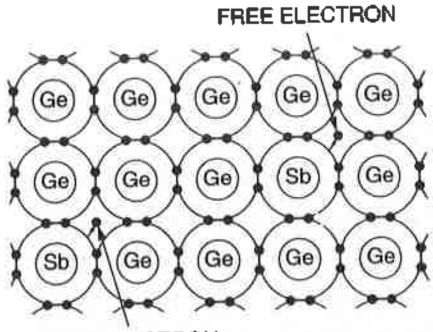


FIGURE 6-40 Effect of adding antimony to germanium to form *n*-type material.

charge of the 51 electrons in each atom. One of 51 electrons is forced out of the outer shell of the Sb atom, and this becomes a free electron. The Sb is called a **donor** because it *donates* electrons to the material.

When the element indium (In) is added to germanium, vacant spaces are left in the valence bonds because indium atoms have only three electrons in the outer shell. The vacant spaces are called **holes.** The holes can be filled by electrons that break away from the valence bonds. When this occurs, another hole is left where the electron previously was situated. Thus the holes appear to move through the material.

The hole represents a net positive charge because a balanced condition requires that a pair of electrons occupy each bond. When one of the electrons is missing, the bond lacks the normal negative charge; hence it is positive and attracts electrons. An illustration of ***p*-type** germanium is shown in Fig. 6-41. The holes can be seen adjacent to the indium atoms. Indium added to germanium is called an **acceptor** because it *accepts* electrons from other atoms.

The *n*-type material of a rectifier is known as the **cathode;** the *p*-type material is the **anode.** The cathode is the electron emitter, or negative connection. The anode is the electron acceptor, or positive connection. These polarities must be observed if the diode is to conduct electricity.

When a piece of *n*-type germanium forms a **junction** with a piece of *p*-type germanium, an interesting phenomenon takes place. Since there are holes (positive charges) in the *p*-type germanium and electrons (negative charges) in the *n*-type germanium, there is a drift of holes and electrons toward the junction. The holes are attracted by the negative charge of the electrons in the *n*-type material, and the electrons are attracted by the positive charge of the holes in the *p*-type material. Some of the electrons diffuse across the junction lo fill holes on the positive side. This movement of charges leaves a large number of negative ions in the *p*-type material farthest from the junction and a large number of positive ions in the *n*-type material farthest from the junction. Remember that the material is electrically neutral, as a whole, before the junction is made, because the number of electrons is balanced by the number of protons. The material is still electrically neutral as a whole after the junction is made, but some portions have negative charges, and other portions have positive charges.

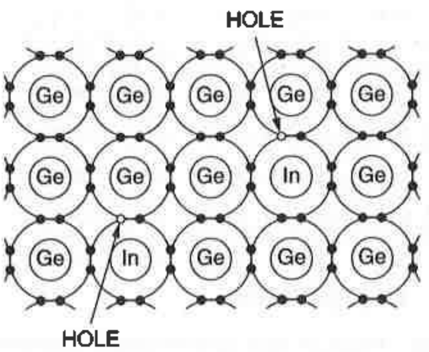


FIGURE 6-41 Addition of indium to form *p*-type material.

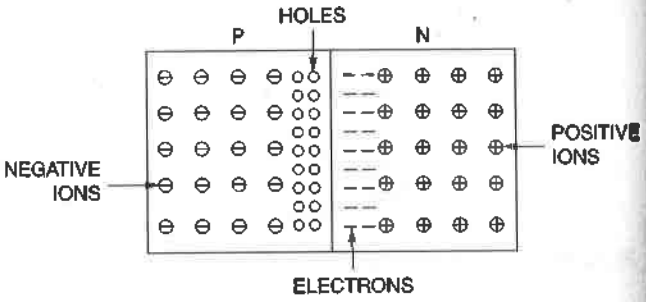


FIGURE 6-42 Junction of *p*- and *n*-type materials to form a potential barrier.

The stationary ions on each side of the junction provide charges that stop the movement of electrons across the junction. These charges result in a **potential barrier** with a voltage of approximately 0.3 for germanium and 0.6 for silicon. Figure 6-42 illustrates the condition that exists when a junction of two different types of germanium is made. Note that holes move toward the junction from the *p*-type material, and electrons move toward the junction from the *n*-type material until the charges are balanced. The previous discussions focused on germanium semiconductors; this same theory applies to silicon semiconductors as well. When arsenic is added to silicon, the material has an excess of electrons and becomes negative. When aluminum is added to silicon the material has too few electrons, and the material becomes positive.

One common use of semiconductors is to create diodes. A diode can be thought of as a one-way gate for electrons; that is, the electrons can flow through the diode in one direction and not the other. Therefore, a diode can be used to prevent current flow if the voltage polarity is **incorrectly** applied to the diode and to allow current flow when voltage polarity is correct. An example of this situation is shown in Fig. 6-43. Here, one can see that as the battery is connected with the polarity one way the diode current will conduct; if the polarity is reversed, the diode will not conduct. Of course, this simplified circuit contains no electrical load and performs no practical function; the circuit is for explanation only; diodes are always used in conjunction with other circuit elements.

In Fig. 6-43(*a*) the battery is connected such that its negative terminal is joined to the *n* side of the diode. In this way the electrons flowing from the negative side of the battery neutralize the effect of the positive ions, which would otherwise affect the current flow. This makes it possible for the electrons to flow across the barrier (junction) to occupy the holes and flow on toward the positive battery terminal. Thus the diode has become a good conductor in one direction, that is, from *n* to *p*. The diode in its conducting mode is said to be **forward-biased.**

In Fig. 6-43(*b*) we observe the condition when the battery is connected in the opposite direction, which is called **reverse bias.** Here the positive terminal of the battery is connected to the *n* side of the diode. The free electrons are drawn toward the positive charge until the potential balances. The holes in the *p* side of the diode move toward the negative charge so there can be no movement of electrons across the junction. Under this condition no current can flow.

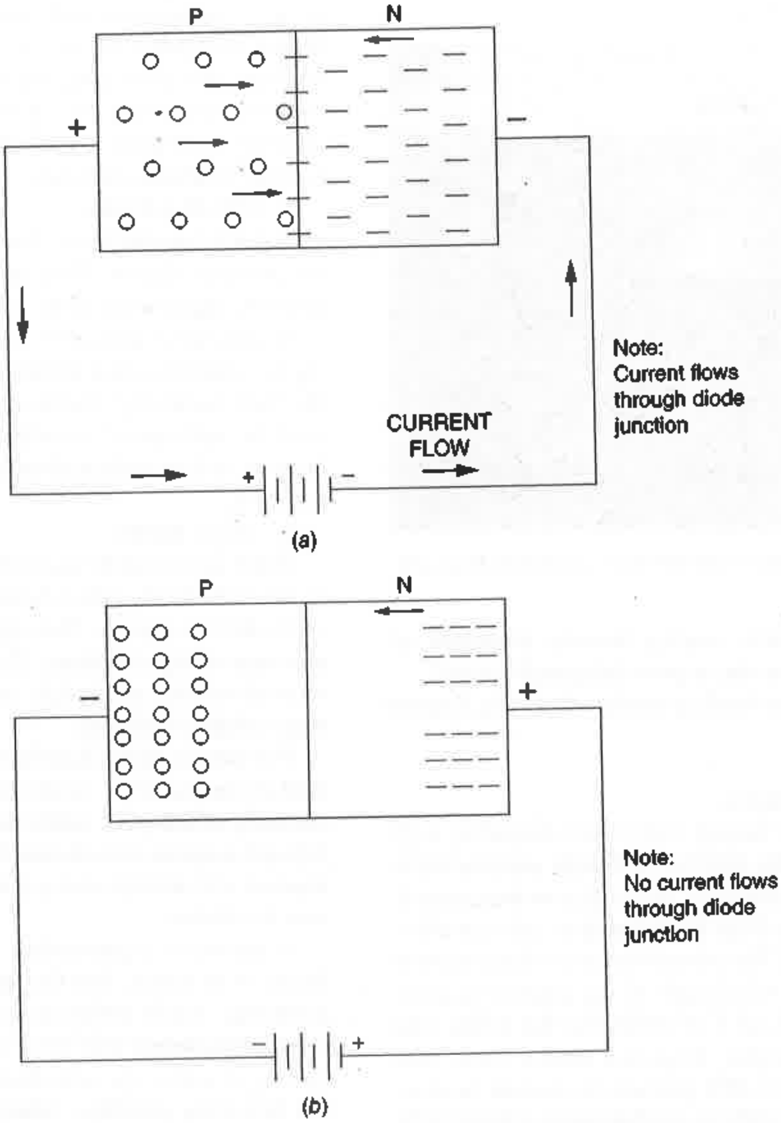


FIGURE 6-43 Diode theory; (*a*) forward biased, (*b*) reverse biased.

Most diodes found in today's modern equipment are silicon junction diodes. This diode is named for the physical connection (or junction) between the N and P materials of the diode. The junction is also referred to as the **depletion region** due to the absence of electrons or holes in this area of the diode. The diode's terminals are attached to each of these regions. The boundary between these two regions, called a **p–n junction**, is where the action of the diode takes place.

There are several types of junction diodes, each designed with a different physical shape or size, different types of electrical connections, or the diode may be one of many specialty diodes (see Fig. 6-44). Power diodes (those used to control relatively high current flow) are typically individual components assembled on a circuit card or mounted on a heat sink to help dissipate heat as seen in Fig. 6-45. Diodes designed to carry very little current flow have become extremely small and are typically formed onto an integrated circuit along with resistors, transistors, and other miniaturized components.

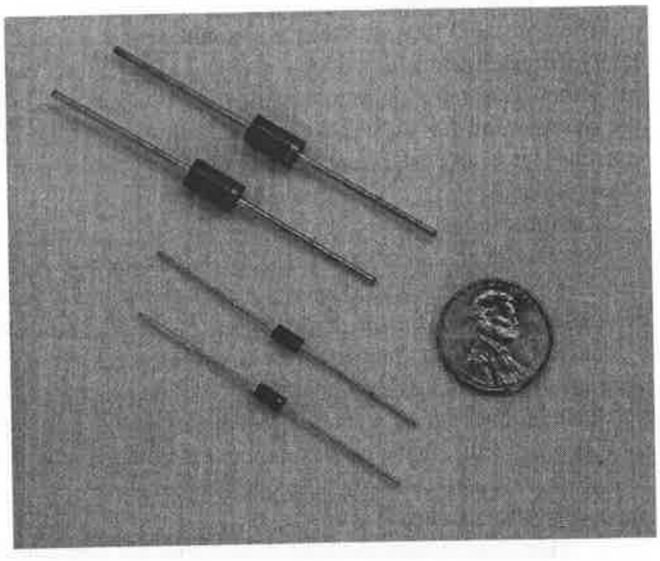


FIGURE 6-44 Typical diodes.

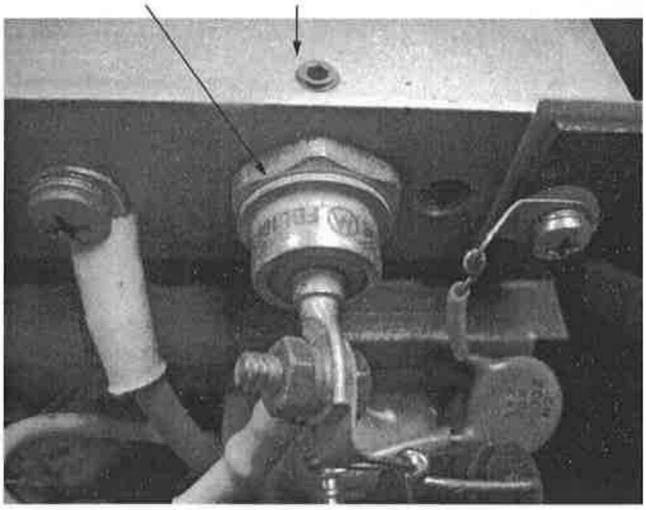


FIGURE 6-45 Power diode mounted to an aluminum heat sink.

Modern computer devices employ literally thousands of diodes, each contained in one or more integrated circuits.

Some common diodes found in modern electronic systems include:

1. Light-emitting diodes

An LED is typically formed with a semiconductor, such as gallium arsenide. This material will emit photons when current flows across the junction. Depending on the material, wavelengths (or colors) from the infrared to the near ultraviolet may be produced. The forward-biased voltage of these diodes depends on the wavelength of the emitted photons: 2.1 V corresponds to red, 4.0 V to violet. The first LEDs were red and yellow, and higher frequency diodes have been developed over time. All LEDs produce incoherent, narrow-spectrum light; "white" LEDs are combinations of three LEDs of a different color, or a blue LED with a yellow coating. Due to their low power consumption and long life cycle, LEDs are becoming common in modern aircraft lighting and flat panel displays used for instrumentation.

2. Laser diodes

When an LED-like structure is contained in a resonant cavity formed by polishing the parallel end faces, a laser can be formed. Laser diodes are commonly used in optical storage devices and for high-speed optical communication. A laser pointer is an example of a common device which uses a laser diode.

3. Photodiodes

Photodiodes are intended to sense light (photodetect). The semiconductor material used to create the diode p-n junction of a photodiode must be sensitive to light, and the diodes must be contained in a material that allows light to pass, such as a clear plastic. When light reaches the semiconductor material the diode produces a DC voltage. Photodiodes are commonly used in solar cells, light sensors, and optical communication devices that typically employ fiber-optic cable.

4. Thermal diodes

This term is used both for diodes that are heat sensitive (monitor temperature), and for heat-pump type diodes that are used for thermoelectric heating and cooling. Heat-pump diodes are made from two semiconductor materials but do not have any rectifying junctions. Heat-pump diodes are currently in limited use; however, they have great future potential to become a very efficient way to move heat for cooling or heating purposes.

5. Schottky diodes

Schottky diodes have a lower forward voltage drop than p-n junction diodes. They also tend to have much lower junction capacitance than p–n diodes, which causes the semiconductor material to operate (change from conducting to nonconducting modes) at very high speeds. Due to the high-switching speeds of a Schottky diode, they are used in high-speed circuitry and RF (radio frequency) devices such as switched-mode power supply, mixers, and detectors.

6. Zener diodes

These diodes can be made to conduct in the reverse-biased mode. This effect, called Zener breakdown, occurs at a precisely defined voltage. This allows the diode to be used as a precision voltage reference. The Zener diode has become the heart of virtually all modern voltage control circuits or solid-state voltage regulators.

The various diodes listed above are some of the most common types; however, numerous other specialty diodes are currently available or under development. As the aerospace industry matures, it is obvious that the use of solid-state components will increase and engineers will continue to find new uses for diodes.

A principal consideration in the installation of power diodes is to ensure that the diode is firmly attached to the mounting, which serves as a **heat sink**. Diodes that carry substantial current will become overheated and damaged or destroyed unless the heat developed is conducted away by the mounting structure. Many power diodes are provided with cooling fins by which heat is dissipated.

Large diodes are constructed with heavy metal bases to be mounted securely to a metal structure heavy enough to act as a heat sink. Before a diode is mounted, the base of the diode should be inspected for cleanliness and smoothness, and the mount to which it is to be attached should be similarly inspected. This is to assure that there will be maximum metal-to-metal contact between the base of the diode and the mounting. In some cases, a heat-conducting gel is placed between the diode base and the mounting to fill any gaps caused by irregularities in the surfaces to be joined. This assures maximum heat conductance from the diode to the mounting.

Heat sinks can also be used for other solid-state devices that generate large amounts of heat. Often cooling fans are used in conjunction with heat sinks to help dissipate heat from the component. A typical heat sink and transistor assembly is illustrated in Fig. 6-46.

Diode Testing. A diode is a one-way gate for electrons; therefore, it can be tested by applying a voltage to the diode and measuring the current flow. The voltage polarity is then reversed, and the current is measured again. An ohmmeter can be used as a source of power for this test.

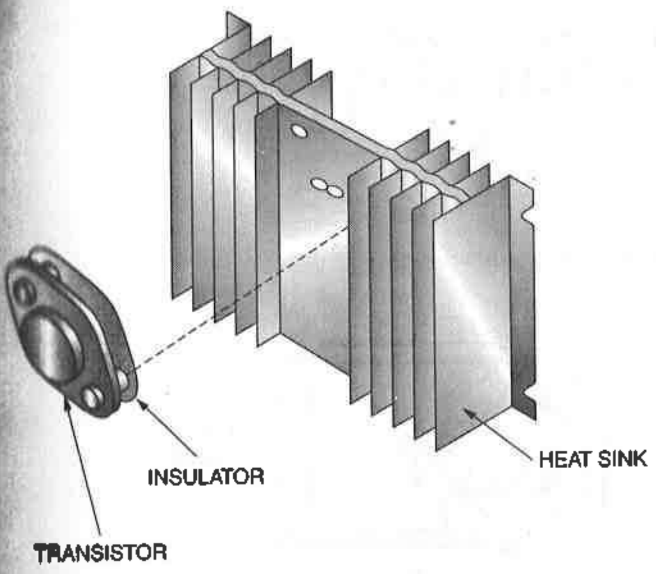


FIGURE 6-46 A transistor heat sink assembly.

A common digital multimeter is designed to perform this test using the **diode test function** of the meter. As shown in Fig. 6-47, a technician must follow these steps to test a diode:

1. Set the meter selection switch to the diode test function.
2. Connect the diode to the meter red and black test probes.
3. Read the indication on the meter display.
4. Reverse the polarity of the meter connections (reverse the red and black meter probes as connected on the diode).
5. Read the indication on the meter display.

During this test, the multi-meter's internal battery will apply a voltage to the diode. If the meter probes are connected to the diode in a forward-biased condition, the diode will conduct. When the meter probes are reversed, the diode will not conduct. The meter will indicate the proper operation of a diode by showing the voltage drop on the forward-biased diode; and no voltage drop on the reverse-biased diode. Therefore, a properly operating silicon diode will indicate approximately 0.6 to 0.7 V drop when the diode is forward-biased. This same diode must indicate 0.0 V drop in the reverse-biased mode to be considered as a functioning diode.

Keep in mind, various meters may have slightly different indications. One common difference is that the display is indicated in millivolts not volts; so a properly functioning forward-biased silicon diode would show 600 to 700 mV. Also remember that all diodes will not have the same voltage drop. A germanium diode will have a voltage drop of approximately 0.3 V when forward-biased. Different specialty diodes may have other voltage values when forward-biased; be sure to refer to the specifications of the diode being tested.

Half-Wave Rectifiers

When a single rectifier (diode) is placed in series with an ac circuit, the result is called **half-wave rectification.** Only one-half of the alternating current can pass through the rectifier and continue to flow through the circuit. As stated earlier, ac current is constantly changing direction and polarity. Therefore, any diode in an ac circuit will receive a current flow in two different directions. In one direction, negative voltage is applied to the cathode and positive is applied to the anode; the diode will conduct and current will flow. In the opposite direction, the diode will offer high resistance and current will not flow. The result is that pulsating direct current will flow through the circuit even though the power supply produces an ac voltage. Figure 6-48*a* illustrates a half-wave rectifier circuit; its associated current curve is illustrated in Fig. 6-48*b*. In this circuit the dc motor will receive a pulsating direct current 60 times per second. The solid line of the current curve represents the pulsating direct current; the dotted line represents the ac wave that is blocked by the half-wave rectifier (diode).

Full-Wave Rectifiers

Half-wave rectifiers make use of only one-half of the ac current available; therefore, they are used in limited applications. Whenever a smoother ripple direct current or a more

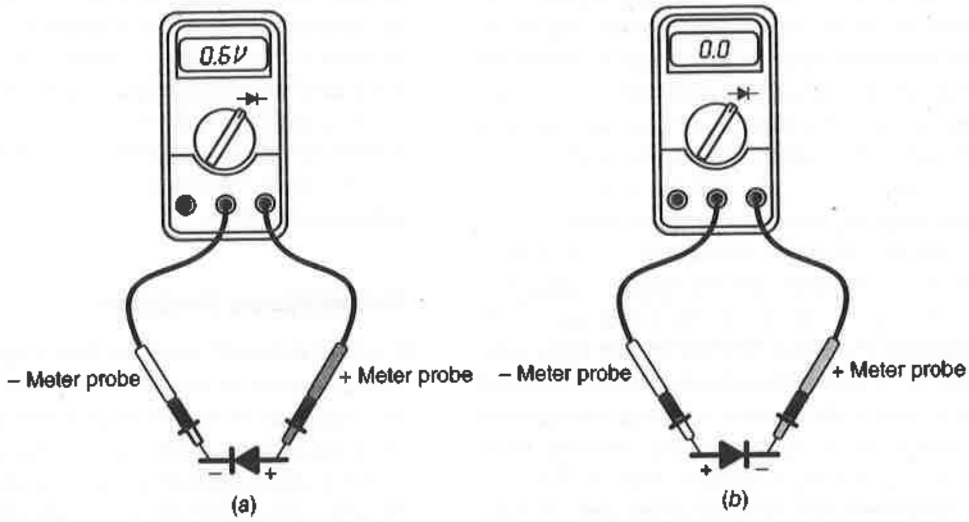
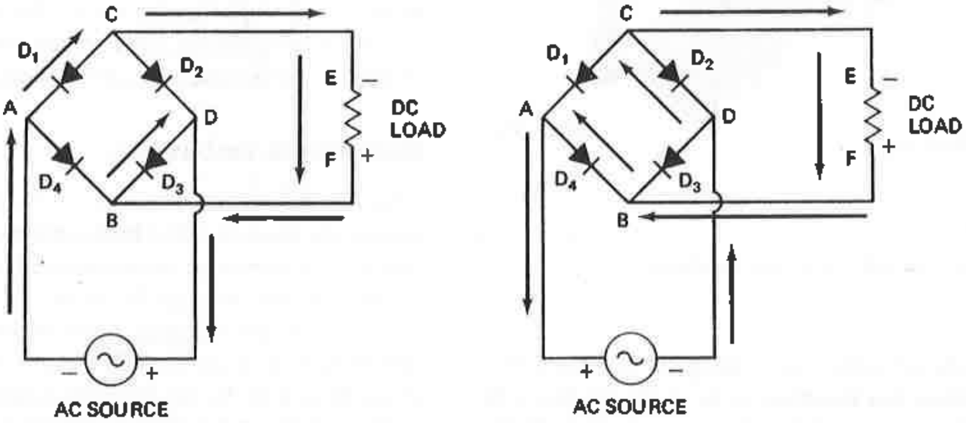


FIGURE 6-47 Testing a diode: (*a*) forward biased, (*b*) reverse biased.

(a) (b)

FIGURE 6-48 (*a*) A half-wave rectifier circuit; (*b*) the associated current curve.



(a) (b)

FIGURE 6-49 A full-wave rectifier circuit.

efficient use of power is required, a **full-wave rectifier** is used. In order to convert both halves of the ac wave to direct current, the diodes must be arranged into a bridge circuit. A full-wave bridge circuit can be made using four individual diodes or a single solid-state rectifier assembly. The rectifier assembly simply contains four diodes combined into a single compact package. The bridge rectifier assembly allows for easy installation to printed circuit boards or other circuits.

A typical bridge rectifier circuit is shown in Fig. 6-49. The ac source is connected to points *A* and *D* (the rectifier input). The rectifier's output, points *C* and *B*, is connected to the dc load. Figure 6-49*a* illustrates the current flow during the first half of the ac wave. At this time, the negative side of the ac voltage is connected to point *A*, the positive to point *D*. The current flows through the forward-biased diode D_1 but is blocked by D_4 and D_2 because they are reverse-biased. The current travels through the dc load and returns to point *B*. At this point, the current will take the path of least resistance back to the positive side of the ac source; thus the current travels through D_3 and the cycle is complete.

During the second half of the ac wave (see Fig. 6-49*b*), the current polarity is reversed, and the negative voltage is now connected to point *D* and the positive to point *A*. The current flows through D_2 and is blocked by the high resistance of D_3 and D_1. Current then travels through the load from point *E to F*; hence the polarity of the dc load remains constant even though the ac voltage reversed polarity. Point *E* remains negative, and point *F* remains positive. The current reaches point *B* and takes the most direct path, through D_4, back to the positive side of the source.

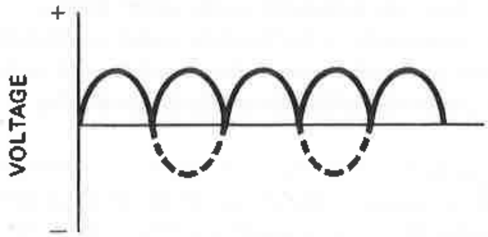


FIGURE 6-50 Ripple dc voltage produced by a full-wave rectifier.

The ac wave is converted into a ripple direct current through the full-wave rectifier. As illustrated in Fig. 6-50, the bottom half of the ac voltage is reversed in polarity to produce a ripple direct current. The ripple dc voltage is designated by the solid line, and the ac voltage is designated by the dotted line. A full-wave rectifier makes total use of the applied ac voltage and produces a relatively smooth dc voltage; therefore, full-wave rectifiers are more common than half-wave rectifiers.

Three-Phase Rectifier

It is often necessary to obtain direct current from three-phase power systems in aircraft; hence three-phase rectifier units are employed. It would be possible to use a single-phase full-wave rectifier in one leg of a three-phase system; however, it is more efficient to use a rectifier system that utilizes the power from all three legs of the three-phase circuit. The out-put of a three-phase alternator is indicated in Fig. 6-51.

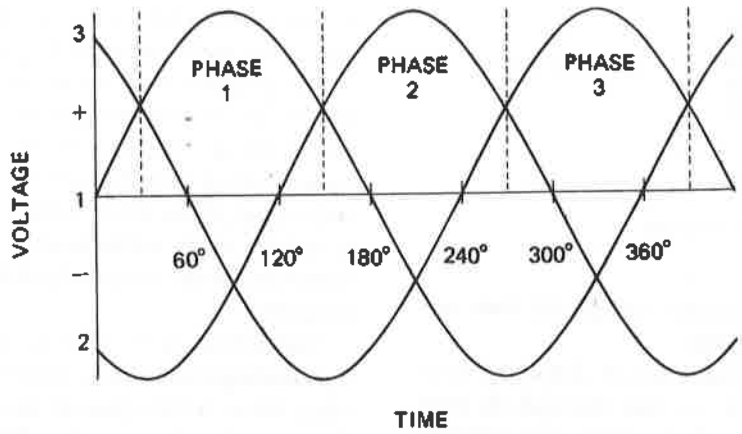


FIGURE 6-51 Output of a three-phase alternator.

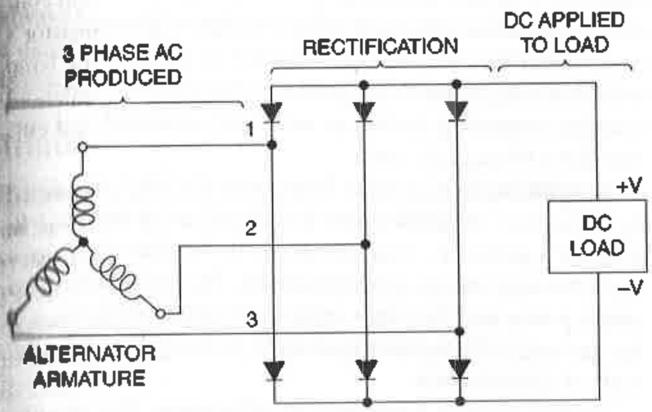


FIGURE 6-52 Full-wave rectifier for a three-phase alternator.

It will be noted in the diagram that the voltages reach maximum 120° apart. A rectifier consisting of six diodes is connected in such a manner as to provide one-way paths for the ac output as shown in Fig. 6-52. It can be seen in the diagram that three-phase voltage is produced by the alternator; the ac is rectified by the arrangement of diodes; and dc voltage is applied to the load.

In Fig. 6-53, the current flow is illustrated by the arrows through each phase of the three-phase system. The solid line represents current flow through phase 1, the long dashed line represents phase 2 current, and the short dotted line represents phase 3 current Each phase of the current is directed through the rectifier in such a manner as to apply a dc voltage to the load.

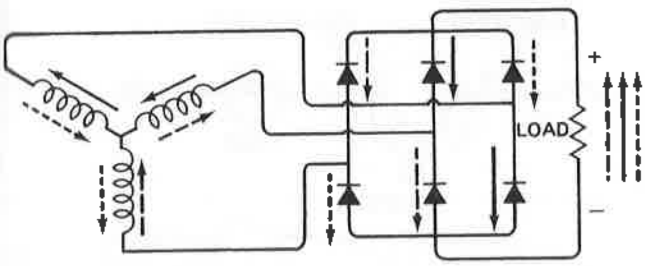


FIGURE 6-53 Current flow through a three-phase rectifier.

TRANSISTORS

A **transistor** is a solid-state device that can be used for controlling electric signals. Transistors are typically mass produced and relatively low in cost. During operation, transistors produce heat that may damage the transistor if the heat becomes excessive. Since even small amounts of heat can damage many transistors, it is often essential to provide heat sinks and adequate air circulation to ensure proper transistor operation.

It was explained earlier, in the discussion of diodes, that *n*-type and *p*-type materials are semiconductors. When formed into a junction, these semiconductors will allow current flow in one direction and block current flow in the opposite direction. When *n*- or *p*-type materials are joined in the correct combination containing two junctions, a junction transistor is formed.

Junction Transistor

As discussed earlier there are two commonly use semiconductor materials, silicon and germanium. Silicon transistors are currently more common than germanium due to their better speed and power efficiencies. There are also a few specialty semiconductors used in ultra high frequency transistors.

The **junction transistor** is only one of several types of transistors currently available. Essentially, they all require junctions established between *n*-type and *p*-type germanium or silicon.

A junction transistor consists of three principal sections and will be manufactured as one piece. In a typical ***npn*** transistor, the semiconductor material consists of a section of *n*-type silicon, then a very thin section of *p*-type silicon, and another larger section of *n*-type silicon. This is shown in Fig. 6-54. One end of this transistor is called

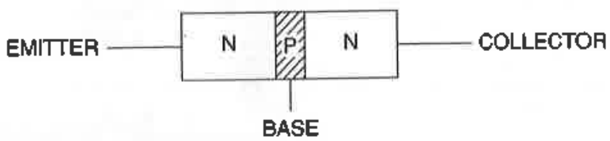


FIGURE 6-54 An *npn* transistor diagram.

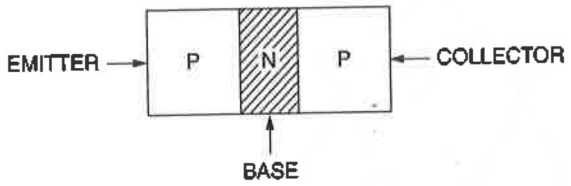


FIGURE 6-55 A *pnp* transistor diagram.

the **emitter**, the small *p*-type section is called the **base**, and the other end is called the **collector**.

A ***pnp*** transistor also contains two *np* junctions; however, in this case the emitter is a *p*-type material, the base is an *n*-type material. and the collector is a *p*-type material. A *pnp* transistor is illustrated in Fig. 6-55. For all practical purposes, *pnp* and *npn* transistors are functionally the same, except their connections have opposite polarities. For example, the emitter of an *npn* transistor is negative because it is an *n*-type material; the emitter of a *pnp* transistor is positive, because it is a *p*-type material. The transistor's schematic symbols make it easy to identify which type of transistor is being used. Figure 6-56 shows the symbols for a *pnp* transistor and an *npn* transistor. It can be seen from this illustration that the arrow, which represents the emitter lead of the transistor, points in opposite directions for the two different types of transistors. The arrow points **in** for *pnp* transistors and points **out** for *npn* transistors. This is easily remembered by noting that the arrow of an *npn* transistor symbol does **not point in** (*npn*). In modern aircraft, switching transistors are now used instead of relays and solenoids for low-power switching. For example, engineers may now design a circuit using a transistor to turn on/off the cabin lights; in the past a relay would have been used. Transistor switches are also found in a variety of digital electronic circuits. In this case, thousands of transistors are formed into an integrated circuit and used to control extremely low power signals for computerized systems.

The direction of the arrow also helps to define the direction of current flow through the transistor. As with diodes, current always flows against the arrow. Therefore, to allow correct current flow through the transistor, any connection at the point of the arrow must be negative. The connection at the back of the arrow must be positive. The *npn* and *pnp* transistors are not interchangeable because of their opposite polarities.

Transistors can be used for switching or amplification. **A switching transistor** is similar to an electrical solenoid or relay; that is, a transistor can act as a remote-control switch. By connecting the correct voltage to the transistor's base connection, the resistance between the emitter and collector is lowered to near zero. The solenoid analogy of a switching transistor is illustrated in Fig. 6-57. The solenoid's coil connection performs a function similar to that of the transistor's base connection; if either is connected to ground, the lamp will illuminate because the emitter-collector or the solenoid (switch) connection lowers to near zero resistance and current flows through the light.

Amplification is another function commonly performed by transistors. **Amplification is defined as an increase in a signal's power.** A weak signal can be fed into a transistor and a stronger output signal produced. The transistor cannot create power and therefore requires an added power source for the amplified signal. Figure 6-58 demonstrates the principle of amplification.

Amplification in a transistor is called **gain.** True amplification of a signal must increase the total power of that signal without changing its characteristics. If the voltage of an input signal increases and the current decreases, as in a step-up transformer, no amplification takes place. To amplify, there must be a total power gain. Transistor gain is symbolized by the Greek letter β (beta).

The gain of a transistor is often defined as the ratio of collector current to base current. That is,

$$\text{Gain} = \frac{\text{collector current}}{\text{base current}}$$

or

$$\beta = \frac{I_c}{I_b}$$

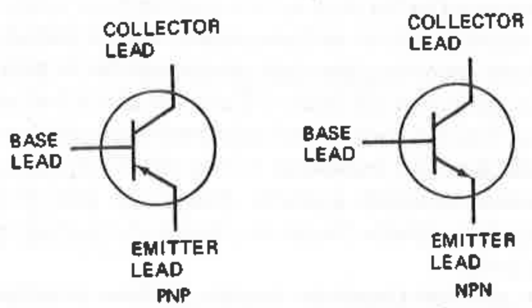


FIGURE 6-56 Schematic symbols of *npn* and *pnp* transistors.

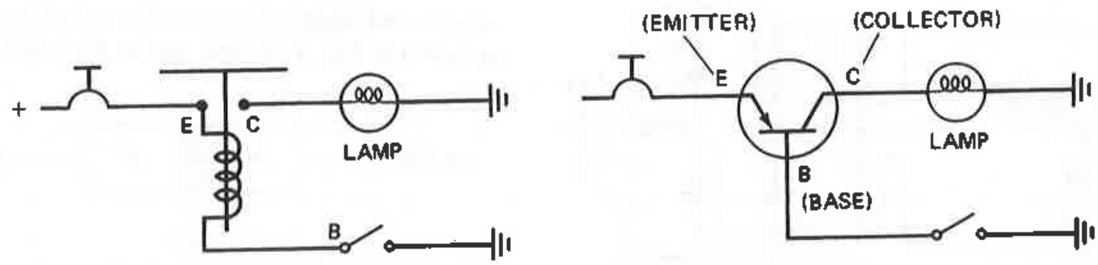


FIGURE 6-57 Solenoid analogy of a switching transistor.

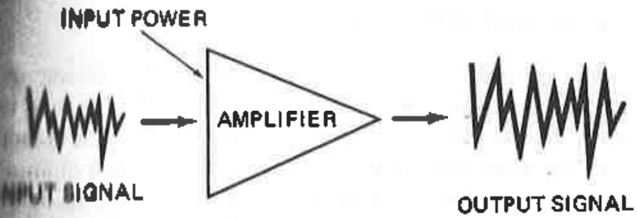


FIGURE 6-58 Principle of amplification.

Power transistors may have a gain as low as 20, and signal transistors will typically have gain over 100. It should be noted that generally, the higher the gain the more signal distortion. For this reason, amplification often takes place through several steps. It is very common to employ a preamplifier before a signal is sent to the power amplifier. This step-by-step amplification concept helps to eliminate signal distortion. Gain is not always a constant number for any given transistor. The gain of a transistor may vary with the collector current or voltage and is often affected by temperature changes.

Transistor Operation

Transistors contain at least two junctions between an *n*-type and a *p*-type material. Both junctions must be biased correctly to allow the transistor to conduct. **For the transistor to be operating, the emitter-base junction of a *pnp* or an *npn* transistor must be forward-biased, and the base-collector junction must be reverse-biased** (Fig. 6-59). As demonstrated in Fig. 6-59, the emitter-base junction of an *npn* transistor is forward-biased when the emitter is negative with respect to the base. The base-collector junction is reverse-biased when the collector is positive with respect to the base. "More positive" in this illustration represents a greater positive voltage at the collector than at the base, labeled "positive."

The junctions of a *pnp* transistor are biased in a conducting mode when the emitter is positive with respect to the base and the collector is negative with respect to the base. It becomes confusing when dealing with transistors if voltage is thought of as only an absolute positive and absolute negative. Voltage of a point must be defined with respect to a second point. Voltage measured at any given point may be negative with respect to one reference and positive with respect to a second. Figure 6-60 demonstrates this concept. Point *B* is negative if measured from point *A*. Point *B* becomes positive if measured from point *C*. This concept of voltage must be employed when studying the operation of transistors.

A diagram of an *npn* transistor circuit is shown in Figure 6-61. As indicated, the electron flow produced by the circuit's dc batteries travels through two paths, the emitter-base path and the emitter-collector path. The emitter-base current is a relatively weak "control" signal. Approximately 1 percent of the total current travels through the emitter-base circuit. This is the signal to be amplified. The current that travels through the emitter-collector circuit is the amplified signal. The majority of the transistor's current, approximately 99 percent, is sent through this path. The current in this path is controlled by the current through the base circuit.

During normal operation of an amplifying transistor. when the base current increases, the collector current will increase proportionally. If the base current decreases, the collector current will decrease. One important characteristic of a transistor is that a change in voltage applied to the emitter-collector circuit will have very little effect on the current of the emitter-collector. Only the emitter-base current/voltage controls the emitter-collector or current. This is why the base component of a transistor is considered the "controlling" element of the transistor and the emitter-collector is considered the "controlled"element of the transistor.

It should be considered that any *np* junction will have a **breakdown threshold**. This threshold is equal to the voltage required to overcome the resistance of the transistor junction in a reverse-biased condition. The breakdown threshold is usually a relatively high voltage applied with reversed polarity. When the transistor is subjected to this, type of voltage, it is often damaged and must be replaced.

As indicated by Fig. 6-62. the *pnp* transistor can have a current ratio similar to that of an *npn* transistor (99 to 1). The emitter-base current is the controlling, weaker signal, while the emitter-collector signal is the stronger signal being controlled. The voltage and current polarity of a *pnp* transistor are reversed from those of an *npn* transistor; therefore, the two types of transistors are not interchangeable. In general, the *pnp* transistor is less popular than the *npn* transistor because the *npn* type responds more quickly to base current changes. This is particularly important when amplifying high-frequency signals.

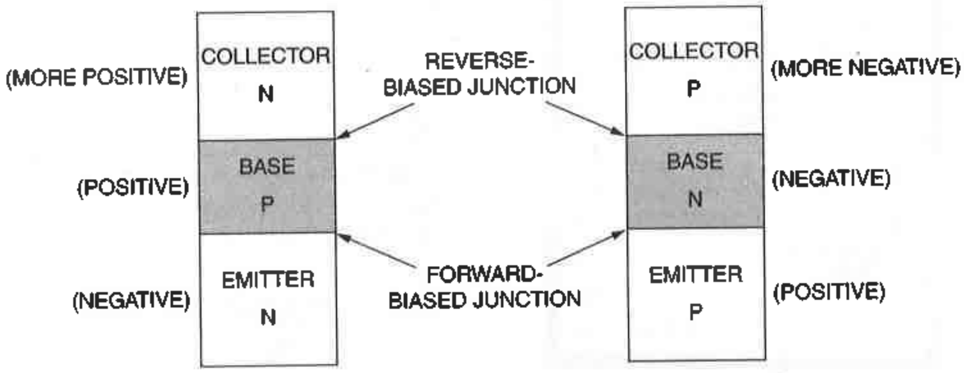


FIGURE 6-59 Transistor junction bias.

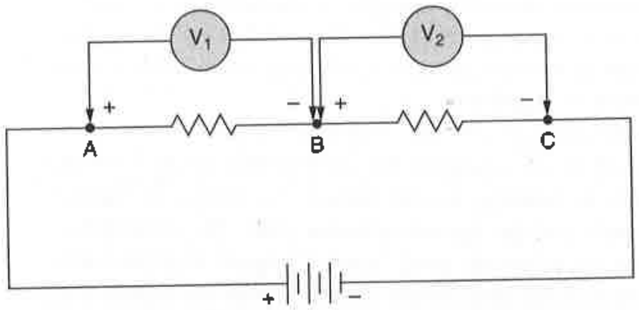


FIGURE 6-60 Voltage measurement: voltage at point *B* is positive with respect to point *C*; point *B* is negative with respect to point *A*.

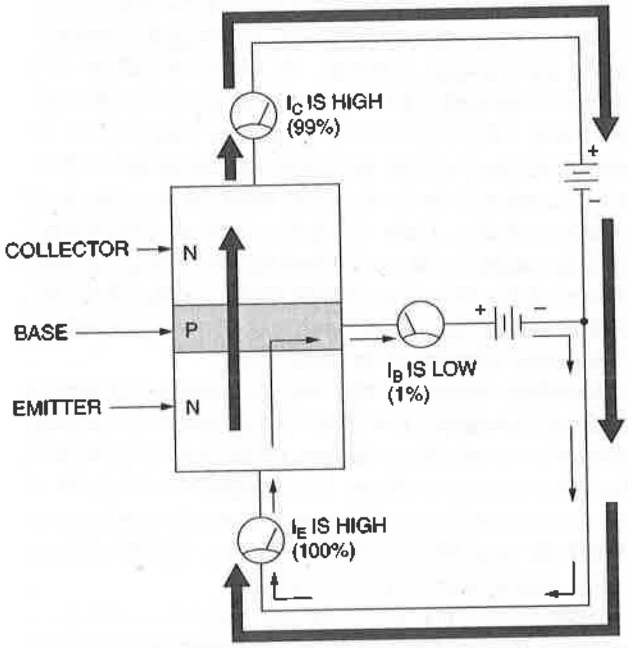


FIGURE 6-61 A current flow diagram of an *npn* transistor.

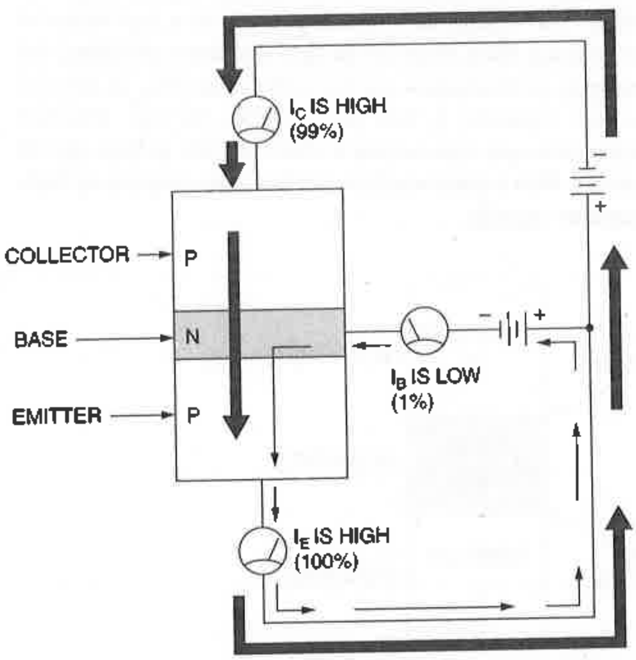


FIGURE 6-62 A current flow diagram of a *pnp* transistor.

A Typical Transistor Circuit

Transistors are found in a variety of electronic devices on modern aircraft. As previously discussed, the transistor is commonly used as either a switch or an amplifier. The circuit shown in Fig. 6-63 is an example of a typical light dimmer circuit using a transistor to control the current flow to the light. Refer to this circuit during the following discussions to help better understand transistor operation.

First, determine what type of transistor is being used and what voltage polarity is needed for the transistor to turn on the light. As seen in the transistor symbol, the arrow within the transistor points outward of the circle. This designates the transistor as *npn*. Since the circuit contains an *npn* transistor, the base connection must be positive, the collector connection must be slightly more positive than the base, and the emitter connection must be negative with respect to both the base and the collector. Each of these connections must be correct for the transistor to conduct.

Second, analyze the dimmer portion of the circuit. Since this is an amplifying transistor, it is designed for a variable signal at the base connection to control the emitter/collector current. The emitter/collector current flow determines the brightness of the light. The potentiometer (P_1) is used to control the current flow to the transistor base connection. (A potentiometer is a simple variable resistor.) The potentiometer would typically be a pilot-activated control mounted on the instrument panel of the aircraft. As the pilot rotates the control knob of the potentiometer the light will increase/decrease brightness. To increase brightness of the lights, the potentiometer is rotated so the center connection (labeled #2 on the diagram) moves up toward connection #1. This causes the base connection of the transistor to receive a greater positive signal. This causes the transistor to allow more emitter/collector current to flow and the light gets brighter. Of course

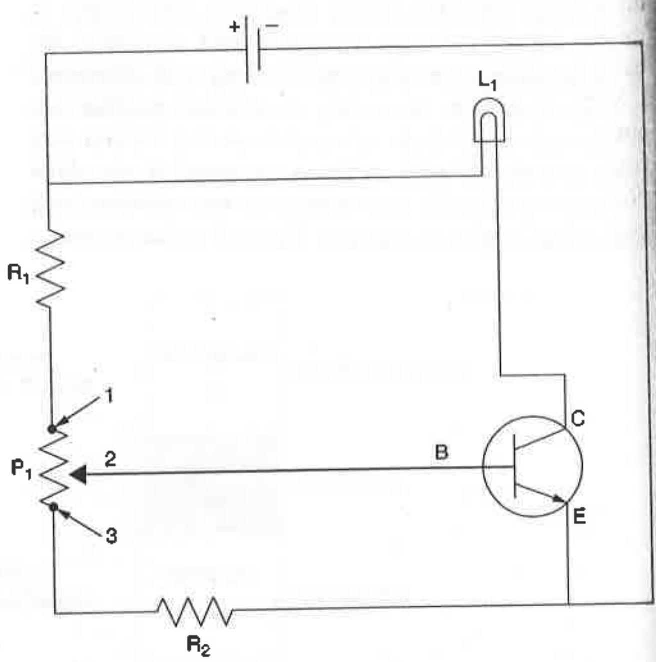


FIGURE 6-63 A transistor dimming circuit.

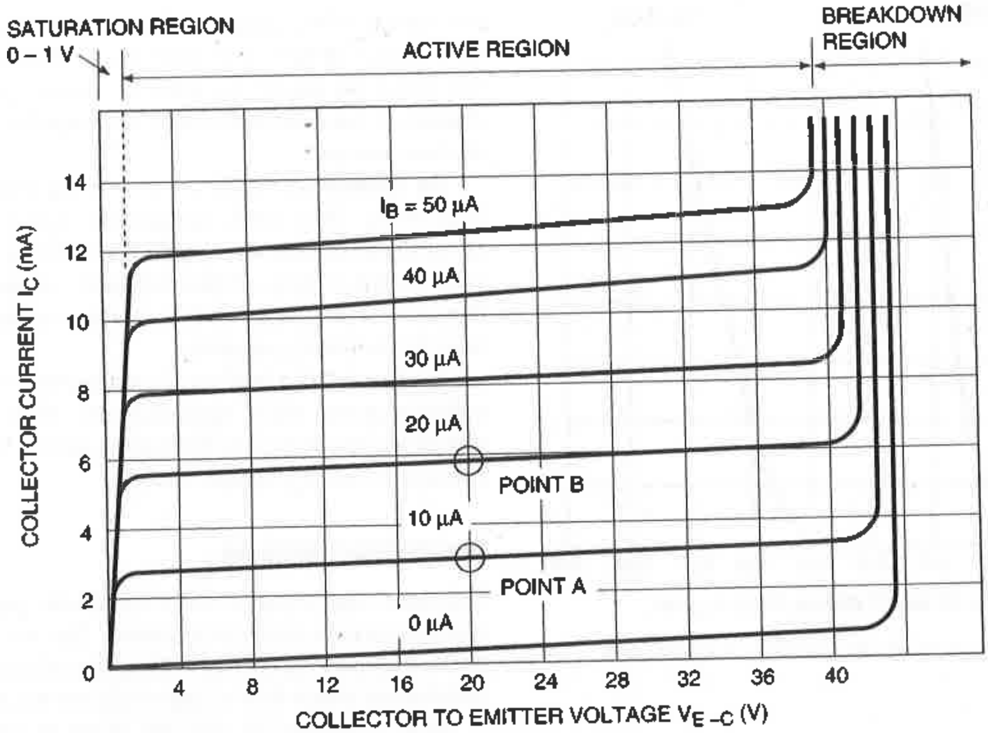


FIGURE 6-64 Collector current curves.

the light dims as the potentiometer moves down toward the # 3 connection. When the base is connected to a greater negative signal the light dims.

Of course, this circuit contains only one lamp; most dimming circuits found on aircraft will control several light bulbs all wired in parallel with each other. The resistors R_1 and R_2 are often referred to as biasing resistors. R_1 is used to create a voltage drop of the battery positive voltage before it reaches the potentiometer. R_2 is used to lower the battery negative voltage prior to reaching the potentiometer. Biasing resistors are typically used to ensure that all elements of a circuit are electrically compatible; hence, to adjust the "bias" of the transistor. For example, R_1 may be needed to ensure that the correct voltage is applied to the base connection of the transistor. Without R_1 the transistor may overheat, create an excess current flow and damage the light. The exact values of any biasing resistors must be determined at the time the circuit is designed.

Transistor Characteristics

One of the best ways to define the operating characteristics of any transistor is by plotting its current flows and voltages. **The collector current curves**, as illustrated in Fig. 6-64 are the most common means of plotting a transistor's characteristics. The horizontal axis is measured in volts and represents emitter-collector bias voltage (V_{e-c}). The vertical axis is calibrated in milliamperes and represents collector current (I_c).

The curves in Fig. 6-64 show the output data (I_B) for any given input situation (V_{e-c} and I_C). From these curves, it is easy to see that most of the variance in output (collector current) is caused by changes in base current, not changes in the emitter-collector voltage. The initial voltage, between 0 and 0.5 V. applied to the emitter-collector circuit does change emitter-collector current by approximately 3 mA. However, a 0.5-V change between 10 and 10.5 V affects emitter-collector current very little. This change in voltage without a proportional change in current shows that transistors do not react similarly to resistors; that is, their current flow is not directly proportional to the voltage applied.

The major factor controlling collector current is base current. Base current (I_B) is measured in microamperes and represented on the right-hand side of the graph. A base current of 10 µA at an emitter-collector voltage of 20 V will allow 3.2 mA of collector current flow (see point *A* in Fig. 6-64). At a base current of 20 µA, the same emitter-collector voltage of 20 V will allow 5.7 mA of collector current flow (sec point *B* in Fig. 6-64). It can easily be seen from examining these two points of the collector curves that a slight change in base current of 10 µA will create a significantly greater change in collector current, 2.5 mA. The weak base signal does control the stronger collector signal, and amplification is present.

We have already seen from Fig. 6-64 how base current controls collector current; it is also true that emitter-base voltage controls collector current. This is because the voltage between the base and the emitter controls the amount of emitter-base current. Figure 6-65 illustrates the relationship between emitter-base voltage and collector current for both germanium and silicon transistors. As the voltage to the emitter-base circuit of either a germanium or silicon transistor increases, the collector current increases. For a germanium transistor, a 0.1-V change (0.2 to 0.3 V) in the emitter-base circuit creates a 12-mA change (2 to 14 mA) in collector current.

The emitter-base voltage required to turn on a germanium transistor is approximately 0.2 to 0.3 V; a silicon transistor

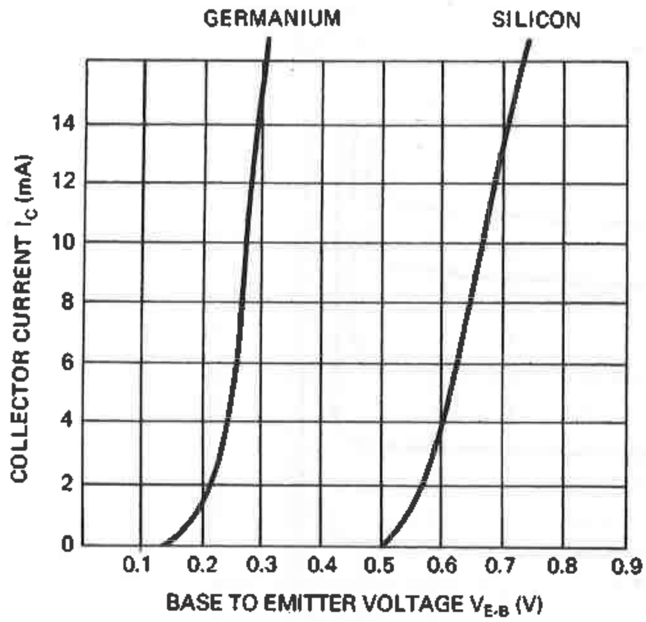


FIGURE 6-65 Voltage curves for germanium and silicon transistors.

requires approximately 0.5 in 0.6 V. Studying these bias voltages may be helpful when troubleshooting transistors and their related circuits. For example, if the bias voltage applied to the emitter-base circuit of a silicon transistor was less than 0.6 V, the technician would not expect the transistor to turn on. If the voltage is above 0.6 V, the transistor should turn on; if it does not, the transistor is probably defective.

Transistor Regions of Operation

There are three regions of operation for transistors: the **active region**, the **saturation region**, and the **breakdown region**. The different regions are defined by the change in collector current due to different voltage levels applied to the transistor's emitter-collector. The **active region** is the flat area of the collector current curves (Fig. 6-64). In this region, the voltage of the emitter-collector must be between 1 and 40 V approximately. The transistor is typically operated in this region for amplifying purposes. In the active region, the changes in the collector current are controlled by changes in the base current.

The **saturation region** is the vertical area of the curves (Fig. 6-64). Here small changes in collector voltage will result in substantial changes in the collector current. Typically in this region, emitter-collector voltage will be less than 1 V, Transistors are often operated in this region when used for switching purposes.

The **breakdown region** of a transistor is the area of the collector curves above approximately 40 V. The transistor should not be operated in this region, since it will most likely damage the semiconductor material.

Transistor Testing

Transistors can be tested with a multimeter, provided that the transistor is removed from its circuit. This test should be limited to transistors that are not extremely delicate and to digital multimeters which have a semiconductor test function.

Prior to testing, be sure the meter is set in the semiconductor test mode as shown earlier in the diode testing section of this chapter. (Transistor testing is very similar to diode testing.) The first test will be made between the collector and emitter connection of the transistor. Connect the meter as shown in Fig. 6-66. As shown here two tests must be made between the emitter and collector; reverse the meter polarity between test one and test two. The meter must show no connection during both tests. Although meters may differ, most will indicate either **OL**, for overload, or **000**, indicating there is no voltage drop across the semiconductor material and no current is flowing between the emitter and the collector.

The second test is made across the emitter/base junction of the transistor (see Fig. 6-67). This is done exactly like

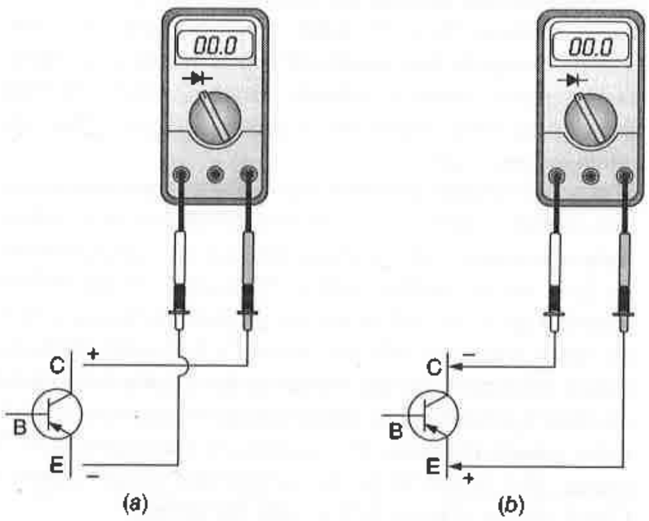


FIGURE 6-66 Testing a transistor with a DMM: (*a*) no connection emitter to base; (*b*) no connection base to emitter.

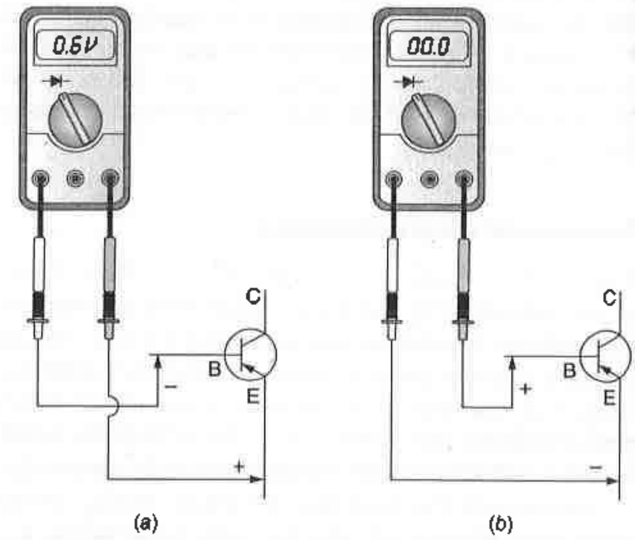


FIGURE 6-67 Testing a transistor with a DMM: (*a*) base/emmitter junction forward biased; (*b*) base/emitter junction reverse biased.

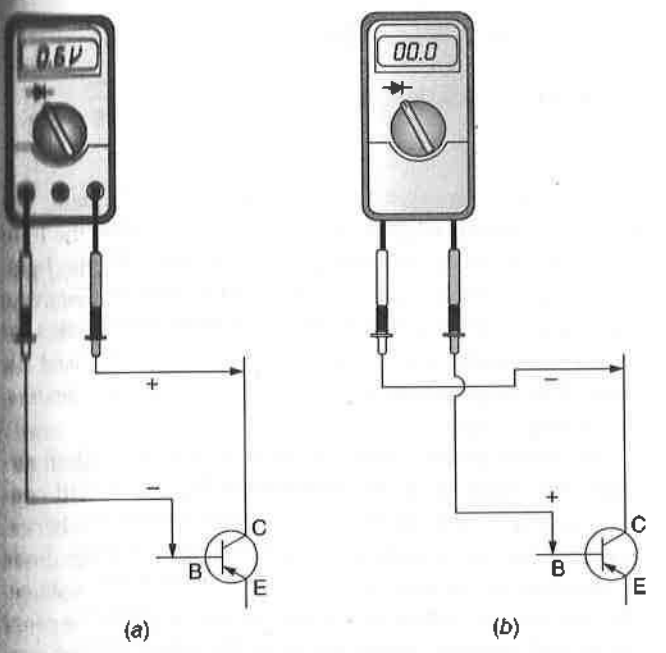


FIGURE 6-68 Testing a transistor with a DMM: (*a*) base/collector junction forward biased; (*b*) base/collector junction reverse biased.

testing the junction of a diode. Simply place the meter on the emitter and base connections, and take the meter reading. Reverse the polarity of the meter probes and once again view the meters display. A good transistor will show the voltage drop across the junction in one test and no voltage drop with the polarity reversed. The voltage drop for a silicone transistor should be between 0.6 and 0.7 V and approximately 0.3 V for a germanium transistor.

The last test is made between the transistor's base and collector junctions. Perform this test as shown in Fig. 6-68. The indications on the meter should show the voltage drop across the junction in one test and show no voltage drop when the polarity is reversed.

There are several transistor testers currently available. These testers will perform a more thorough test than a typical hand-held meter. However, transistors seldom partially fail, and any complete failure is detectable with any semiconductor tester. One advantage of most transistor checkers is that they often have "in-circuit" test capabilities. This is very important when dealing with transistors soldered in place. Often the removal of such a transistor will damage the component; therefore, in-circuit testing is the preferred method. Voltmeters and oscilloscopes can also be used to test transistors if the circuit is complete and normal operating power is available.

OTHER SOLID-STATE DEVICES

There are several types of hybrid solid-state devices currently available. Many of these have been designed to function under specific conditions and perform specific operations. Eight specialized semiconductors are commonly known as JFETs, MOSFETs, thyristors, zener diodes, light-emitting diodes, photodiodes, LASCRs, and LCDs.

The **junction field-effect transistor** (JFET) is very similar to a junction transistor; however, a JFET is considered to be voltage-sensitive; a junction transistor is current-sensitive. Figure 6-69 shows the symbol of a JFET. The connections of a JFET are the **gate**, which is the control lead, and the **drain** and the **source**, which are the leads being controlled. If the voltage applied between the gate and the source is inceased, the current flow between the drain and source will increase. This relationship is illustrated in Fig. 6-70. The JFET is used in circuits where the voltage input must control the current output. One such circuit is found in digital voltmeters and oscilloscopes.

Another advantage of the JFET is that it will produce a very low noise output. This makes the JFET a perfect device for amplifiers with weak input signals. The major disadvantage of a JFET is that it is less sensitive to voltage changes than a junction transistor.

The **metal-oxide semiconductor field-effect transistor** (MOSFET) has a source, gate, and drain similar to the connections of a JFET. The major difference is that the gate is insulated from the current channel of the drain and source. The structure and the schematic symbol of a MOSFET are illustrated in Fig. 6-71. The major advantage of a MOSFET is that either a positive or negative voltage can be applied to the gate to produce a drain-source current flow.

A **thyristor** is a semiconductor that is used for switching purposes. A thyristor contains four layers of semiconductor

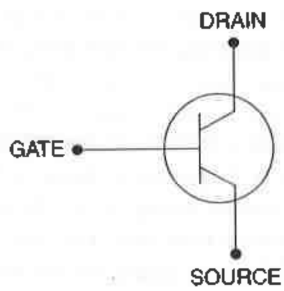


FIGURE 6-69 JFET symbol.

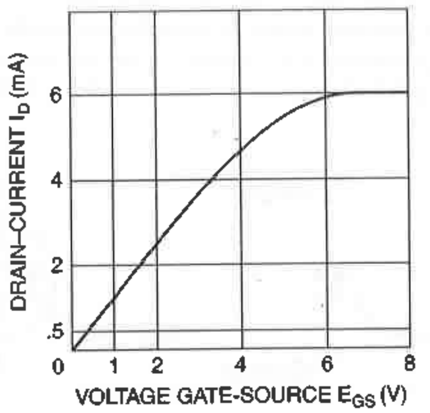


FIGURE 6-70 The relationship between gate voltage and drain-source current for a JFET.

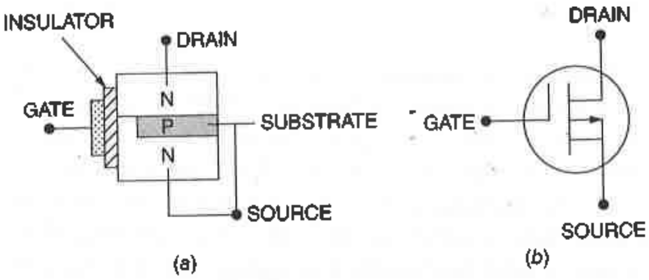


FIGURE 6-71 A MOSFET: (*a*) structure of an *n*-type MOSFET; (*b*) symbol for an *n*-type MOSFET.

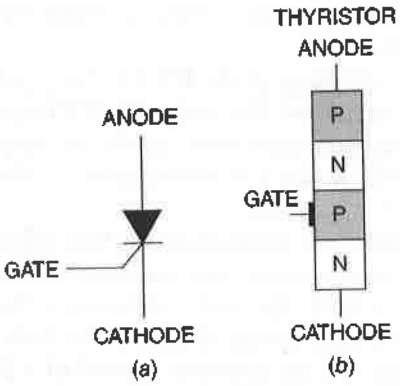


FIGURE 6-72 Thyristor: (*a*) symbol; (*b*) four layers and three junctions.

material and the *n-p* junctions as shown in Fig. 6-72. In many cases a thyristor may replace a solenoid or relay for controlling the load current to motors. Electrical load switching through thyristors is advantageous because there are no moving parts; thus problems with wear, corrosion, and arcing are eliminated.

There are two common types of thyristors, the **silicon controlled rectifier** (SCR) and the **triode ac semiconductor** (triac). The SCR symbol is shown in Fig. 6-73*a*, and the triac symbol is shown in Fig. 6-73*b*. Either the SCR or triac will allow current to flow once a certain level of gate signal is achieved. If the gate signal is then removed, the current will continue to flow through the anode-cathode circuit until that signal is interrupted. Thyristors are often referred to as a latched device because once the semiconductor is turned on it will stay on or "latched" until reset. This characteristic of a thyristor makes it ideal for switching warning circuits on aircraft. For example, if an excessive temperature is reached in a turbine engine for only a split second and

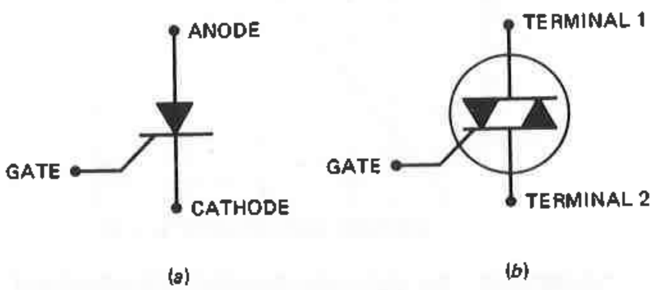


FIGURE 6-73 Thyristor symbols: (*a*) an SCR and (*b*) a triac.

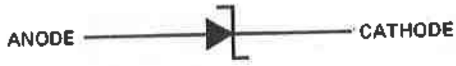


FIGURE 6-74 Schematic symbol of a zener diode.

then decreases, an engine warning light will illuminate. The light will continue to glow until the pilot interrupts the light circuit and turns off the thyristor, thus turning off the light. The thyristor has made it possible for the pilot in receive a continuous indication of a warning condition that existed for only a very short time period. Thyristors are also used for controlling large amounts of current flow to motors, heaters, or lighting circuits.

The **zener diode** is also a popular device on modern aircraft. The zener diode, as illustrated in Fig. 6-74, will conduct electricity only under certain voltage conditions; hence, it is ideal for use in voltage regulator circuits. A zener diode is designed to operate at or above its breakdown voltage. The breakdown voltage is a given voltage at which the zener diode will conduct; below this level the zener will not conduct. The **avalanche effect** is caused when a zener reaches its breakdown voltage in a reverse-bias mode. If the correct value of reverse voltage (negative anode, positive cathode) is applied to the zener. it will act as a very low resistance. Below this voltage the zener will offer high resistance. This is known as the avalanche effect because the zener offers nearly infinite resistance until the breakdown voltage is reached. At that point the resistance falls dramatically to nearly zero (an avalanche). As with conventional diodes, if the polarity is reversed, the zener diode will not conduct.

Bidirectional zener diodes are also found on many aircraft. These diodes are often connected in parallel with the magnetic coil of a relay or solenoid (Fig. 6-75). Bidirectional zener diodes are used to eliminate voltage spikes (transients) that are created during the expansion or contraction of the magnetic field of the relay (solenoid) coil. Similar to zener diodes, the bidirectional zener will conduct current above a certain voltage level. However, the bidirectional zener will conduct current in either direction or polarity.

The **light-emitting diode** (LED) is widely used on aircraft instruments and test equipment. Single LEDs are used as indicator lights. An arrangement of LEDs, such as in Fig. 6-76, is used to display letters and numbers. LEDs require 1.5 to 2.5 V and 10 to 20 mA to produce adequate light for most applications. For an LED to conduct, the applied voltage must be connected in the forward-biased condition.

The light of an LED comes from the energy given off when the diode is forward-biased. At this time, free electrons

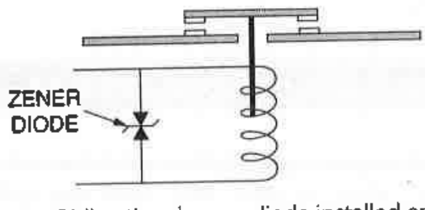


FIGURE 6-75 Bidirectional zener diode installed on a solenoid coil.

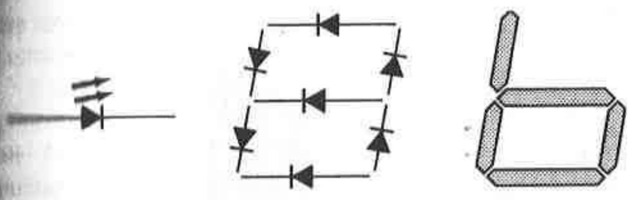


FIGURE 6-76 Light-emitting diodes: (a) a schematic symbol; (b) an LED arrangement to display a digit; (c) an LED display of the digit 6.

travel from a high to a low energy level and produce light and heat. Those diodes which do not emit light will expend all their "extra" energy in heat. LEDs expend most of their extra energy in light. The various colors available from LEDs are determined by their active elements, such as gallium, phosphorus, and arsenic. LEDs that produce red, green, yellow, blue, orange, and infrared light are all currently available.

Photodiodes are semiconductors that respond to light. Photovoltaic diodes, or solar cells, as they are commonly called, produce a dc voltage when they are exposed to light. A relatively small amount of power is produced by photovoltaic cells; however, through the use of modern electronics, several calculators and other low-power devices can operate using the current produced by photovoltaic cells. Outside the earth's atmosphere, the sun's rays are much stronger and help create a greater amount of electric power through photodiodes. Several modern satellites operate solely on electric power generated by photovoltaic cells.

A **light-activated SCR** (LASCR) is a device that is turned on by light rays. In this device, when the light is strong enough, the valence electrons of the gate become free electrons and allow current to flow from the cathode to the anode. Figure 6-77 shows the symbol of an LASCR. The arrows indicate the light needed to trigger the LASCR. As with SCRs, LASCRs will continue to conduct after the trigger source is removed. In other words, when the light source has diminished, the LASCR will continue to offer very low resistance (a closed circuit).

Thermistors are heat-sensitive devices used on some aircraft to monitor the temperature of certain electric equipment. For example, nickel-cadmium battery sensors may use thermistors to monitor the battery temperature. As the name implies, *thermistor* comes from the words *thermal* and *resistor.* Thermistors are semiconductor devices that change resistance as their temperature changes. Thermistors are

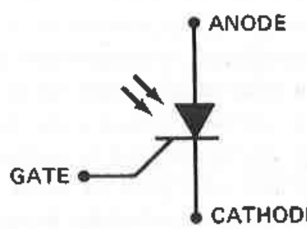


FIGURE 6-77 Schematic symbol of an LASCR.

formed from metal oxides and coated with an epoxy, glass, or similar material. There are a variety of thermistor styles, such as rods, discs, and washers, which are mounted within a temperature probe.

Liquid crystal displays (LCDs) are found in many state-of-the-art aircraft instruments. The display can be configured to form letter and number patterns, or it can form a full picture. A basic LCD is gray; however, many modern displays employ color filters to create a full color image. Full color LCDs have now replaced the traditional instruments on most modern aircraft. LCDs are the display of choice due to their weight savings and electrical efficiencies.

Liquid crystal displays gel their name from the *liquid crystal* that is used to arrange light patterns within the unit. Liquid crystals are fluid materials that contain molecules arranged in crystal forms. The molecules are typically twisted and therefore "bend" the light that passes through the crystal (see Fig. 6-78*a*). If a voltage is applied to the liquid crystal, the molecules align and the light passes "straight" through the material (see Fig. 6-78*b*). LCDs use this phenomenon to align light waves with polarized filters. The polarized filters block, or pass, the light to form specific patterns for the display.

Figure 6-79 shows a typical 7-segment liquid crystal display. In this example, voltage is applied to the individual segments to form the number 5. The segments that do not have voltage applied are *light gray.* The light waves pass through these segments and reflect off a mirror mounted behind the rear polarizer. The segments that form the number 5 are dark gray, since they reflect the light. The liquid crystals of these displays are aligned by an applied voltage.

PRINTED CIRCUIT BOARDS

Modern electronic equipment uses **printed circuit boards** (PCBs), which provide a mounting surface and the electric current paths for the individual components of a system. Printed circuit boards are typically constructed of a rigid insulator material approximately $\frac{1}{16}$ in. thick. The surface of the board is covered with a copper foil, and holes are drilled through the materials where component connections are made (see Fig. 6-80). Printed circuit boards allow for compact installation of hundreds of individual components into electronic equipment. On some equipment the PCBs, known as *cards,* can be easily removed for repair.

During the construction of PCBs, the copper foil covers the entire surface of the insulator board. The foil is then etched with chemical solvents to form the specific current paths needed for the circuits. The components are installed on the board and soldered to the copper foil. In many cases the complete assembly (components and PCB) is covered with a protective coating to seal out moisture. This protective coating must be removed prior to replacement of components on a PCB. Be sure to follow the manufacturer's recommendations for component replacement.

Surface mounted components are designed to be mounted to both sides of a printed circuit board. As seen

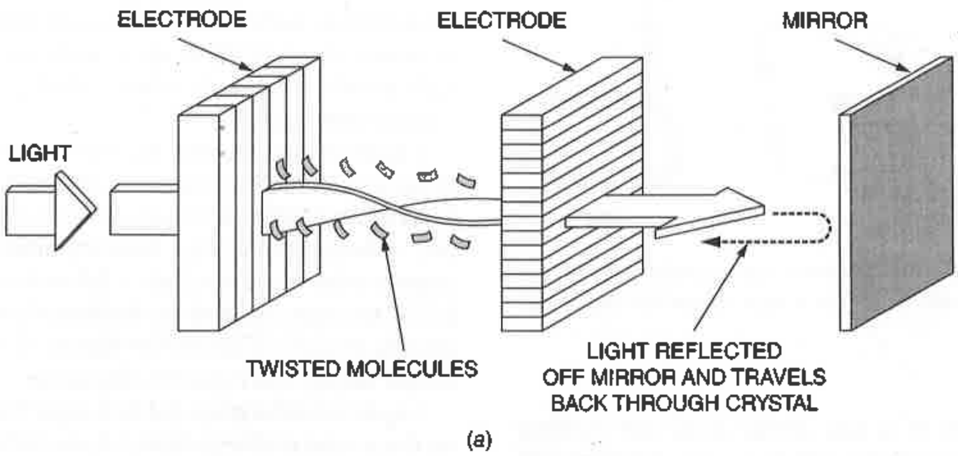


FIGURE 6-78 Liquid crystal theory: (*a*) With no current applied to the electrodes, light passes through the polarizer. Light reflects off the mirror and passes through the polarizer again. This segment is light. (*b*) With current applied to the electrodes, light does not travel through the polarizer. This segment is dark.

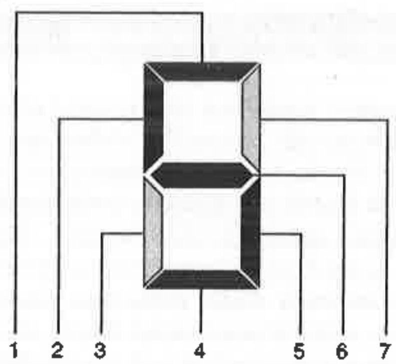


FIGURE 6-79 A 7-segment liquid crystal display. Electrodes 1, 2, 4, 5, and 6 are energized to form the number 5.

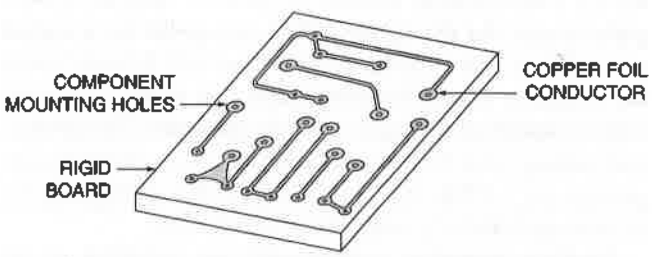


FIGURE 6-80 A printed circuit board.

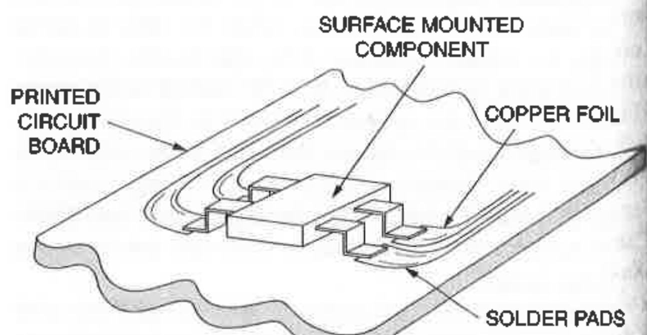


FIGURE 6-81 An example of a surface mounted component.

in Fig. 6-81, the component leads do not extend through the PCB. The leads are bent at a 90° angle and sit flat on the surface of the PCB. The leads are then soldered to the copper foil conductor and secured in place. This arrangement allows for installation of components on both sides of the PCB; hence a more compact unit can be designed. Virtually all types of electrical components, from resistors to integrated circuits, can be designed for surface mounting. In most cases, components designed for surface mounting are extremely small and difficult to handle. In many cases, component identification is virtually impossible since the parts are too small to print identification numbers or resistor color codes on their surface.

It is difficult to install and remove surface mounted components owing to their compact design. Special soldering and desoldering equipment is vital to the success of a component replacement. Surface mounted components should be removed and installed only by technicians well trained in PCB and surface mounted repair techniques.

CATHODE-RAY TUBE

For many years the **cathode-ray tube** (CRT) has been familiar to millions of persons as the picture tube in a television set. The CRT in a television is designed to reproduce an undistorted picture on a screen. The picture is developed from a series of pulses and varying voltages applied to the elements of the tube.

Fundamentally, the CRT consists of an electron "gun," a phosphorescent screen, and deflecting devices to control the movement of the electron beam "shot" from the gun. A diagram of a CRT is shown in Fig. 6-82. As in any other thermoemitting tube, the heated cathode supplies the electron emission, and these electrons are accelerated toward the screen by the positive charges on the anodes. The intensity of the electron beam is regulated by means of the control grid charge. After the electron beam is accelerated and focused by the anodes, it is controlled in direction by the **deflection plates**. When the electrons strike the phosphor-coated screen, they cause a bright spot to appear. If an alternating voltage is applied to the vertical deflection plates, the spot will move up and down and form a straight line, as shown in Fig. 6-83*a*. In like manner, if an alternating voltage is applied to the horizontal deflection plates, a horizontal straight line will appear on the screen, as in Fig. 6-83*b*.

The deflection of the electron beam can be accomplished by either electrostatic or electromagnetic means. Electrostatic deflection positions the electron beam by producing electric fields that change the direction in which the beam travels. **Deflection plates**, which create the electric field, are typically used in CRTs for oscilloscopes and many aircraft instrument displays. Electromagnetic fields are used to direct the electron beam in many television receivers and similar video displays. **Deflection coils** create magnetic fields to direct the electron beam in both the horizontal and vertical direction.

The CRT screen is coated on the inside with a phosphorous material that glows after being hit by an electron beam. The time required for the phosphorous material to glow is determined by the sweep time of the electron beam. Any point of the CRT screen must glow until the electron beam returns to that spot and reactivates the phosphorous material.

A color CRT uses three electron beam guns in order to achieve the three primary colors. A separate gun is needed for each color: red, blue, and green. The screen of a color CRT is made of three separate phosphorous materials; the type of phosphorous material determines the color achieved when the electron beam strikes the CRT screen. The CRT screen is divided into hundreds of groups of three small dots of phosphorus, one each for red, blue, and green. Each electron beam must pass through a **shadow mask** before it reaches its respective phosphorous dot. The shadow mask helps to prevent overlap of the electron beams into any incorrect color dot. A diagram of a color CRT is shown in Fig. 6-84. When one electron beam reaches its color dot on the CRT screen, that color appears on the face of the CRT. If two or three electrons reach their corresponding phosphorous dots in any given area, the colors blend together to create a new color. For example, if the red, blue, and green guns are emitting electrons directed to the same area of the CRT screen, white is produced. If the red and blue guns emit electrons to their respective phosphorous dots, the color mauve (bluish-purple) will be produced. Color CRTs are still very popular in aircraft weather radar systems and instrument display panels; however as previously mentioned, flat panel LCDs are found in most modern installations. Although CRTs are very reliable, they require more power and are heavier than a typical full color LCD.

Every CRT requires some external form of control for the electron beam(s). These controls must turn on or off and control the intensity of the electron beam(s) at the correct time intervals. The direction of the electron beam(s) must also be controlled in order to ensure that the beam(s) travels

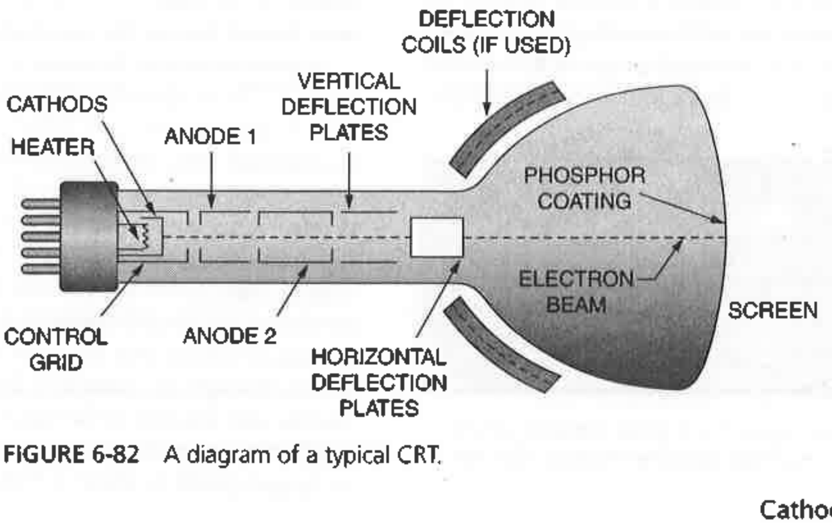


FIGURE 6-82 A diagram of a typical CRT.

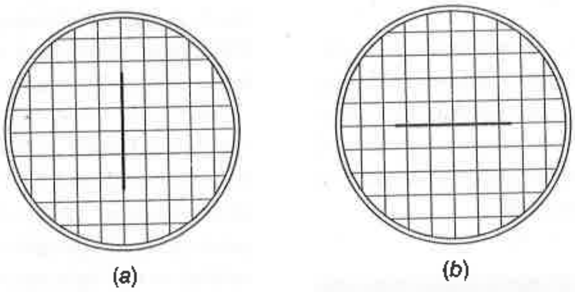


FIGURE 6-83 Effects when ac voltage is applied to the deflection plates.

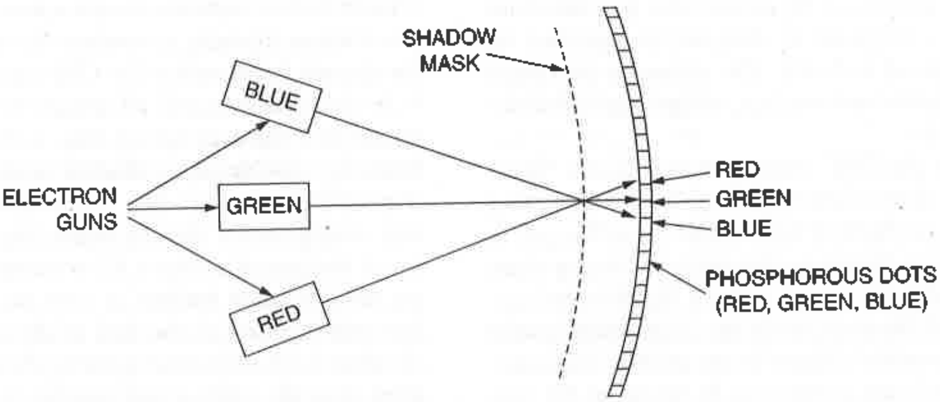


FIGURE 6-84 A diagram of a color CRT.

to the correct portion of the CRT screen in the correct sequence. These controls are usually provided through a variety of complex circuits. Although either digital or analog signals can be used for this purpose, most modern airborne equipment employs digital techniques.

FLAT PANEL DISPLAYS

The instrument panel of a modern aircraft often contains several flat panel displays which provide information to the pilot and copilot. As shown in Fig. 6-85, virtually all conventional "round-dial" instruments found on older aircraft have been replaced with high-tech displays. Most of the modern flat-panel displays use LCD technologies. The basic operational theory of LCDs discussed earlier in this chapter applies to all LCD flat panel displays; however, backlighting and color filters have been added along with an intricate control system for each LCD.

FIGURE 6-85 A modern instrument panel replaces conventional instruments with multiple flat panel displays. See also color insert.

A modern flat panel display is comprised of thousands of tiny liquid crystals; each connected in what is known as an active matrix. The active matrix uses **thin-film transistors** (TFT) to turn on/off each LCD at the appropriate time. Each LCD of the active matrix has a dedicated red, blue, or green (RBG) color filter; each RBG-colored LCD is called a sub-pixel. The combination of all three RBG sub-pixels is called a pixel. The greater the number of pixels per square inch the higher the image quality of the flat panel display. Typically, aircraft displays have a high pixel density and therefore, have a very high image resolution. The TFTs are used to control the large number of sub-pixels through a matrix of electrical connections formed into the flat panel structure.

A modern aircraft flat panel is full color and back lit with either LEDs or specialized fluorescent lighting. With either light source, special light diffusers are incorporated in order to create an even light distribution. Backlighting is necessary in improve readability in all lighting conditions and, of course, during night flights. Figure 6-86 shows the construction of a typical pixel used to make up a modern flat panel display. Here it can be seen that the light source, located at the rear of the display, projects light through the polarizers, the liquid crystal, and the color filter. Of course light only travels through the polarizing lenses when the appropriate electric signal is sent to the liquid crystal. In order to achieve a full color spectrum, each red, blue, or green sub-pixel can be turned on/off to allow as little or as much light to pass

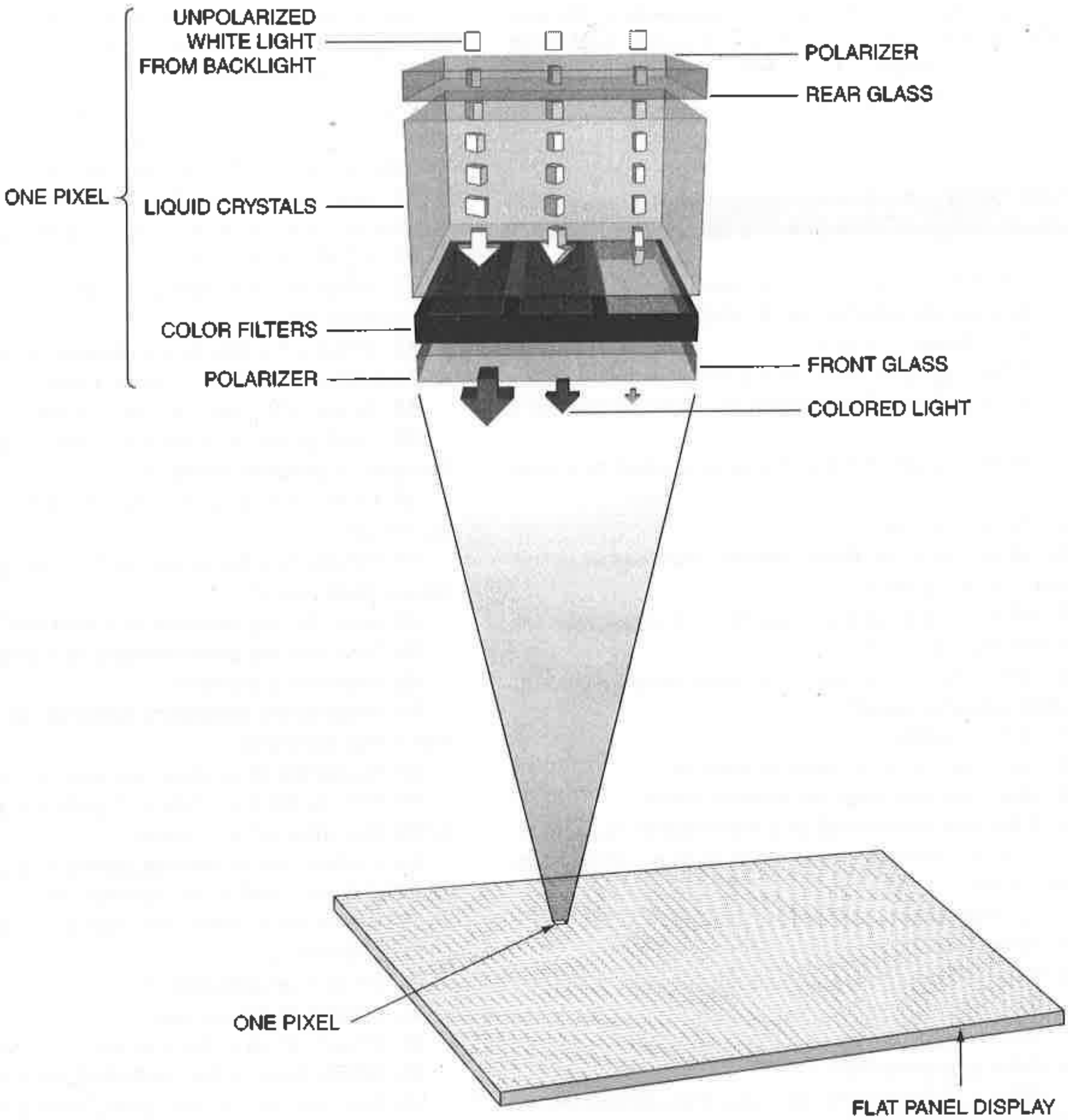


FIGURE 6-86 Flat panel display contruction.

as needed. The pixels of the display are controlled at a very high refresh rate in order to create a seamless image as the display picture changes.

Some modern flat panel displays incorporate **touchscreen technologies**. A touchscreen is specially designed display that can detect the presence and location of a touch within the display area. The term generally refers to touching the display with a finger, hand, or stylus. Touchscreens have been common in devices such as game consoles, tablet computers, and smartphones for several years; and recently they have grown in popularity on various types of aircraft displays for noncritical systems. There are obvious disadvantages using a touchscreen while flying through turbulent air; therefore, most touchscreens are designed to operate only while the aircraft is on the ground. One common use of touchscreens is the display used for preflight planning known as the **electronic flight bag**. The touchscreen has one main advantage; it enables a user to interact directly with the image shown on the display, rather than indirectly with a pointer controlled by a mouse, touchpad, or keyboard.

There are several different technologies used for the construction of touchscreens; however, most common displays detect human touch through a change of capacitance. Since the human body is an electrical conductor, touching the surface of the display alters the screen's electrostatic field. This change can be measured as a change in capacitance. Different technologies may be used to determine the location of the touch. The location is then sent to the controller for processing.

Some touchscreens are made up of a matrix of rows and columns of conductive material, layered on sheets of glass. This can be done by etching a conductive grid pattern of electrodes on either a single or dual glass pane. Voltage applied to this grid creates a uniform electrostatic field, which can be measured.

When a conductive object, such as a finger, comes into contact with the panel, it distorts the local electrostatic field at that point. This is measurable as a change in capacitance by the touchscreen control circuit.

REVIEW QUESTIONS

1. Describe the purpose of an electrical switch.
2. Why should switches be derated for some circuits?
3. Describe a DPST switch.
4. Where are *limit switches* found on aircraft?
5. What is meant by the normally closed contact of a switch?
6. What is meant by the common contact of a limit switch?
7. Describe a fuse.
8. What must be done before resetting a circuit breaker that is tripped?
9. What should be the capacity of a circuit breaker used with No. 16 wire?
10. When may more than one circuit be protected by the same circuit breaker?
11. Define *resistor*.
12. Name the general types of resistors.
13. Give the color code for resistor values.
14. If the first color band of a fixed resistor is orange, the second is green, and the third is blue, what is its resistance value?
15. By what other names is a variable resistor commonly called?
16. What is the principal difference between a potentiometer and a rheostat?
17. Define *capacitor*.
18. What is a dielectric?
19. What is the formula for capacitors connected in parallel? in series?
20. Describe the time constant for capacitors.
21. What is the function of an inductor in an electronic circuit?
22. Compare inductance with capacitance.
23. What precaution must be taken in connecting an electrolytic capacitor in a circuit?
24. What is meant by the wattage of a resistor?
25. What units are usually used to indicate capacitance in an electronic circuit?
26. What is a step-up transformer? A step-down, transformer
27. Describe the operating principles of a transformer.
28. Compare the number of windings in the primary coil of a step-up transformer with the number of windings in the secondary coil.
29. Give the formula for expressing the voltage values in the circuits of a transformer with respect to the number of turns in the primary and secondary windings.
30. Give the formula for maximum current values in the primary and secondary windings of a transformer.
31. What is a rectifier?
32. What are the two principle materials used in a semiconductor?
33. What is the difference between an *n*-type material and a *p*-type material in a semiconductor?
34. Explain the operation of a *diode*.
35. What is the difference between a half-wave rectifier and a full-wave rectifier?
36. Draw a full wave rectifier circuit for a single-phase AC circuit.
37. What procedures are used to test a diode with a digital multimeter?
38. Describe the purpose of a heat sink.
39. Describe the characteristics of a zener diode.
40. Describe a thyristor.
41. What is the difference between an *npn* transistor and a *pnp* transistor?
42. Name the three main sections of a transistor.
43. Discuss the importance of temperature with respect to the operation of a transistor.
44. Explain the difference between a junction field-effect transistor and a junction transistor.
45. Which lead carries the majority of the current in a junction transistor?
46. What is amplification?
47. What is transistor gain?
48. Which circuit is the *control* circuit of a transistor?
49. Which circuit is the *controlled* circuit of a transistor?
50. Describe the process used to test a transistor with a digital multimeter.
51. What is an LED?
52. What is a cathode-ray tube?
53. How is the direction of the electron beam(s) changed within a CRT?
54. What are the three colors used in a color CRT?
55. What is the purpose of the shadow mask of a CRT?
56. What is a *flat panel display* and how are they used on aircraft?
57. Describe the operation of an LCD.
58. Describe the function of the active matrix with respect to an LCD flat panel display.

Digital Electronics 7

INTRODUCTION

Digital systems became practical with the invention of the integrated circuit. However, there have been several examples of digital circuits throughout the evolution of electronics. The first means of transmitting an information signal, the telegraph, relied on basic digital principles. The telegraph used a code system of voltage on and voltage off combinations to produce letters, words, and, therefore, information. This concept of voltage on and voltage off is the heart of the modern digital circuit.

Currently, integrated circuits are capable of providing thousands of combinations of voltage on and voltage off signals. This large number of voltage combinations per component allows modern digital circuits to perform a seemingly infinite number of tasks. Digital circuits are used extensively on modern aircraft computer systems. Computers operate virtually every system on a state-of-the-art airplane. The concept of digital electronics has changed the way we design, fly, and maintain aircraft. Modern aircraft, such as the Boeing 777, the Airbus A-380 and the Boeing 787 employ a complete fly-by-wire system; that is, the flightdeck controls are linked to the control surfaces only through electrical wiring and computer systems. These aircraft are often referred to as "the more electric airplane" There are several computers used on modern aircraft that control a variety of functions. Some common examples are flight management computers, thrust management computers, and bus power control computers. There are also numerous peripheral devices used to send information to, or receive information from, the different computers.

This chapter will introduce the language used by computers and the basic functions of digital circuits, computers, and various peripheral devices. The electronic structure of computers will also be presented, including integrated circuits, microprocessors, and data transfer systems.

THE DIGITAL SIGNAL

A **digital signal** is one that contains two distinct values. These values are often considered to be on and off, or 1 and 0. An analog signal, on the other hand, is one that contains an infinite number of voltage values. A digital signal is represented in Fig. 7-1. As illustrated, if zero voltage is present at point A, it is considered a digital 0; 5 V positive at point A is considered a digital 1. In this circuit the digital 0 is created when the switch is open. The digital 1 is created when the switch is closed, thus connecting point A to the 5-V positive source.

An analog signal created by a variable resistor is shown in Fig. 7-2. In this circuit + 5 V, or digital 1, is present at point A of the circuit, when the potentiometer is set to position 1. Zero voltage, or digital 0, is present when the potentiometer is moved to position 2. As illustrated by the graph of Fig. 7-2*b*, the analog signal does not produce a distinct value of + 5 or 0 V. As the potentiometer moves from position 1 to position 2, it provides an infinitely variable voltage, ranging from 0 to + 5 V.

Logic circuits, the fundamental components of all computers, utilize digital signals. Through the use of integrated circuits, thousands of combinations of 1 s and 0 s can be produced and manipulated to perform a countless number of functions. A modern aircraft flight computer receives millions of digital input signals during a typical flight. These signals

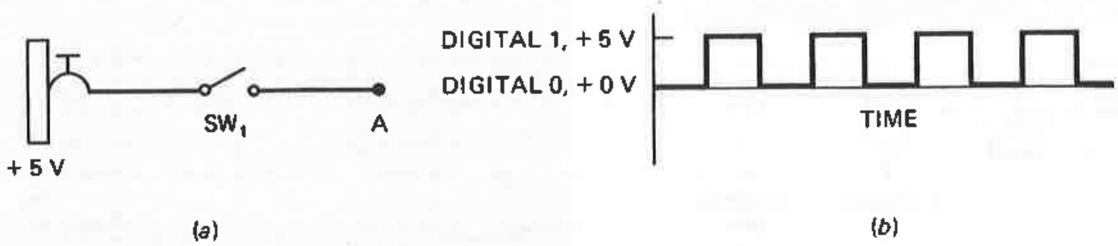


FIGURE 7-1 A digital signal: (*a*) a simple digital circuit; (*b*) a digital waveform.

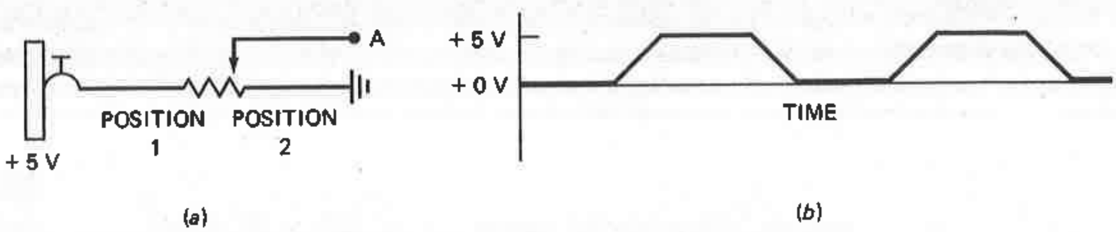


FIGURE 7-2 An analog signal: (*a*) a simple analog circuit; (*b*) an analog waveform.

are compared and processed by the computer circuits. The computer then produces output signals that are also composed of a combination of 1 s and 0 s. The computer's output signals may be used to display data on flight instruments, control flight altitudes, maintain engine power, and provide fault information on system malfunctions.

DIGITAL NUMEROLOGY

In order for a computer to understand a variety of information, a code system must be used that is composed of digital 1 s and 0 s. The **binary number system**, as the name implies, is composed of two components, 1 and 0. There are several varieties of binary systems used in modern computers. These code systems provide the "language" for communication between computers and their related components. For examples, a digital combination of 1011 might represent the number eleven. If a binary code is used to represent or label a particular component, the digital combination of 1001 might represent temperature probe no. 1. As illustrated in Fig. 7-3, an input code of 1001 1011 might represent 11° measured at temperature probe no. 1. Virtually any binary code system may be used as a computer's language, as long as all components of the system are programmed for the same code. Digital 1s and 0s are often used to represent other characteristics of aircraft systems. For example, a light being on is often represented by a digital 1; the light off equals digital 0. An item being present as stated, such as hydraulic pressure, is represented by a digital 1. A digital 0 would be used to represent the absence of hydraulic pressure. The list below presents common designations of the binary digits 1 and 0.

1	2
Positive voltage	Negative voltage (positive logic)
On	Off
Yes	No
Present as stated	Not present as stated
True	False
Conduction	Nonconduction

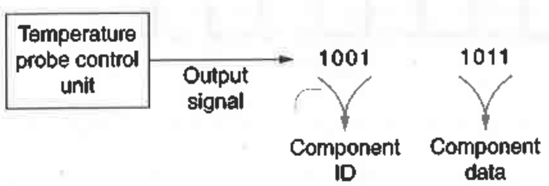


FIGURE 7-3 Representation of digital to binary conversions.

Decimal System

In any number system a symbol is given to each quantity to be represented. The **decimal number system** uses 10 figures to represent the quantities 0 through 9. Each quantity of dots shown in Table 7-1 is represented by a symbol of the decimal system. This example of the decimal number system may seem quite obvious; however, this is only because we use this system during everyday activities. We already recognize what quantity each symbol represents. Unfortunately, the decimal number system is not suited for use as a computer language, because the digital system contains only two symbols, 1 and 0.

Binary Numbers

The **binary number system** represents different quantities using only two symbols, 1 and 0. If a quantity larger than 1 must be represented by binary numbers, the symbols systematically repeat. As in the decimal number system, the binary system repeats by adding to the left of the first digit. The column just to the left of the first digit is considered a **higher-order column**. In a number comprised of a series of digits, the digit farthest to the right is known as the **least significant digit** (bit) and the digit farthest to the left is known as the **most significant digit** (bit). The term **digit** is typically used to indicate a number in the decimal system (0-9); the term *bit* is typically used to indicate a number in the binary system (0-1).

In Table 7-2 each quantity of dots is represented by a symbol of the binary number system. Each digit of a binary number has a specific value. As illustrated, the first digit of a binary number is represented by 2 to the power 0, for a decimal value of 1; the second digit equals 2 to the power 1, for a

TABLE 7-1 Representation of the decimal number system.

Decimal number symbol	Quantity of dots
0	none
1	•
2	••
3	•••
4	••••
5	•••••
6	••••••
7	•••••••
8	••••••••
9	•••••••••

TABLE 7-2 The binary number system: (*a*) the value of binary numbers; (*b*) the value of binary digits.

Binary number symbol	Quantity of dots
0	none
1	•
10	• •
11	• • •
100	• • • •
101	• • • • •
110	• • • • • •
111	• • • • • • •
1000	• • • • • • • •
1001	• • • • • • • • •

(a)

Binary digit	10th	9th	8th	7th	6th	5th	4th	3rd	2nd	1st
Power	2^9	2^8	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Decimal value	512	256	128	64	32	16	8	4	2	1

(b)

decimal value of 2; the third digit equals 2 to the power 2, for a decimal value of 4: and so on. The decimal value of 2^0 is 1, the decimal value of 2^1 is 2, the decimal value of 2^2 is 4, and so on.

To determine the total decimal value of any binary number, add the individual values (2^0, 2^1, 2^2, etc.) of the digits containing a binary 1. Any digit with a binary 0 has a value of zero; therefore, it need not be added. For example, the binary number 101 is equal to the decimal number 5. This is found by adding the individual values: the first digit, 2^0 (1), plus the third digit, 2^2 (4), or $(1 + 4 = 5)$. Note that the second digit is not added because it is a binary zero. The total decimal value of the binary number 111011 is determined as follows: $2^5 + 2^4 + 2^3 + 2^1 + 2^0 = 32 + 16 + 8 + 2 + 1 = 59$. Studying Table 7-3 will help you understand the concept of binary number values.

A decimal number may be converted to its binary equivalent by sequentially dividing the number by 2 and recording each remainder. The quotient from the first division must be divided by 2 and its remainder recorded. This process is repeated until the quotient is 0. The remainders make up the binary number. The following example indicates this conversion system:

Conversion of decimal number 96 to its binary equivalent:

	Quotient	Remainder
$\frac{96}{2}$ =	48	0 least significant
$\frac{48}{2}$ =	24	0
$\frac{24}{2}$ =	12	0
$\frac{12}{2}$ =	6	0
$\frac{6}{2}$ =	3	0
$\frac{3}{2}$ =	1	1
$\frac{1}{2}$ =	0	1 most significant
Decimal number 96 = binary number 1 1 0 0 0 0 0		

As illustrated, 96 is divided by 2 and the remainder, 0 is recorded. The quotient, 48, is divided by 2 and the remainder recorded. Twenty-four is divided by 2, and so on. The binary number is found by listing the calculated remainders. To determine the binary number, simply record each remainder, starting from the bottom of the list. The bottom digit of the remainder list becomes the left-most digit of the binary number. The top digit of the list becomes the right-most digit of the binary number. Two more examples of the conversion from decimal numbers to binary numbers are shown in Fig. 7-4.

The binary number code is the language of logic circuits and computers. The decimal code system is the language of humans. If we desire to communicate with computers, we must understand their language. Conversely, computers and their related components must be capable of converting information to the decimal system for the display of human-compatible information. Comprehension of the binary code system is essential for a basic understanding of computer operations.

The term **bit** may be used when referring to binary digits. One bit is equal to one binary digit. A bit will always be expressed as a high (1) or low (0) logic level. Bits handled as a group are referred to as a **byte**. Therefore, an eight-digit binary number is a byte containing eight bits. Another category of data is called the **word**. A word is a grouping of bits that the computer uses as a standard information format. For example, many systems communicate using a 16-, 32-, or 64-bit word. Each word for a

TABLE 7-3 Conversion of binary numbers to their decimal equivalents (101 binary = 5 decimal; 111011 binary = 59 decimal).

Binary digit	6th	5th	4th	3rd	2nd	1st	
Power	2^5	2^4	2^3	2^2	2^1	2^0	
Decimal value	32	16	8	4	2	1	
				1	0	1	4 + 1 = 5
	1	1	1	0	1	1	32 + 16 + 8 + 2 + 1 = 59
			binary number				decimal equivalent

	Quotient	Remainder
$\frac{18}{2}$ =	9	0
$\frac{9}{2}$ =	4	1
$\frac{4}{2}$ =	2	0
$\frac{2}{2}$ =	1	0
$\frac{1}{2}$ =	0	1

Decimal number = 18
Binary number = 10010
(a)

	Quotient	Remainder
$\frac{69}{2}$ =	34	1
$\frac{34}{2}$ =	17	0
$\frac{17}{2}$ =	8	1
$\frac{8}{2}$ =	4	0
$\frac{4}{2}$ =	2	0
$\frac{2}{2}$ =	1	0
$\frac{1}{2}$ =	0	1

Decimal number = 69
Binary number = 1000101
(b)

FIGURE 7-4 Examples of decimal to binary conversions.

particular system will conform to a specific format that enables the computer to decode the message.

Addition of Binary Numbers

Addition using any number system is a means of combining quantities. For example, in the decimal system 6 + 1 = 7 may represent a quantity of X's or X X X X X X plus X equals X X X X X X X. In the binary system, quantities may be added in a similar manner. In binary, 110 + 1 = 111 would represent 6 + 1 = 7 of the decimal system.

There are four basic rules to remember when adding binary numbers:

Rule no. 1: 0 + 0 = 0
Rule no. 2: 0 + 1 = 1
Rule no. 3: 1 + 0 = 1
Rule no. 4: 1 + 1 = 10

In the binary system only two symbols are used, 1 and 0; therefore, when 1 and 1 are added, we must record zero and carry the 1 into a higher-order column. This is identical with the process used in the decimal system, as illustrated in Fig. 7-5. To add the binary 100 and 100, the process would be as follows:

$$\begin{array}{r} 100 \\ +\,100 \\ \hline 1000 \end{array}$$

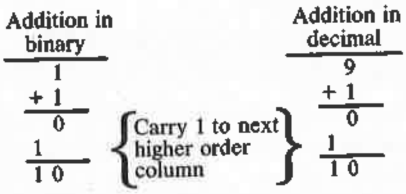


FIGURE 7-5 Comparison of addition of binary numbers and addition of decimal numbers.

Addition of 11011 + 110		Addition of 11000 + 1101		Addition of 11101 + 11101	
Binary	Decimal	Binary	Decimal	Binary	Decimal
11011	27	11000	24	11101	29
+ 110	+ 6	+1101	+ 13	+11101	+ 29
100001	33	100101	37	111010	58

FIGURE 7-6 Examples of binary addition showing decimal equivalents.

That is, first, 0 + 0 = 0; second, 0 + 0 = 0; and third, 1 + 1 = 10. If the binary numbers 11 and 11 were added, the process would be as follows:

$$\begin{array}{r} 11 \\ +\,11 \\ \hline 110 \end{array}$$

That is, first, 1 + 1 = 10; here it becomes necessary to record the 0 and carry the 1 to the next higher-order column. Second, 1 + 1 + 1 = 11; therefore, the result is 110. Figure 7-6 shows three more examples of binary addition.

Subtraction of Binary Numbers

There are four that apply to binary number subtraction; they are as follows:

Rule no. 1: 0 − 0 = 0
Rule no. 2: 1 − 0 = 1
Rule no. 3: 1 − 1 = 0
Rule no. 4: 10 − 1 = 1

When subtracting binary numbers, start with subtraction in the right-hand column and proceed to the left. Borrow from the adjacent higher-order column when necessary. That is, if the right-hand column is 0 − 1, borrow from the adjacent column in order to subtract 1 from 10 (10 − 1). Next, subtract in the adjacent column to the left; once again borrow if necessary. Repeat this procedure until a subtraction has been done in each column. For example, in subtracting 110 from 1101, proceed as follows:

$$\begin{array}{r} 1101 \\ -110 \\ \hline 111 \end{array}$$

First, subtract in the right column (1 − 0 = 1); second, subtract in the adjacent column (0 − 1; with a carried digit, 10 − 1 = 1); third, subtract in the next column (0 − 1; with a carried digit, 10 − 1 = 1). The fourth column no longer exists because we borrowed the 1 for subtraction in the third column. In decimal form the same subtraction would be 13 − 6 = 7.

Three more examples of binary number subtraction are given in Fig. 7-7. The respective decimal equivalents are also shown.

Subtraction of 1011 + 100		Subtraction of 1110011 − 101001		Subtraction of 111000 − 101	
Binary	Decimal	Binary	Decimal	Binary	Decimal
1011	11	1110011	115	111000	56
− 100	− 4	−101001	− 41	− 101	− 5
111	7	1001010	74	110011	51

FIGURE 7-7 Examples of binary subtraction showing decimal equivalents.

Binary Multiplication and Division

In order to multiply or divide binary numbers, four rules must be considered; they are as follows:

Rule no. 1: $0 \times 0 = 0$
Rule no. 2: $0 \times 1 = 0$
Rule no. 3: $1 \times 0 = 0$
Rule no. 4: $1 \times 1 = 1$

To multiply a binary number, use the same procedures that are used for multiplying decimal numbers; that is, multiply to form partial products and add. For example, to multiply 10 by 11, proceed as follows:

10
× 11
10 (partial product)
10 (partial product)
110 (addition of partial products)

Division of a binary number is performed in a manner similar to division of a decimal number. To divide 1110 by 10, proceed as follows:

111
10)1110
10
11
10
10
10
0

Always divide the left-most digits first and progress to the right; the procedure is complete when the remainder is zero. Several examples of multiplication and division problems are given in Fig. 7-8. The decimal equivalents are also given.

BINARY CODE SYSTEMS

General Theory

There are several varieties of code systems used to convert information bits into letters or decimal numbers. The pure binary number system is often too clumsy for a computer to manipulate data quickly. Three of the more common systems used to produce a faster computer are called the **binary-coded decimal, octal notation,** and **hexadecimal** systems. All of these systems utilize the binary digits 1 and 0 to represent decimal, or base 10, numbers.

11010 × 110: 00000, 11010, 11010 = 10011100 | 26 × 6 = 156
1011 × 11: 1011, 1011 = 100001 | 11 × 3 = 33
110001 × 1000: 000000, 000000, 000000, 110001 = 110001000 | 49 × 8 = 392

(a)

1100)1101100 = 1001: 1100, 11, 00, 110, 000, 1100, 1100, 0 | 12)108 = 9: 108, 0
11)10101 = 111: 11, 100, 11, 11, 11, 0 | 3)21 = 7: 21, 0

(b)

FIGURE 7-8 (a) Examples of binary multiplication with decimal equivalents; (b) examples of binary division with decimal equivalents.

Binary-Coded Decimal System

The **binary-coded decimal** (BCD) system uses a group of four bits to represent each digit of a decimal number (see Fig. 7-9). Each digit of the decimal system (1 to 9) can be represented by four binary digits. For example, 9 in the decimal system equals 1001 in the binary system; 2 in decimal equals 0010 in binary. This system is extremely useful when dealing with large quantities of data interchanged between the inputs and outputs of a computer system.

One disadvantage of the BCD numbering system is that there are must 4 bits used to represent any decimal number. In some cases, this creates a BCD number with "unused bits" as shown in Fig. 7-9. When using BCD, the decimal number 9 is the highest possible number for any single digit. This creates a situation where there are six BCD bit combinations which are unusable as a decimal digit. In some cases, these "unused bits" are often given specific meanings by a computer programmer to help increase data capacity of the system. The additional digits are often assigned with various alphabetic symbols, or other simple-types of data,

Decimal Number	BCD Number
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001
—	1010
—	1011
—	1100
—	1101
—	1110
—	1111

Decimal values higher than 9 do not exist as a single digit. — BCD combinations are not used to represent numbers 0–9. (applies to the rows 1010 through 1111)

FIGURE 7-9 Decimal number and BCD equivalent.

thus expanding the possibilities to carry information by each four-bit BCD byte.

Octal Notation System

The **octal notation** system is a binary representation of an octal number. **Octal numbers** are composed of eight different symbols. Since computers can handle only two symbols, 1 and 0, octal notation was developed. Octal notation is comprised of a series of three-bit groups. Since the largest decimal number represented by three binary digits is 7 (111), this is a base 8, or octal, system. In short, octal notation is a means to represent octal (base 8) numbers in a binary language. A typical octal notation number might be (001)(100)(111). Each three-bit group represents a specific octal number, and those octal values are added to determine the total value of the number. Of course a computer would not add the parenthesis so the actual octal number would be 001 100111. It is important to note that the octal number is always in multiples of three bits. In some cases, this may look odd since the most significant bit (far left) is a zero (0). Octal notation is useful for certain programming techniques where large quantities of binary numbers must be manipulated. Octal notation is also used for the transmission of data by aircraft computers and their related peripherals.

The octal notation system has a base of 8; that is, each three-bit binary group **(triad)** is a given value of eight to a power 0, 1, 2, 3, etc. The values of each octal triad are shown in Table 7-4(*a*). Table 7-4*b* shows the octal notation value 001010100001 converted to its decimal equivalent, 673. To determine the decimal value of an octal notation number, find the decimal value of each triad and sum those values. To find the value of a triad, multiply the decimal equivalent of the base 8 number (8^0 or 1, 8^1 or 8, 8^2 or 64, etc.) by the decimal equivalent of the triad (001 = 1010 = 2011 = 3, etc.). For example, to convert 001 010 100 001 to decimal form, proceed as follows: First, determine the decimal value of each triad. The decimal value of the first triad equals 001×8^0, or $1 \times 1 = 1$. The second triad group is 100×8^1, or $4 \times 8 = 32$. The third triad group is 010×8^2, or $2 \times 64 = 128$. The fourth triad group is 001×8^3, or $1 \times 512 = 512$. Next, sum the values of the individual triad groups: $1 + 32 + 128 + 512 = 673$. The decimal value of the octal notation 001 010 100 001 is 673.

To determine the octal notation code of a decimal number, proceed as follows. First, divide the decimal number by 8, and record the quotient and the remainder. Second, divide the previous quotient by 8, and record the quotient and remainder. Repeat this procedure until the quotient is zero, and then convert each remainder into a three-digit binary number (triad). Last, record each triad, starting from the bottom and moving upward to determine the octal notation code.

To determine the octal code for the decimal number 741, proceed as follows:

Division	Quotient	Remainder	Triad Equivalent of Remainder in Binary
$\frac{741}{8}$	92	5	101 (least significant triad)
$\frac{92}{8}$	11	4	100
$\frac{11}{8}$	1	3	011
$\frac{1}{8}$	0	1	001 (most significant triad)

TABLE 7-4 The octal notation system: (a) the decimal equivalents of triad groups; (b) conversion of octal notation number 001 010 100 001 to decimal number 673.

Three-digit group (triad)	5th	4th	3rd	2nd	1st
Power of eight	8^4	8^3	8^2	8^1	8^0
Decimal value of base eight number	4096	512	64	8	1

(a)

Triad group	4th	3rd	2nd	1st
3-digit octal notation	001	010	100	001
Decimal equivalent of triad	1	2	4	1
Power of eight	8^3	8^2	8^1	8^0
Decimal value of base eight number	512	64	8	1
Decimal equivalent of octal groups	(1 × 512) 512	(2 × 64) 128	(4 × 8) 32	(1 × 1) 1

Sum the decimal equivalents of each octal group
512 + 128 + 32 + 1 = 673
Octal notation 001 010 100 001 = decimal 673

(b)

Conversion from octal notation to decimal

	101 010 octal
equals	$(101 \times 8^1) + (010 \times 8^0)$
equals	$(5 \times 8) + (2 \times 1)$
equals	$40 + 2$
equals	42 decimal

	100 010 111 100 octal
equals	$(100 \times 8^3) + (010 \times 8^2) + (111 \times 8^1) + (100 \times 8^0)$
equals	$(4 \times 512) + (2 \times 64) + (7 \times 8) + (4 \times 1)$
equals	$2048 + 128 + 56 + 4$
equals	2, 236 decimal

(*a*)

Conversion of 2460 decimal to octal notation

Division	Quotient	Remainder	Triad equivalent of remainder	
[illegible]	307	4	100	Least significant
[illegible]	38	3	011	
[illegible]	4	6	110	
[illegible]	0	4	100	Most significant

Octal code 100 110 011 100 equals decimal 2460

Conversion from 137 decimal to octal notation

Division	Quotient	Remainder	Triad equivalent of remainder	
[illegible]	17	1	001	Least significant
[illegible]	2	1	001	
[illegible]	0	2	010	Most significant

Octal code 010 001 001 equals decimal 137

(*b*)

Figure 7-10 (*a*) Conversion of octal notation numbers to decimal numbers; (*b*) conversion of decimal numbers to octal notation numbers.

The triad list is 001 011 100 101, which is the octal notation code of the decimal number 741. Figure 7-10 shows several examples of conversions from octal notation to decimal and from decimal to octal codes. In the triad groups used in the preceding examples, each triad is separated by a blank space. In a typical computer language, the blank space would be removed, and the triad groups would be bunched together. For example, the octal notation number 100 011 010 111 would be represented as 100011010111.

Hexadecimal Number System

The **hexadecimal number system** (Hex) uses base 16. Hexadecimal **numbering** systems are used for a variety of computer **functions** due to their ability to represent large binary **values**. The hexadecimal number system uses the numbers 0 through 9, along with the letters A, B, C, D, E, and F, to make up the 16 symbols. The relationship between the hexadecimal, decimal, and binary numbers is shown in Table 7-5.

TABLE 7-5 The relationship between decimal, hexadecimal, and hexadecimal notation.

Decimal	Hexadecimal (16 symbols)	Hexadecimal notation (four bit group)
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
10	A	1010
11	B	1011
12	C	1100
13	D	1101
14	E	1110
15	F	1111

Hexadecimal Notation

As previously mentioned, hexadecimal numbers are comprised of 16 symbols (0-F). In hexadecimal notation, each of these 16 symbols is represented by a four-bit binary group as seen in Table 7-5. Any time hexadecimal numbers are represented in a four-bit binary group, the actual name of the numbering system is **hexadecimal notation**; however, it is often referred to as simply as **hex** or **hexadecimal**.

It is easy to get confused between the terms **hexadecimal** and **hexadecimal notation**; however, keep in mind that groups of four binary bits are used in hexadecimal notation and 16 separate symbols (0-F) are used in hexadecimal.

Hexadecimal to Decimal Conversion

Each digit in a base 16 number possesses a magnitude that corresponds to that digit's position. The right-most digit in a sequence, or the least significant digit (LSD), has a magnitude of 16^0, or 1. The left-most digit in the sequence, or the most significant digit (MSD), has a magnitude of 16^{n-1}, where n is the number of digits in the sequence. To convert the number 653_{16} to its decimal equivalent:

$$653_{16} = 6 \times 16^2 + 5 \times 16^1 + 3 \times 16^0$$
$$= 1536 + 80 + 3$$
$$= 1619_{10}$$
$$FA2_{16} = 15 \times 16^2 + 10 \times 16^1 + 2 \times 16^0$$
$$= 3840 + 160 + 2$$
$$= 4002_{10}$$

Note that 15 was substituted for F and 10 was substituted for A in the second example.

Decimal to Hex Conversion

As with decimal to binary conversion, repeated division is used to calculate the equivalent base 16 number.

To convert 324_{10} to its hex equivalent:

$$\frac{324}{16} = 20 + \text{remainder of } 4$$

$$\frac{20}{16} = 1 + \text{remainder of } 4$$

$$\frac{1}{16} = 0 + \text{remainder of } 1$$

Therefore, $324_{10} = 144_{16}$.

To convert 412_{10} to its hex equivalent:

$$\frac{412}{16} = 25 + \text{remainder of 12 (12 will be converted to "C")}$$

$$\frac{25}{16} = 1 + \text{remainder of } 9$$

$$\frac{1}{16} = 0 + \text{remainder of } 1$$

Therefore, 412_{10}, $= 19C_{16}$.

Note how the remainders of the division processes form the digits of the hex number.

Hex to Hexadecimal Notation

To create a hexadecimal notation number each hexadecimal digit is converted to its 4-bit binary equivalent.

To convert $2F9_{16}$ to hexadecimal notation:

$$\begin{array}{ccc} 2 & F & 9 \\ \downarrow & \downarrow & \downarrow \\ 0010 & 1111 & 1001 \end{array}$$

Therefore $2F9_{16} = 001011111001$ (hexadecimal notation)

Hexadecimal to Hex Conversion

This is simply a matter of converting each group of 4 binary digits to its hexadecimal equivalent. Starting from the right of the binary number, count every 4 bits and convert.

To convert 10110001101 to its hexadecimal equivalent:

$$101\,100011\,01 = \underbrace{0101}_{5}\ \ \underbrace{1000}_{8}\ \ \underbrace{1101}_{D}$$

Therefore, 101 100011 01 hexadecimal notation $= 58D_{16}$.

LOGIC GATES

An Introduction

Logic gates, or **gates**, are fundamental functions performed by computers and related equipment. A single integrated circuit (IC) within a computer contains several gate circuits. Each gate may have several inputs and must have only one output. There are seven, commonly used logic gates: the **AND**, the **OR**, the **INVERT**, the **NOR**, the **NAND**, and the **exclusive OR** and the **exclusive NOR**. The name of each gate represents the function it performs.

Truth tables are a systematic means of displaying binary data. Truth tables illustrate the relationship between a logic gate's inputs and output. This type of data display can be used to describe the operation of a gate or an IC. For troubleshooting purposes, the truth table data for a specific IC is often reviewed in order to determine the correct output signal for a given set of inputs.

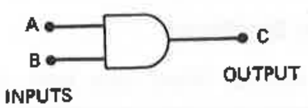
Each logic gate has a symbol of a specific shape. The symbols are designated to "point" in a given direction. That is, the inputs are always listed on the left of the symbol and the output on the right. Since logic gates operate using digital data, all input and output signals will be composed of 1 s or 0 s. Typically, the symbol 1 represents "on," or voltage positive. The symbol 0 represents "off," or voltage negative. Voltage negative is often referred to as zero voltage or the circuit's ground.

The AND Gate

The **AND gate** is used to represent a situation where all inputs to the gate must be 1 (on) to produce a 1 (on) output. For an AND gate, input no. 1, input no. 2, input no. 3, etc., must be 1 to produce a 1 output. If any input is a 0 (off), the output will be 0 (off). The symbol and the truth table for a two-input AND gate are illustrated in Fig. 7-11.

A simple AND circuit may be represented by two switches in series used to turn on a light. If both switches (inputs) are on (1), the light will turn on (1). If either switch is off (0), the light will be off (0). Figure 7-12 illustrates this simple AND circuit.

A different AND circuit is shown in Fig. 7-13. This circuit uses solid-state components to produce the gate; therefore, it is more consistent with those circuits found within an IC. In this circuit, each diode is reverse-biased by a positive signal at inputs A and B, respectively. If both inputs are positive (1), the diodes are both reverse-biased and no current flows through R_1; therefore, there is no voltage drop over R_1, and point C is positive. If either input is negative (0), current will flow through R_1, and point C will be negative (0) owing to the voltage drop across R_1. In this circuit the only way to produce a positive at point C (a 1 output) is to provide both diodes with a positive voltage (both inputs are 1); therefore, the circuit performs an AND function.

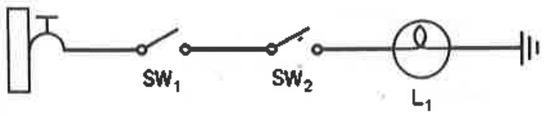


(a)

INPUTS		OUTPUT
A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

(b)

FIGURE 7-11 An AND gate: (a) logic symbol; (b) truth table.

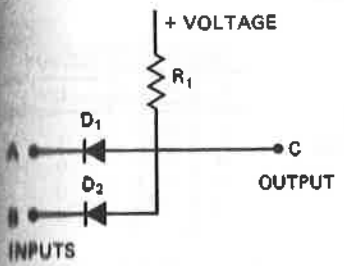


(a)

INPUTS		OUTPUT
SW1	SW2	L1
0	0	0
0	1	0
1	0	0
1	1	1

(b)

FIGURE 7-12 An AND circuit: (a) series circuit; (b) truth table.



(a)

INPUTS		OUTPUT
A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

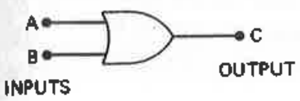
(b)

FIGURE 7-13 An AND gate: (a) solid-state AND circuit; (b) truth table.

The OR Gate

The **OR gate** is used to represent a situation where any input being on (1) will produce an on (1) output. For an OR gate, input no. 1 or input no. 2 or input no. 3, etc., must be 1 to produce a 1 output. Only if all inputs become 0 will the OR gate produce a 0 output. If any input is a 1, regardless of the other input values, the OR gate will produce a 1 output. A two-input OR gate symbol and the corresponding truth table are illustrated in Fig. 7-14.

A simple OR circuit may be composed of two switches in parallel, controlling one light, as illustrated in Fig. 7-15. If either switch is on (1), the light will turn on (1).



(a)

INPUTS		OUTPUT
A	B	C
0	0	0
0	1	1
1	0	1
1	1	1

(b)

FIGURE 7-14 An OR gate: (a) logic symbol; (b) truth table.

Figure 7-16 shows a solid-state OR circuit and its corresponding truth table. In this circuit, if a positive voltage (1) is applied to either input, the corresponding diode will be forward-biased and current will flow through R_1 which makes point C positive(1).

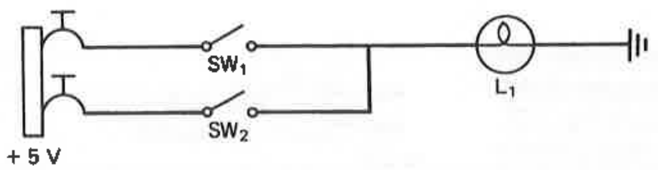
Point C will be negative only if there is no current flow through R_1. This occurs when both inputs are negative. If either or both inputs become positive, the output is positive; therefore, this is an OR circuit.

The INVERT Gate

The **INVERT gate** is used to reverse the condition of the input signal. The INVERT gate contains only one input and one output, and it is most often used in conjunction with other gates. The INVERT gate is sometimes referred to as a **NOT** gate. The symbol and truth table for an INVERT gate are shown in Fig. 7-17.

An INVERT circuit might be composed of a switch controlling a normally closed relay that turns on or off a light. As illustrated in Fig. 7-18, if the switch is turned on (1), the light is off (0).

A basic solid-state inverter circuit containing a transistor is illustrated in Fig. 7-19. As shown by the circuit's truth table, if the input is negative voltage (0), the transistor is reverse-biased and point B is positive (1). Point B becomes positive owing to the lack of current through R_1. If no current flows in R_1, there will be no voltage drop across R_1; therefore, point B is positive. If point A becomes positive, the transistor is forward-biased and point B is connected to ground (0) through the emitter-collector circuit of the transistor; therefore, point B is negative (0).

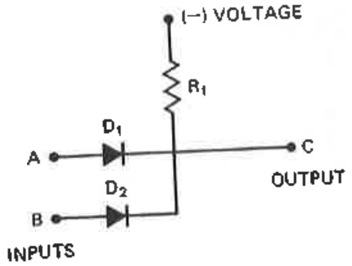


(a)

INPUTS		OUTPUT
SW1	SW2	L1
0	0	0
0	1	1
1	0	1
1	1	1

(b)

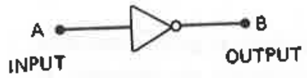
FIGURE 7-15 An OR circuit: (a) parallel circuit; (b) truth table.



INPUTS		OUTPUT
A	B	C
0	0	0
0	1	1
1	0	1
1	1	1

(b)

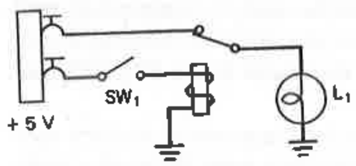
FIGURE 7-16 An OR gate: (a) solid-state OR circuit; (b) truth table.



INPUT	OUTPUT
A	B
0	1
1	0

(b)

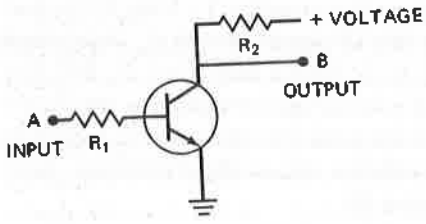
FIGURE 7-17 An INVERT gate: (a) logic symbol; (b) truth table.



INPUT	OUTPUT
SW1	L1
0	1
1	0

(b)

FIGURE 7-18 An INVERT gate: (a) simple INVERT circuit; (b) truth table.



INPUT	OUTPUT
A	B
0	1
1	0

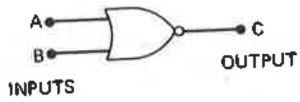
(b)

FIGURE 7-19 An INVERT gate: (a) solid-state INVERT circuit; (b) truth table.

The NOR Gate

The **NOR gate** is an OR gate with an inverted output. This results in a gate where any input being 1 will create a 0 output. The NOR symbol and truth table are given in Fig. 7-20.

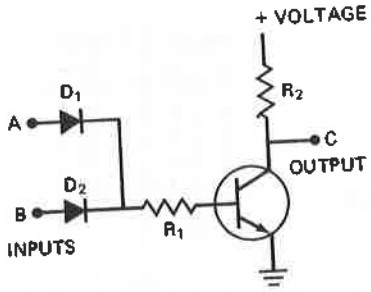
The electronic circuit used to represent a NOR symbol is illustrated in Fig. 7-21. If the inputs of this circuit are both negative (0), the transistor is reverse-biased and the output is positive (1). If either input is positive (1), the corresponding diode conducts and the transistor is forward-biased.



INPUTS		OUTPUT
A	B	C
0	0	1
0	1	0
1	0	0
1	1	0

(b)

FIGURE 7-20 A NOR gate: (a) logic symbol; (b) truth table.



INPUTS		OUTPUT
A	B	C
0	0	1
0	1	0
1	0	0
1	1	0

(b)

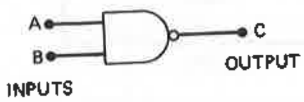
FIGURE 7-21 A NOR gate: (a) solid-state NOR circuit; (b) truth table.

This, in turn, connects point C to ground (0), and the output becomes negative (0).

The NAND Gate

The **NAND gate** is an AND gate with an inverted output. The output of this gate will be 1 if any input is 0. This, of course, is the exact opposite of the situation with an AND gate. The symbol and truth table of a NAND gate are shown in Fig. 7-22. The circuit for a NAND gate is shown in Fig. 7-23. If either input is connected to a negative voltage (0), the corresponding diode is forward-biased. Current then flows from the negative input voltage through R_1 to the positive source. Current takes this path instead of flowing from ground (0) through the emitter-base circuit and through R_1 and R_2 to the positive source. Since no current flows in the emitter-base circuit, the transistor is reverse-biased and point C is positive (1).

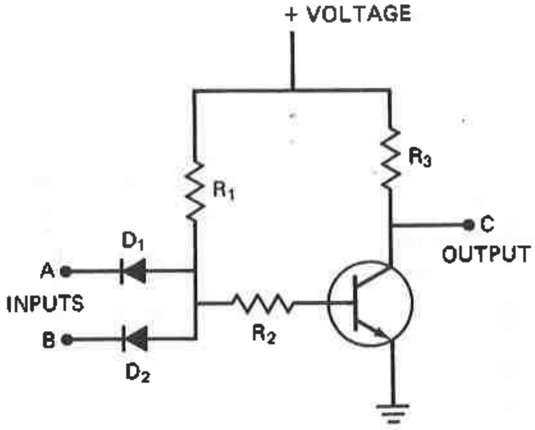
If both inputs are connected to a positive (1) source, both diodes are reverse-biased, the transistor is forward-biased, and point C is connected to ground (0); therefore, the output is 0.



INPUTS		OUTPUT
A	B	C
0	0	1
0	1	1
1	0	1
1	1	0

(b)

FIGURE 7-22 A NAND gate: (a) logic symbol; (b) truth table.

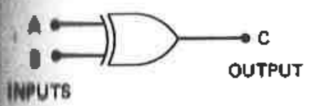


(a)

INPUTS		OUTPUT
A	B	C
0	0	1
0	1	1
1	0	1
1	1	0

(b)

FIGURE 7-23 A NAND gate: (a) solid-state NAND circuit; (b) truth table.



(a)

INPUTS		OUTPUT
A	B	C
0	0	0
0	1	1
1	0	1
1	1	0

(b)

FIGURE 7-24 An exclusive OR gate: (a) logic symbol; (b) truth table.

The Exclusive OR Gate

The **exclusive OR gate** is designed to produce a 1 output whenever its input signals are dissimilar. An illustration of the exclusive OR symbol is shown in Fig. 7-24*a*. This gate compares a maximum of two input signals to determine its output. The exclusive OR gate is often referred to as a digital comparator. As shown in Fig. 7-24*b*, if the input signals are like values, the output is 0; if the input signals are unlike values, the output is 1.

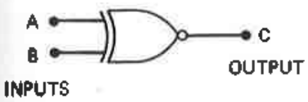
The Exclusive NOR Gate

The **exclusive NOR gate** produces an output pattern exactly opposite that of an exclusive OR gate. As seen in Fig. 7-25, the output of an exclusive NOR is a digital 1 any time the inputs are alike (both digital 1 or both digital 0). As with the exclusive OR, there can be two inputs to an exclusive NOR gate.

Variation of Basic Gates

The basic logic gates can be used in an infinite number of combinations. This variety of gate combinations allows a computer to perform a multitude of functions. One typical combination of logic gates adds an INVERT gate to the input of an AND or OR gate. A symbol and truth table for an AND gate with an inverted input are shown in Fig. 7-26. An inverted input is often referred to as a NOT input.

The circuit for an AND gate with an inverted input is shown in Fig. 7-27*a*. As illustrated, this circuit is simply a combination of an INVERT circuit and an AND circuit. INVERT gates are often added to the inputs, or outputs, of the basic gales previously discussed. Three other basic gate combinations are illustrated in Fig. 7-28. In the previous examples, each gate was displayed with only two inputs; however, many circuits have three or more inputs. This applies to all gates except the INVERT, the exclusive OR, and the exclusive NOR. The INVERT will always have only one input; the exclusive OR and exclusive NOR will always have two inputs. A multi-input gate can be constructed from several gates linked together as shown in Fig. 7-29. In this configuration, three AND gates are used to construct a four-input circuit. A four input AND gate and the related truth table are also shown in Fig. 7-29.

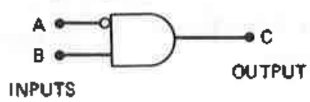


(a)

INPUTS		OUTPUT
A	B	C
0	0	1
0	1	0
1	0	0
1	1	1

(b)

FIGURE 7-25 An exclusive NOR gate: (a) logical symbol; (b) truth table.

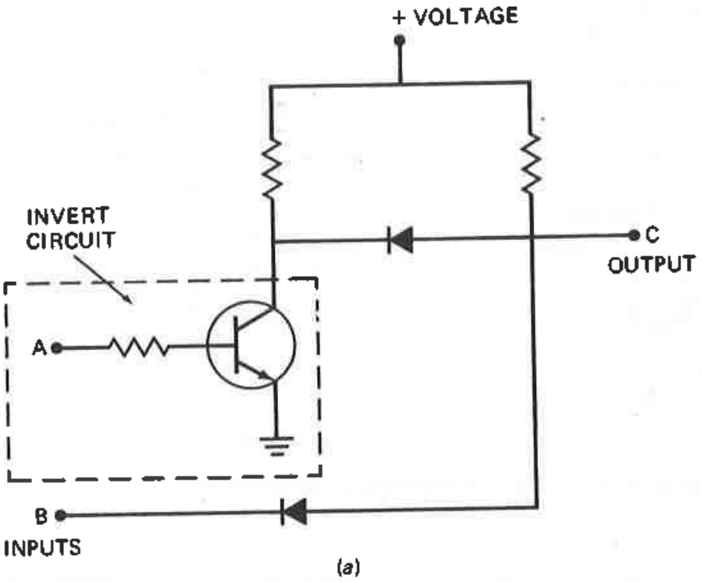


(a)

INPUTS		OUTPUT
A	B	C
0	0	0
0	1	1
1	0	0
1	1	0

(b)

FIGURE 7-26 An AND gate with an inverted input: (a) logic symbol; (b) truth table.

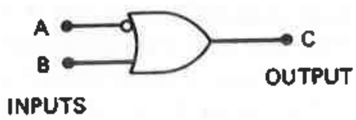


(a)

INPUTS A	INPUTS B	OUTPUT C
0	0	0
0	1	1
1	0	0
1	1	0

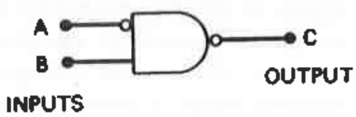
(b)

FIGURE 7-27 An AND gate with an inverted input: (a) solid-state circuit; (b) truth table.



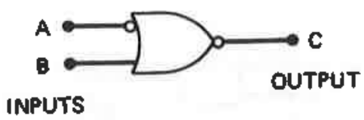
INPUTS A	INPUTS B	OUTPUT C
0	0	1
0	1	1
1	0	0
1	1	1

(a)



INPUTS A	INPUTS B	OUTPUT C
0	0	1
0	1	0
1	0	1
1	1	1

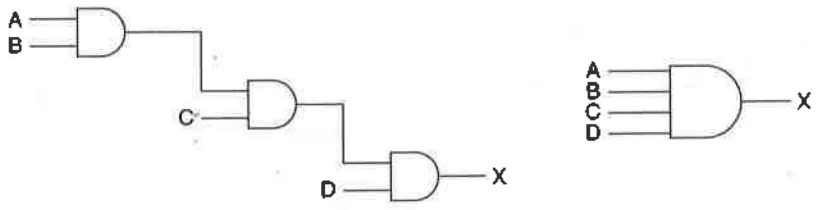
(b)



INPUTS A	INPUTS B	OUTPUT C
0	0	0
0	1	0
1	0	1
1	1	0

(c)

FIGURE 7-28 Variations of basic logic gates: (a) an OR gate with an inverted input; (b) a NAND gate with an inverted input; (c) a NOR gate with an inverted input.



(*a*) Constructed of 3 and gates

(*b*) A four-input and gate

Inputs				Outputs
A	B	C	D	X
0	0	0	0	0
0	0	0	1	0
0	0	1	0	0
0	0	1	1	0
0	1	0	0	0
0	1	0	1	0
0	1	1	0	0
0	1	1	1	0
1	0	0	0	0
1	0	0	1	0
1	0	1	0	0
1	0	1	1	0
1	1	0	0	0
1	1	0	1	0
1	1	1	0	0
1	1	1	1	1

(*c*) The truth table

FIGURE 7-29 A four-input and circuit: (*a*) constructed of 3 AND gates; (*b*) a four-input gate; (*c*) the truth table.

Positive and Negative Logic

As stated earlier, logic circuit input and output signals consist of two distinct levels. These levels are often referred to as binary 1 and binary 0. The actual voltage levels required to achieve a binary 1 or 0 may vary between circuits.

If **positive logic** is used in the digital circuit, a binary 1 equals a high voltage level and a binary 0 equals a low voltage level. The actual voltage values may be both positive, both negative, or one positive and one negative. The only stipulation for positive logic is that a binary 1 be created by a greater positive voltage than a binary zero. Four examples of a digital signal are shown in Fig. 7-30. Each signal represents the greater positive voltage value as a binary 1; therefore, each example employs the positive logic concept. Most digital systems employ positive logic throughout the entire computer and related component circuitry.

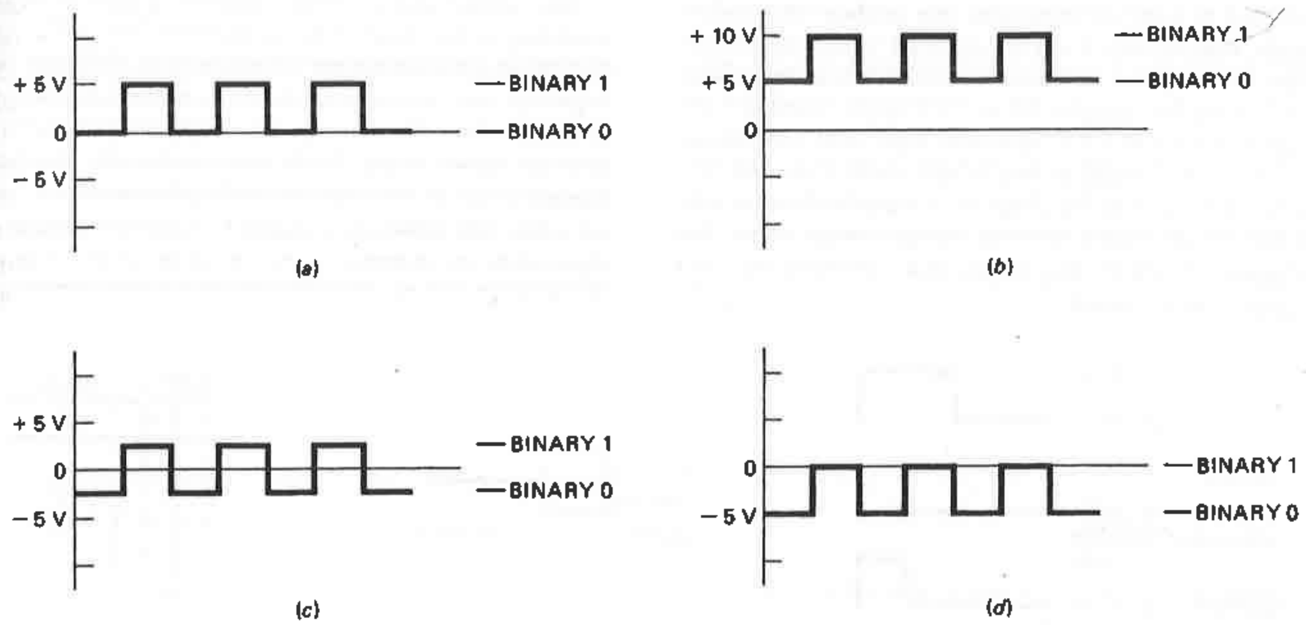


FIGURE 7-30 Four examples of positive logic digital signals: (*a*) binary 1 = + 5 V, binary 0 = + 0 V; (*b*) binary 1 = + 10 V, binary 0 = + 5 V; (*c*) binary 1 = + 2.5 V, binary 0 = −2.5 V; (*d*) binary 1 = + 0 V, binary 0 = −5 V.

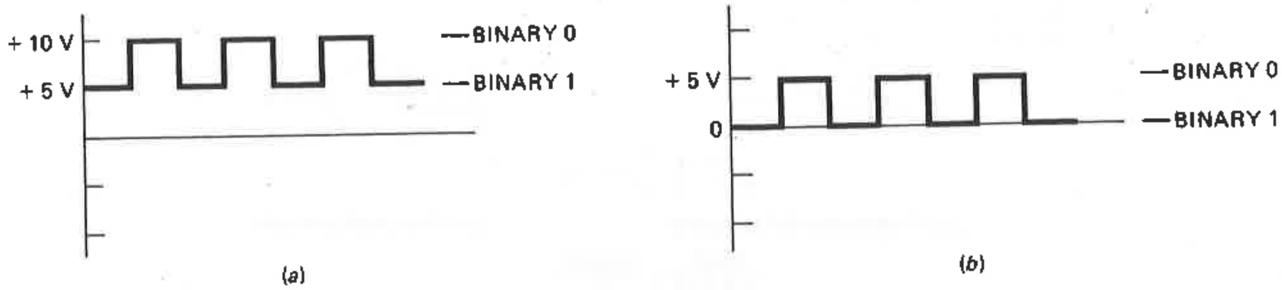


FIGURE 7-31 Examples of negative logic digital signals: (*a*) binary 1 = + 5 V, binary 0 = + 10 V; (*b*) binary 1 = + 0 V, binary 0 = + 5 V.

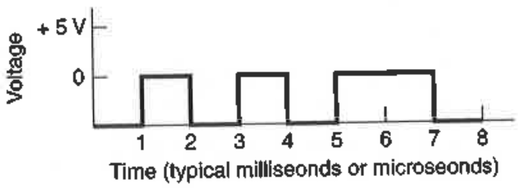


FIGURE 7-32 A typical digital waveform.

The voltage levels of any digital system are designed into the circuit by the limitations of the individual components. Since countless varieties of ICs are available, the circuit's design engineer must decide which voltage values best suit the design parameters. For most digital circuits, the two different logic states (1 or 0) are represented by two different voltage levels; however, a few specialty circuits may use current levels to determine logic states. In either case a threshold is designed for each logic family. (A **logic family** is a group of digital circuits that have similar characteristics.) If the voltage (or current) falls below the threshold, the connection is "low," when above the threshold, the connection is "high." Intermediate levels (those in between the low and high thresholds) are undefined and will typically not be recognized by the circuit. The most reliable circuits are designed to avoid circumstances that produce intermediate levels; thus creating a circuit where all results are predictable. It is common to allow some tolerance in the voltage levels used; for example, 0.0 to 1.0 V might represent logic state 0, and 4.0 to 5.0 V represents logic state 1. A voltage of 1.1 to 3.9 V would be invalid and would occur only in a fault condition or during a logic level transition because even digital circuits cannot instantly change voltage levels. The tolerance of each IC must be known to determine the exact voltage values required.

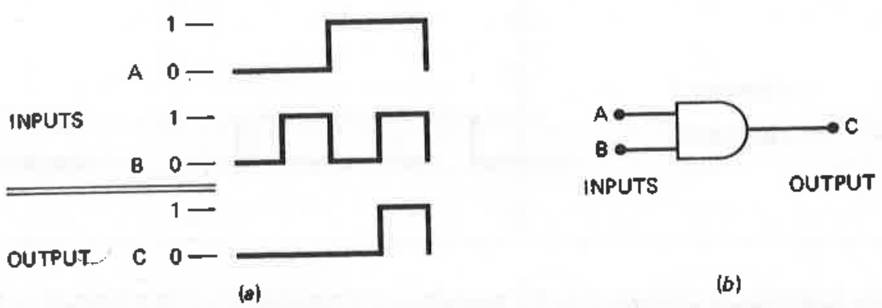
The **negative logic** concept defines binary 1 as the lower voltage value and binary 0 as the higher voltage value (more positive). Although less popular, negative logic is used in some systems in order to meet certain design parameters. Examples of negative logic digital signals are shown in Fig. 7-31. As illustrated, the binary 0 is the higher positive voltage value, and the binary 1 is the lower voltage value.

Display of Digital Data

The display of digital data can take several forms. The **truth table** and the **voltage waveform graph** are two common ways to display digital data. Truth tables have been discussed previously in this chapter; voltage waveform graphs will be presented in the following paragraphs.

The digital waveform may be used to describe the operation of any digital circuit by displaying its input and output data. Figure 7-32 shows a typical digital waveform. As illustrated, the vertical line represents voltage values, and the horizontal line represents time. The manipulation of most digital signals requires an extremely short time interval; therefore, the horizontal axis is often scaled in milliseconds or microsecond. One millisecond equals one-thousandth of a second; one microsecond equals one millionth of a second.

The vertical axis on some waveform graphs is labeled according to the binary code, as shown in Fig. 7-33*a* This illustration demonstrates the waveform of an AND gate. The horizontal and vertical axes have been eliminated to help clarify the data. The corresponding logic symbol and truth table are shown in Fig. 7-33*b* and *c*. From this waveform diagram it can be seen that the AND gate produces a 1 output when both inputs are a digital 1. Waveform displays of digital data are commonly used during the troubleshooting of computer circuits. An extremely high speed oscilloscope



INPUTS		OUTPUT
A	B	C
0	0	0
0	1	0
1	0	0
1	1	1

(*c*)

FIGURE 7-33 Digital data: (*a*) waveform graph; (*b*) logic gate symbol; (*c*) truth table.

can display a digital waveform with a pulse time of less than 1 ms. The waveform displayed by the scope can be compared with known operational data in order to evaluate the circuit's performance.

INTEGRATED CIRCUITS

An **integrated circuit** (IC) is simply an assembly of diodes, transistors, and/or other circuit elements combined into an extremely small package. Since a computer "thinks" by moving electrons through a variety of circuits, it is important to keep circuits as close together as possible to reduce the electron travel time. The greater the number of circuits contained in a small area, the faster the computer. In order to produce an extremely small circuit, most manufacturers use a process called **photolithography**. This process has been used to produce ICs capable of handling thousands of bits (1 s and 0 s). Recall that a *bit* is equal to one piece of digital information.

Photolithography imprints a circuit on a silicon wafer by focusing a pattern of light into a concentrated area. This process is similar to that used in a darkroom to imprint a negative's image on photographic paper. Chemical solvents are then used to etch the circuit's design into the silicon. By adding other materials to specific areas of the silicon wafer, "doping" of the circuit is accomplished. A second layer of silicon may be added and another combination of circuits produced within the IC. The silicon wafers are then cut to size and assembled into the IC package. Figure 7-34 shows various silicon wafers ready to be cut and assembled into ICs. Extremely small gold wires are used to connect the silicon to the IC pin terminals. The silicon chip is usually housed in a plastic package which holds the silicon wafer and the external electrical connections.

Figure 7-35 shows three **40-pin microprocessors**. From the top down, they are a ceramic piggyback package microprocessor, a standard ceramic package microprocessor, and a standard plastic package microprocessor. A microprocessor is a complex or very large scale IC and will be discussed later. These microprocessors each contain 40 pin terminals, which are used to transmit the electrical signals between the circuit board and the silicon wafer.

Integrated circuits are produced in a wide range of circuit complexities. Some ICs are simple adders or subtracters of binary digits, some ICs are dedicated memory devices, while others contain an entire digital system similar to a simple computer or calculator. Integrated circuits are often defined according to the complexity of the circuitry contained in the silicon wafer. When ICs were first developed, only a few transistors could be placed on a chip. As manufacturing techniques improved, it became possible to shrink the size of circuit components and today millions and even billions of transistors can be placed on one integrated circuit.

The first integrated circuits called **small-scale integration (SSI)** often contained as few as five to ten transistors and typically had 8 to 16 external electrical connections, where the IC was soldered to a printed circuit board. SSI circuits were crucial to early aerospace projects, and these

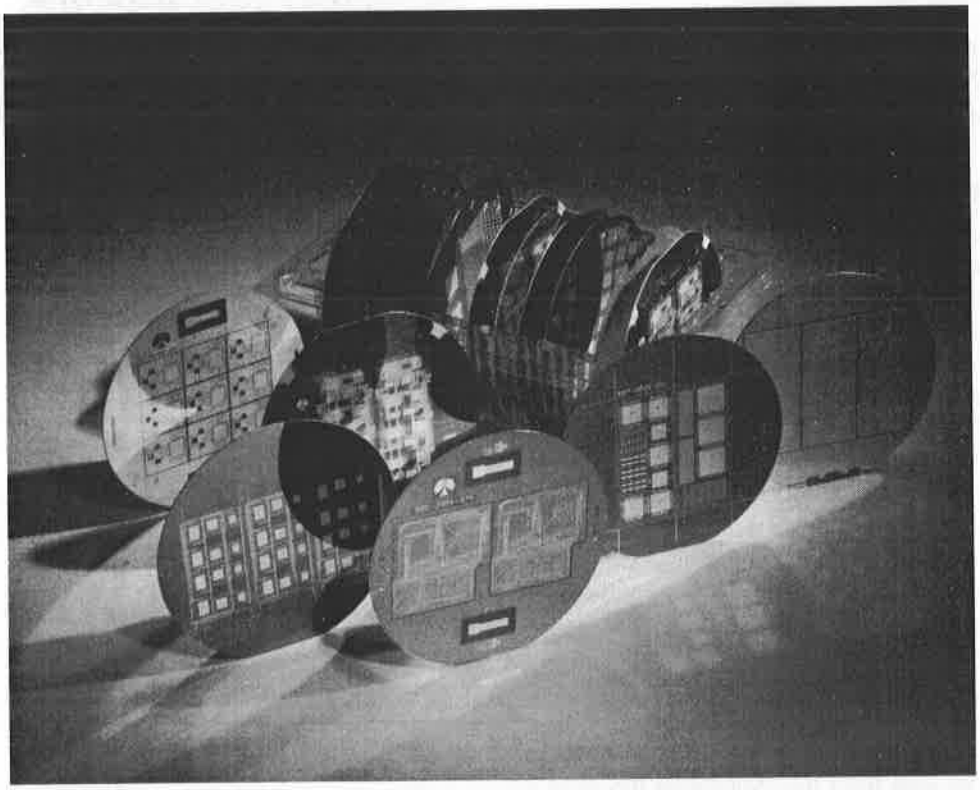


FIGURE 7-34 Silicon wafers ready to be cut and assembled into ICs. (*Collins Divisions, Rockwell International.*)

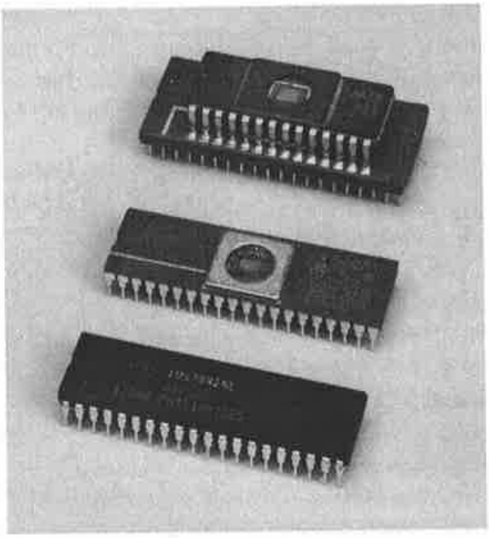


FIGURE 7-35 Three 40-pin microprocessors. (*Texas Instruments, Inc.*)

aerospace projects helped inspire development of the technology. **Medium-scale integration (MSI)** circuits are ICs containing hundreds of transistors on each chip. **Large-scale integration (LSI)** chips containing tens of thousands of transistors became popular in the 1970s to create the first generation of microprocessors. **Very large-scale integration (VLSI)** IC development started with hundreds of thousands of transistors in the early 1980s, and it continues beyond several billion transistors today. VLSI chips contain many thousands of logic gates in a single package in order to create complex microcomputers.

Integrated circuits are often divided into classes called **logic families**. A family contains ICs that operate at similar power levels and speeds. Two common logic families are the **TTL** and **CMOS** families.

The TTL Logic Family

A **transistor-transistor logic**, or TTL, circuit contains bipolar transistors as its primary elements. All TTL ICs operate with a +5-V power source and positive logic; therefore, binary 1 equals + 5 V, and binary 0 equals ground or +0 V. Most TTL circuits will accept voltage values within a certain tolerance; for example, binary 1 = 2.6 V to 5.0 V and binary 0 = 0.0 V to 0.8 V. There are five common TTL circuits; they are the **standard TTL**, the **low-power TTL**, the **high-power TTL**, the **Schottky TTL**, and the **low-power Schottky TTL**. The members of the TTL family employ slightly different circuit components to perform various logic functions. The use of different components often changes the power requirement of the circuit. When the power requirement of the circuit changes, typically the speed of the circuit changes. As a general rule, faster circuits consume more power.

An example of a basic TTL inverter circuit is shown in Fig. 7-36. It can be seen from this illustration that even a simple TTL inverter contains four bipolar transistors.

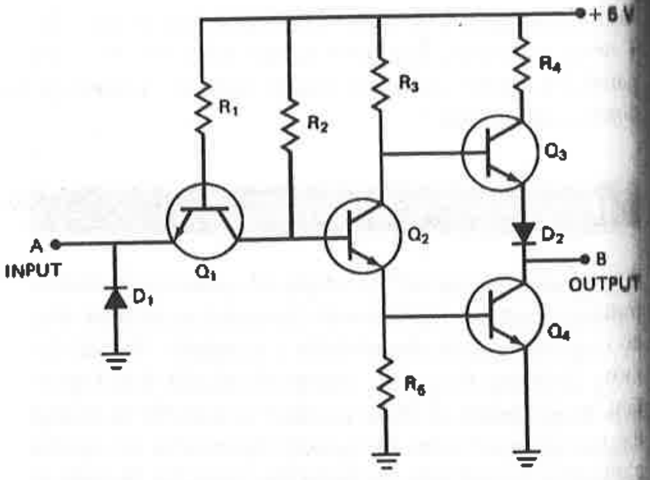


FIGURE 7-36 A TTL inverter circuit.

The CMOS Logic Family

CMOS is the acronym for **complementary metal-oxide semiconductor**. A CMOS is a metal-oxide semiconductor field-effect transistor (MOSFET) using both *p* and *n* channel inputs. The schematic in Fig. 7-37 is a CMOS inverter. This circuit replaces the bipolar junction transistors of the TTL gates with MOSFET devices. The major advantages of the CMOS logic family devices are that they are less susceptible to electrical interference and require less power than TTL devices. CMOS devices will also operate over a wider range of input voltage levels, typically between + 3 and + 18 V. Most modern ICs are of the CMOS logic family.

Integrated Circuit Standards

The most obvious standard for ICs is the connecting pin arrangement. As illustrated in Fig. 7-38, all ICs adhere to the **dual in-line package (DIP) standard**. This means there is

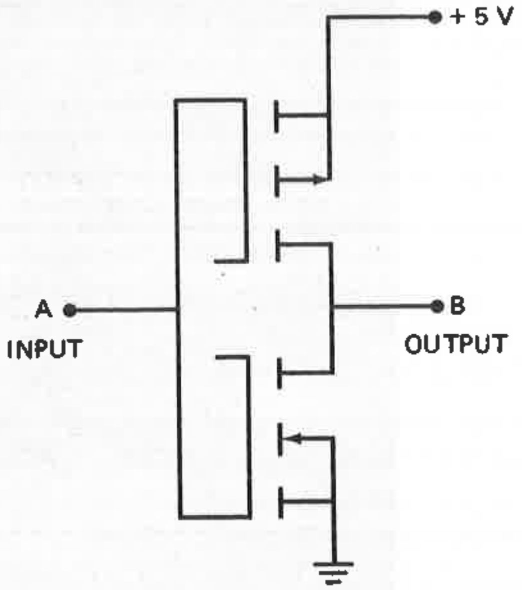


FIGURE 7-37 A CMOS inverter.

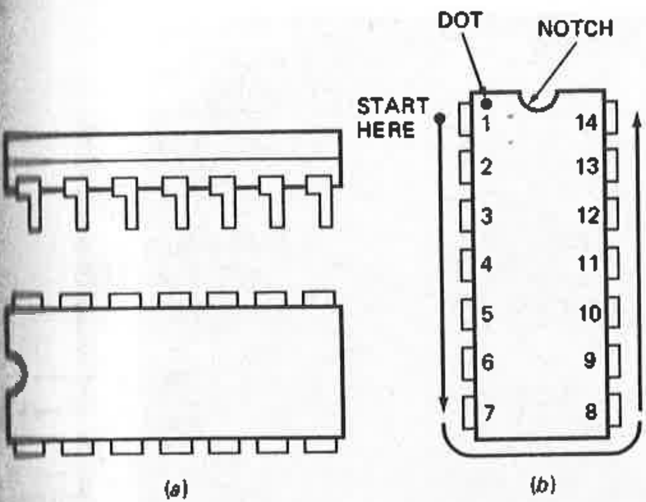


FIGURE 7-38 IC connection arrangement: (a) typical IC pins; (b) pin numbering configuration.

an equal number of connections (pins) on both sides of the IC, spaced within specific dimensions. Integrated circuits are available in 8-, 14-, 16-, 18-, 24-, 28-, and 40-pin configurations. Generally speaking, an IC with a greater number of pins is capable of performing a greater number of logic-functions.

The pin numbering arrangement is also part of the DIP standard. If the IC is viewed vertically, as in Fig. 7-38*b*, the top left pin is number 1. The pin numbers progress in a counterclockwise direction, down the left side of the IC and then up the right side. To identify the upper left corner of an IC, manufacturers place a notch or dot on each component. The notch, or dot, should be on top when the IC is viewed vertically with the terminal pins facing away.

A typical IC pin diagram is shown in Fig. 7-39. This IC is a type 7408 TTL unit containing four 2-input AND gates. This IC is known as a quadruple 2-input AND gate. The power connections of this IC are pins 7 and 14, as labeled. Diagrams such as this one become very useful during the

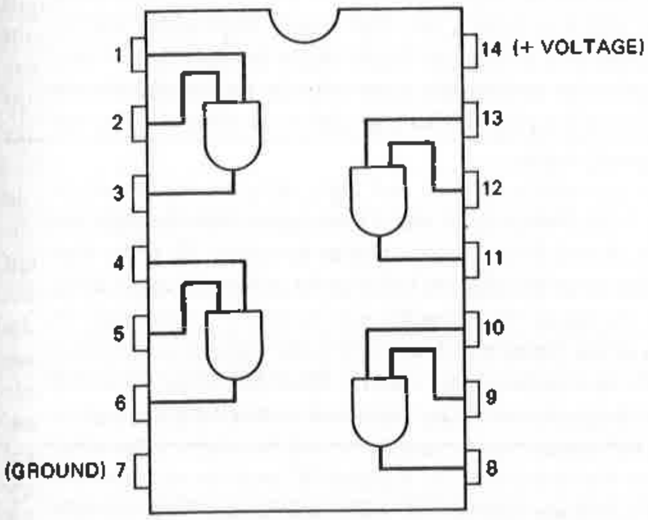


FIGURE 7-39 A 7408 TTL IC logic circuit diagram.

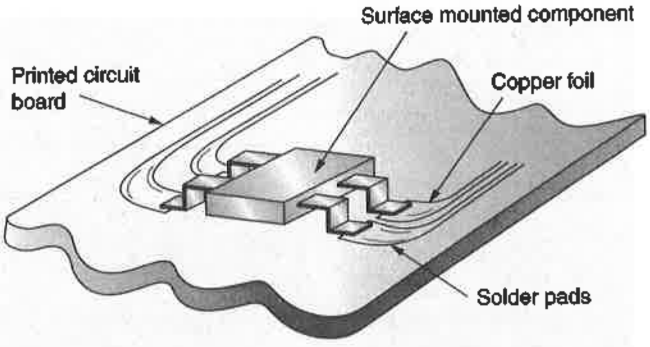


FIGURE 7-40 An example of a surface mounted component.

design or troubleshooting of electric devices containing integrated circuits.

In order to build faster and more powerful computers, IC manufacturers are constantly looking for ways to shrink circuitry. Recently a new line of electronic parts has been introduced; these parts are known as **surface mounted components**. As seen in Fig. 7-40, the electrical connections on these components are bent at a 90° angle, which allows the components to sit flat on the printed circuit board (PCB). The components are then attached by soldering their leads to the surface of the PCB. Traditional components contained leads that were mounted through the PCB and soldered on the side opposite the component. Figure 7-41 shows both a standard and a surface mounted IC for comparison.

Surface mounted components enable manufacturers to install electronic parts on both sides of a printed circuit board. This technique can, in effect, double the computing capacity of any given PCB. There are some problems associated with surface mounted components; for example, (1) compact installations require more cooling air, (2) the parts are made smaller than conventional ICs, resistors, capacitors, etc., and so removal and replacement are extremely difficult, and (3) identification of these subminiature components is difficult, since in many cases there is no room to print identification numbers on the part.

The DIP Switch

A **DIP switch** is a common switching device used in computers and logic circuits. All DIP switches adhere to the dual in-line package format; therefore, they are compatible with standard circuit board configurations. Figure 7-42 shows several DIP switches. Most DIP switches are double-throw, two-position switches; thus their inputs must be connected to one of two different outputs, as illustrated in Fig. 7-43. The input of a DIP switch is connected to ground (0) or voltage positive (1) for most logic circuits. This schematic shows four independent switches contained in one housing. Each pole is shown connected to the 5-V positive throw.

Most ICs require that each input be connected to a binary 1 or 0 signal. For example, a TTL device will assume a binary 1 for an unconnected input; a CMOS device will increase its power consumption and may overheat if its inputs are

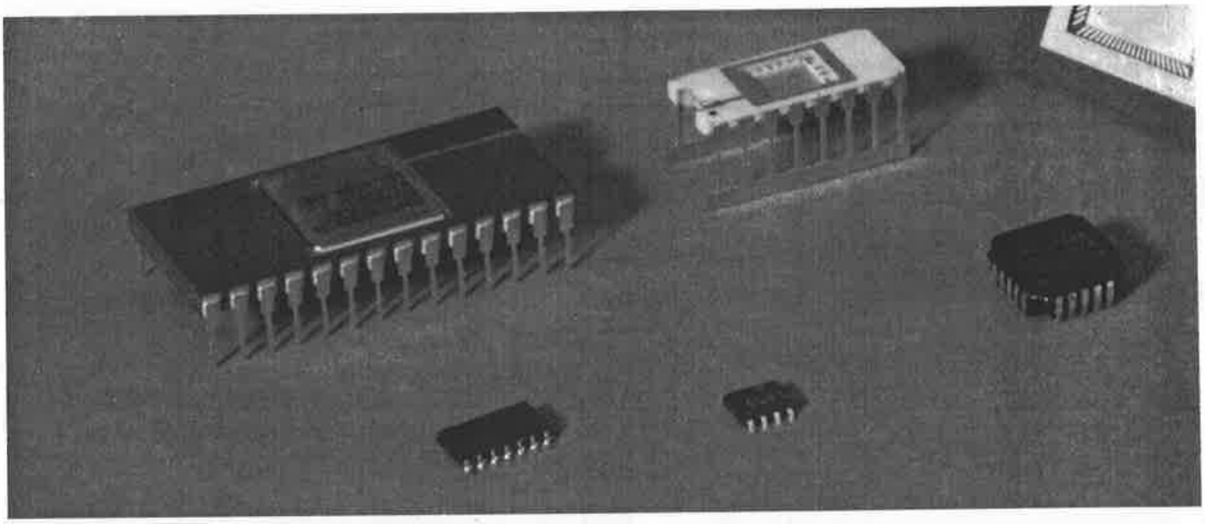


FIGURE 7-41 Examples of common integrated circuits: (top) standard ICs, (bottom) surface mounted ICs. (*Collins Divisions, Rockwell International.*)

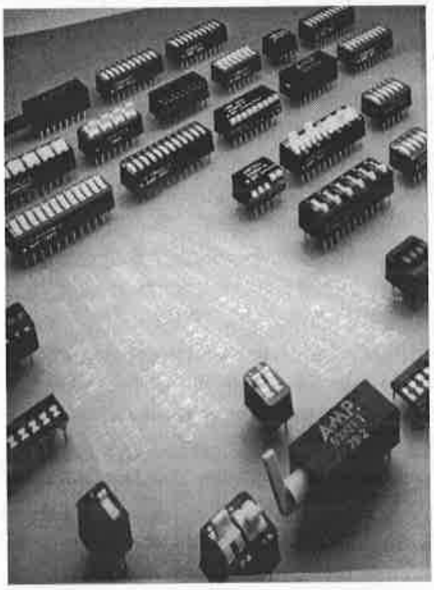


FIGURE 7-42 Typical DIP switches. (*AMP Products Corporation.*)

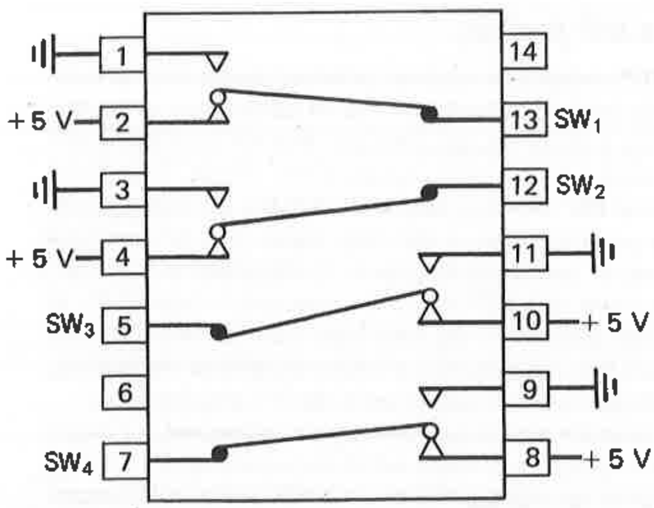


FIGURE 7-43 Typical connections of a DIP switch.

disconnected. Considering these problems, it is easy to understand why single-pole, double-throw DIP switches are used when controlling logic circuit inputs.

COMMON LOGIC CIRCUIT FUNCTIONS

There are several basic logic circuits that are common to almost every computer or related peripheral device. These circuits use simple combinations of the AND, OR, INVERT, and exclusive OR gates. Five of the most common logic circuits are **adders, subtracters, clocks, latches**, and **flip-flops**.

Adders and Subtracters

Adder and **subtracter** circuits are used to perform basic calculations in computer systems. **Adders**, as their name implies, add binary digits. Since binary numbers consist of only two digits, 1 and 0, it is almost always necessary to carry a digit to the next higher-order column when adding. For example, in binary numbers 1 + 1 = 10; two single digits were added to form a two-digit result. **Half-adder** circuits are capable of adding two binary digits, but they cannot carry a digit to the next higher-order column. **Full-adder** circuits use a combination of two half-adders in order to carry any necessary digits.

A full-adder symbol and logic diagram are shown in Fig. 7-44. Points A, B, and CI are inputs into the logic circuits. A and B are the two bits to be added; CI is the digit carried from the adjacent lower-order column (if applicable). The outputs of the full-adder are CO and S; S represents the sum of the digits added, and CO is the bit to be carried over to the next higher-order column. Each full-adder is capable of adding only two binary digits and a carried digit; therefore, one full-adder must be used for every two digits to be added in any binary calculation. A typical IC used for adding binary digits contains several full-adder subcircuits. This provides the IC with the capability to sum several binary digits.

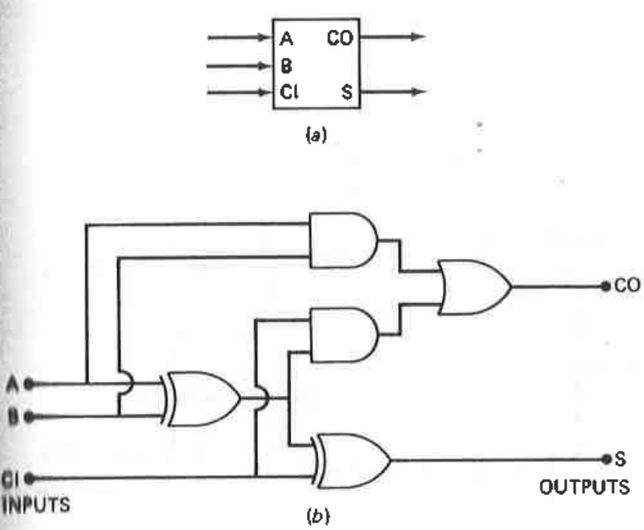


FIGURE 7-44 Full-adder: (*a*) logic symbol; (*b*) logic circuit diagram.

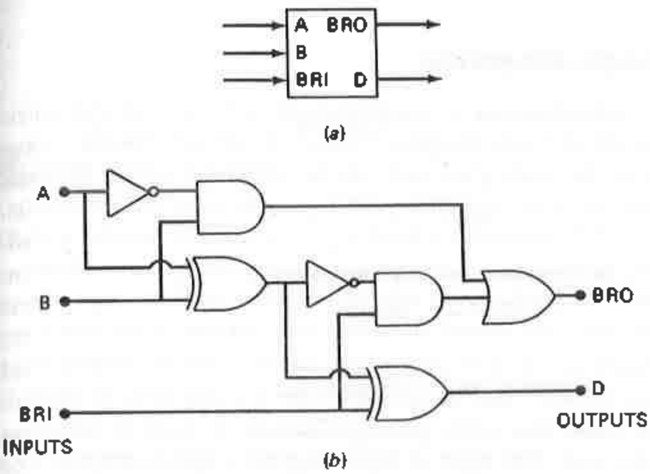


FIGURE 7-45 Subtracter: (*a*) logic symbol; (*b*) logic circuit diagram.

Subtracter circuits are a combination of basic gates, as shown in Fig. 7-45. The inputs to a subtracter are A, B, and BRI; A and B are the digits for the subtraction, and BRI is the digit borrowed from the subtraction in the adjacent lower-order column (if applicable). The outputs are D, the difference between the digits in the subtraction, and BRO, the digit to be borrowed from the adjacent higher-order column (if applicable).

Digital Clock Circuits

Certain functions of digital circuits require a consistently timed binary signal. A **digital clock** provides a stable frequency of binary 1s and 0s. The heart of a digital clock is an oscillator, or multivibrator circuit. A crystal material is commonly used to control the pulse time of a logic circuit to produce a consistent binary 1 and 0 waveform. This type of waveform is known as a **square wave.** Figure 7-46 shows a typical crystal-controlled multivibrator and its corresponding waveform. Although more complex arrangements are used, the most common clock output signal is a simple square wave with a 50 percent duty cycle, usually with a fixed, constant frequency. The duty cycle is the time that square wave spends in an active state as a fraction of the total time of one complete cycle. Figure 7-46(*b*) shows a typical square wave with a 50 percent duty cycle.

Latches and Flip-Flop Circuits

Latches and **flip-flop** circuits are combinations of logic gates that perform basic memory functions for computers and peripherals. Both types of circuits retain their output signal even after the input signal has been removed; therefore, these circuits "remember" the input data. There are two basic latch circuits, the **RS latch** and the **data-type latch.** As illustrated in Fig. 7-47, the RS latch contains two input signals, *set* S and *reset* R, and two output signals, Q and $\bar{Q}$. A binary 1 at the S input will set the latch memory, and Q will equal 1, while $\bar{Q}$ will be 0. A binary 1 at the R input will reset the latch, and Q will equal 0, while $\bar{Q}$ equals 1.

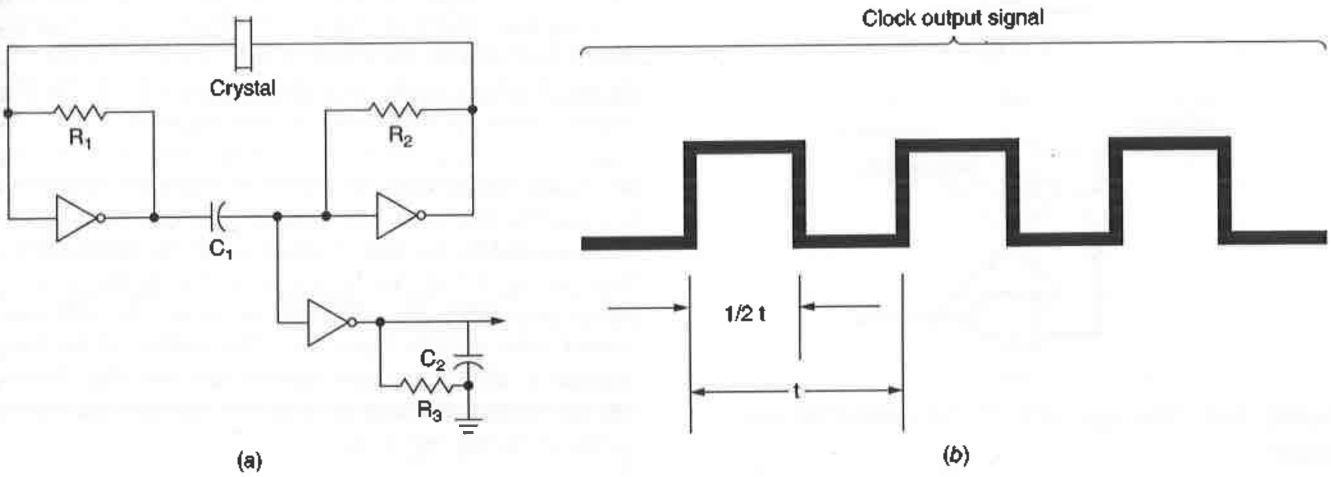


FIGURE 7-46 A crystal-controlled multivibrator: (*a*) the circuit diagram; (*b*) clock output, 50% duty cycle.

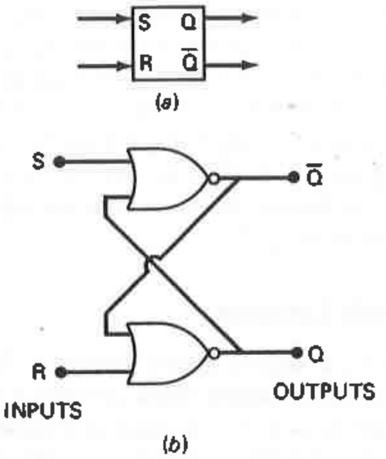


FIGURE 7-47 RS latch: (*a*) logic symbol; (*b*) logic diagram.

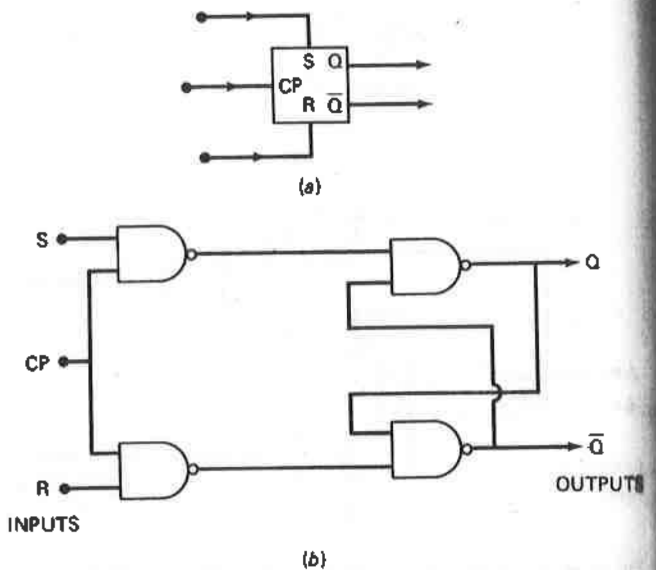


FIGURE 7-49 A digital flip-flop: (*a*) logic symbol; (*b*) logic diagram.

The data-type (d-type) latch contains only one input signal, as shown in Fig. 7-48. In this circuit, an input, D, of binary 1 will set the latch (Q = 1, $\bar{Q}$ = 0). Binary 0 at D will reset the latch (Q = 0, $\bar{Q}$ = 1).

Flip-flop circuits are similar to latch circuits; however, flip-flops change their output upon the presence of a trigger pulse. As shown in Fig. 7-49, a flip-flop circuit contains three inputs. The set S and reset R signals are identical with those of a latch circuit. The **clock pulse** (CP) is an input that controls the circuit switch time. That is, the flip-flop will change its output signals (Q and $\bar{Q}$) only at given time intervals. The switching time intervals are determined by the clock pulse and the set or reset signals.

The advantage of using a clock input for a memory circuit is that all flip-flop output signals change at the same time. This becomes very important when several memory circuits are used simultaneously. If one circuit was to change its output signal out of sequence, the entire memory might become invalid.

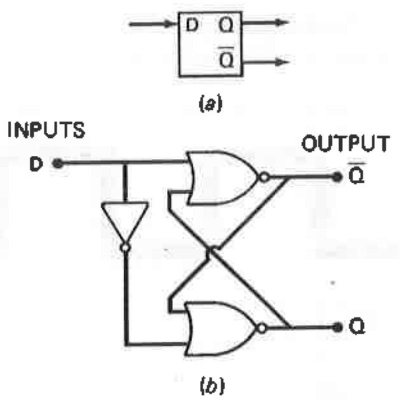


FIGURE 7-48 Data-type latch: (*a*) logic symbol; (*b*) logic diagram.

Logic Diagrams

A **logic diagram** is a simplified schematic of a complex digital circuit. Logic diagrams of digital circuits will typically show only the logic gates and not the actual transistors, diodes, and resistors performing the logic functions. For example, Fig. 7-50 represents a landing gear down indicator and warning horn system. A comparable analog circuit is also shown. In order for the down light to illuminate, all three gears must be down and locked; therefore, an AND gate is used for this function. All three gears must not be down and locked and the throttle must be closed for the warning horn to sound. A NOR and AND gate combination is used to perform this task. This type of logic diagram is quite common for describing modern aircraft electrical systems. As in this circuit representation, most logic diagrams do not show ground connections.

Logic diagrams are not limited to describing electric circuits. Many complex mechanical systems can be simplified by using logic diagrams. Figure 7-51 shows a logic diagram used to represent the pneumatic sources available for starting the no. 2 turbine engine of a three-engine aircraft. On this airplane, there are four means to start engine no. 2. To start engine no. 2 using engine no. 3 compressor bleed air, the pneumatic overpressure valve must be closed (off) and valve 2-3 must be open (on). This means of starting engine no. 2 is represented by the logic symbols within the lower dashed lines (see Fig. 7-51*b*). To start engine no. 2 using the auxiliary power unit (APU), the APU must be on and the APU load control valve must be open (on). This portion of the logic diagram is within the upper dashed lines (see Fig. 7-51*b*). The rest of the logic diagram is used to represent alternative means of starting engine no. 2.

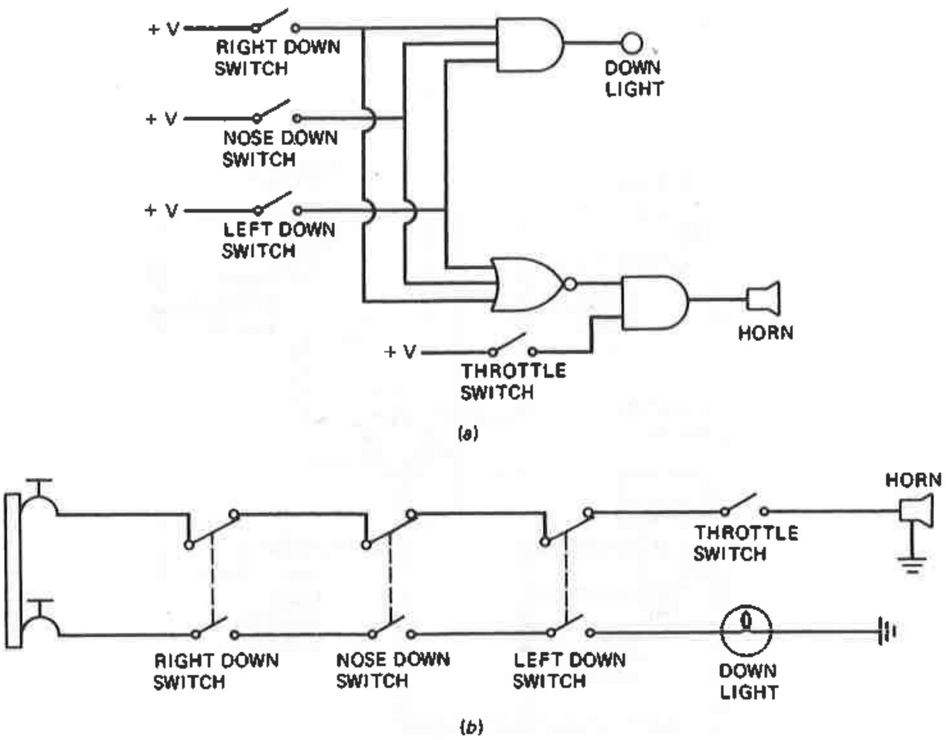


FIGURE 7-50 Representation of landing gear circuit: (*a*) logic diagram; (*b*) circuit schematic.

MICROPROCESSORS

Microprocessors are simply complex digital circuits that can be thought of as miniature computers. Microprocessors are typically very large scale ICs that contain thousands of gates arranged to perform specific functions. A common example of a microprocessor is found in every handheld calculator. The calculator's microprocessor performs all the necessary functions for the calculator's operation. In effect, the microprocessor is a computer designed for one function, to calculate numbers.

All microprocessors are made up of at least three basic elements: the central processing unit (CPU), the arithmetic logic unit (ALU), and a memory. The CPU is the primary control element of the microprocessor. The CPU processes and directs data according to requests made by the operator or another circuit in the system. The CPU coordinates the activities of the ALU, which performs the various calculations of the binary numbers to perform a specific function. The ALU performs its functions through the use of a variety of logic gates.

The memory of a microprocessor may be one of two types, permanent or temporary. The permanent memory provides information for the basic operations of the microprocessor. The temporary memory is used as a "notepad," or for short-term storage of data needed during the manipulation of numbers.

As seen in Fig. 7-52, all microprocessors require some means to communicate with the rest of the system. This communication link is called the **data bus**. The microprocessor also needs some type of timing device that is used to coordinate the activities of the system. A **synchronizer** or **clock** circuit is used for this function. Some microprocessors contain an internal clock, and some are accessed through the data bus.

Microprocessor Operation

The specific operation of a microprocessor is determined by the program contained in the memory and information received from data inputs. However, virtually all microprocessors follow a standard operating protocol. At power-up a microprocessor always starts at its **initialization routine**. The program functions of the microprocessor are divided into several subroutines. **Subroutines** are basically small programs that operate when called for by the CPU. The initialization routine is an example of a subroutine. When performing a routine, the CPU retrieves the routine's operating instructions from memory and performs the required operations; then it moves on to the next routine. This process is repeated until all functions have been completed or until the process is interrupted by a higher-order command.

During operation, the microprocessor must have a means of communication with the rest of the computer system. As mentioned above, the communication is accomplished through a data bus. A **data bus** can be used to connect various digital circuits within an electronic component, or it can be used to connect several independent components or systems located in various sections of the aircraft. The purpose

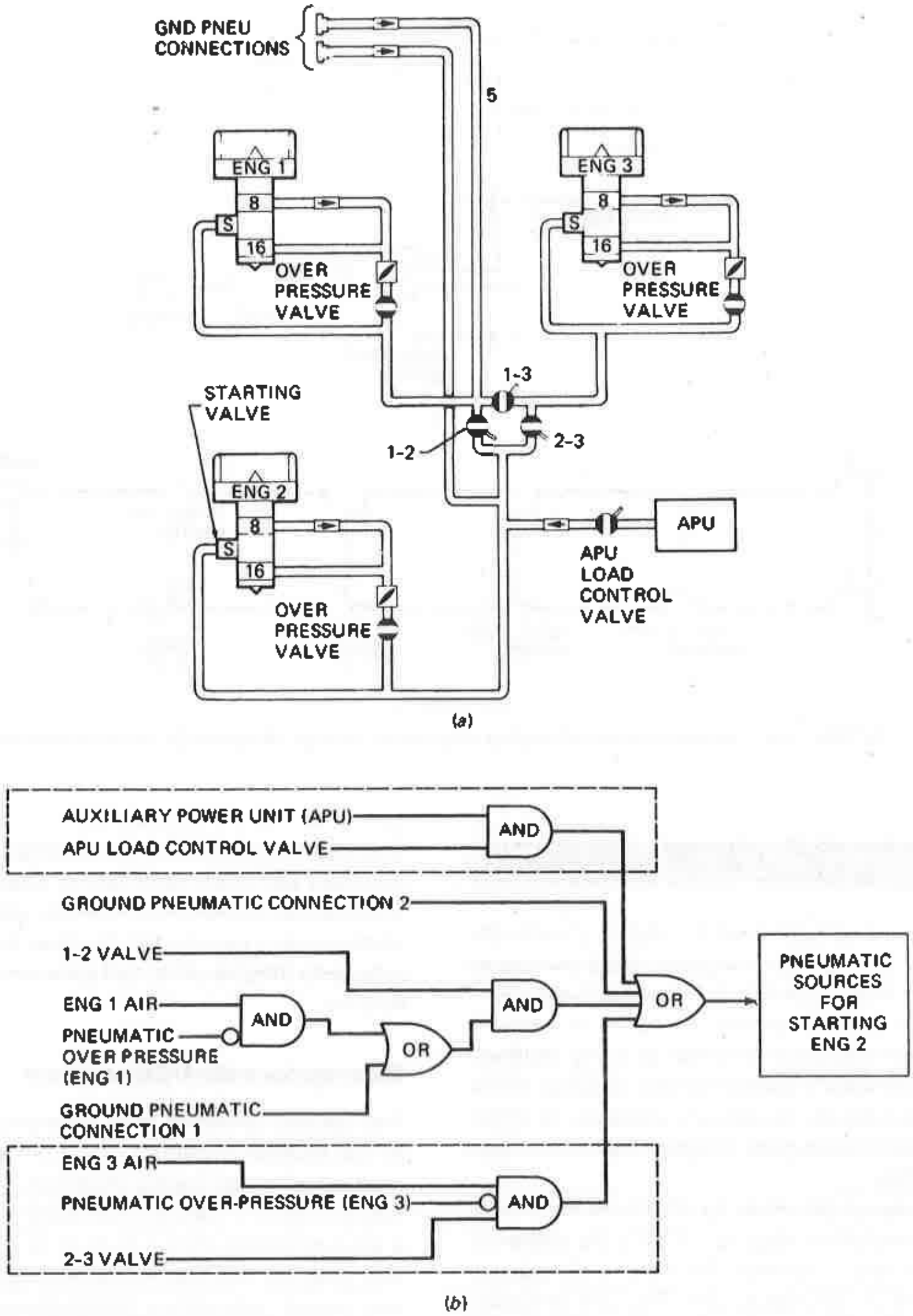


FIGURE 7-51 Various means of starting engine no. 2: (*a*) pictorial representation; (*b*) logic diagram. (*McDonnell Douglas Corp.*)

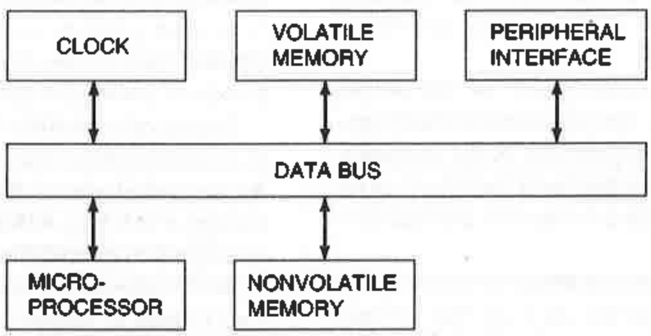


FIGURE 7-52 A typical microprocessor data link.

of a data bus is to transfer a digital signal from one circuit to another and this can be accomplished using electrical or light energy. One common data bus is made of a shielded pair of copper wires used for the transmission electrical data. When light is used to transmit the digital data signal, a fiber optical cable is used to create the data bus. The concepts of digital data bus technologies will be discussed in greater detail later in this chapter.

COMPUTER OPERATIONS

Every computer contains five fundamental sections: input, control, memory, processing, and output. Each of these sections manipulates binary digits through the use of logic circuits. The entire computer is composed of a power supply, microprocessor-based circuitry, and related peripherals. **Peripherals** are typically devices that allow the computer to communicate with humans or other electronic devices. For example, a keyboard is an input peripheral; a printer or a flat panel display is used as an output peripheral. Figure 7-53 shows the flow diagram of a typical computer. As illustrated, the **central control unit** must connect to each section of the computer in order to coordinate the activities of the entire system. Strict coordination is essential for the proper operation of any computer. Each system must operate only upon command by the central control unit. To coordinate the computer activities, the central control unit must have access to an accurate timing source. The computer's **clock** is used to perform this synchronizing function. A simple clock is an oscillator circuit used to generate a constant-frequency digital pulse. This pulse is used as a time base for all computer operations. The clock can be an integral part of the control unit, or it can be a separate element. The clock speed is often a good reference to determine how fast a computer can perform specific

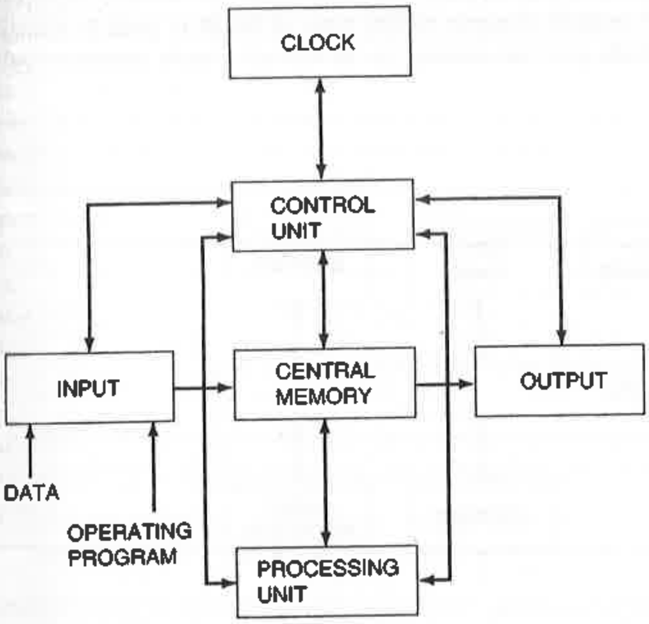


FIGURE 7-53 Computer block diagram.

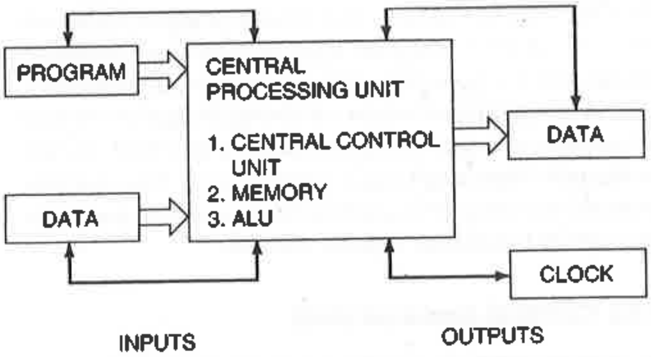


FIGURE 7-54 Central processing unit block diagram.

functions. It should be noted, however, that different sections of a computer system may operate at different speeds. For example, it is very common to have a home computer with a high-speed microprocessor and an external Ethernet connection that operates at a slower clock speed.

The Central Processing Unit

The **central processing unit (CPU)** is the circuitry within a computer, or computerized device like a cell phone, that carries out the instructions of a computer program by performing the basic arithmetical, logical, and input/output operations of the system. The CPU of any computer performs the actual addition and subtraction and other logic functions. That is, the CPU receives input data, manipulates that data in accordance with specific instructions, and responds with the respective output data. Figure 7-54 shows a block diagram of a typical CPU. The input to a CPU usually consists of a program, which is needed to "run" the specific jobs of the computer, and the input data, which is the information to be processed. The output data of the CPU is created by the manipulation of the input data in accordance with the computer program. For example, the input data to a typical CPU might be wind velocity and direction, airspeed, temperature, and distance to a destination. The output data might be the display of true airspeed and the time to the destination. Of course, the input would also include the program (such as mathematical equations) necessary to manipulate the data. In many cases the program is contained within the CPU memory and need not be added to the CPU input for each operation.

The input keyboard, the CPU, and the output display of a typical airborne flight computer are linked as shown in Fig. 7-55. The lines connecting the keyboard, the CPU, and

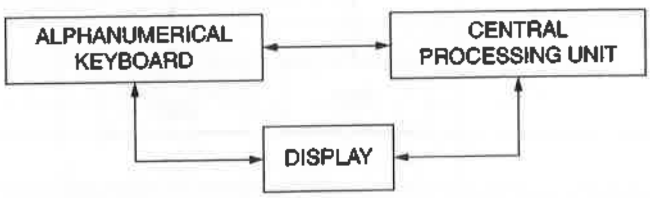


FIGURE 7-55 Data link to CPU.

the CRT represent the data link between these components. The CPU of every computer must be capable of communicating with its input and output peripherals. A computer's central processing unit can be subdivided into three essential subsystems: the **central control unit**, the **memory**, and the **arithmetic logic unit** (ALU). Depending on the computer, these subsystems can be combined in one microprocessor, or they can be completely separate elements.

The Central Control Unit

A control system is used to coordinate the functions performed by each section of the computer. To do this, a communication link must be provided between the central control unit (CCU) and the various computer sections. A **data transfer bus** is typically used to provide this communication link. A data transfer bus is a digital connection, or link, between two or more digital devices. On some systems, this is a two-way communication bus; on other systems, the data bus is a one-way link. In Fig. 7-54 the two-way data transfer is shown as a thin dark line pointing in both directions; the oneway data bus is shown as a wide line pointing in only one direction. There are a variety of different data bus systems currently being used. Data transmission will be discussed later in this chapter.

Since the CCU performs the main coordination of the functions of each peripheral device, it must be connected to each unit via a data transfer bus. The concept of a CCU and data bus is illustrated in Fig. 7-56. Here each section of the computer is linked to the data bus, which is linked to the CCU.

Memory

The memory of a CPU is often divided into two basic categories: **volatile memory** and **nonvolatile memory**. Data in a nonvolatile memory will *not* be destroyed when the computer is turned off. Memory of this type may be contained on magnetic disks, on magnetic tape, or within special ICs. The data in a volatile memory are lost whenever the computer loses electric power. Data of this type are simply stored by ICs containing latch or flip-flop circuits. When the power is removed from an IC, the memory returns to a neutral state, and the data are erased.

Data stored in any memory must first be converted into the binary language. The memory unit then "remembers" the appropriate byte combinations of 1 s and 0 s. These combinations are labeled in order to facilitate future access. Often a computer will have several memory units, some volatile, some nonvolatile. Most aircraft computers contain a relatively large nonvolatile memory in order to store the information necessary to process the flight data. Aircraft memory (either volatile or nonvolatile) is typically created using semiconductor circuits as opposed to magnetic discs, such as a hard drive found on a typical home computer. Semiconductor memory contains no moving parts and therefore creates a more reliable source for data storage, hence improving flight safety.

Semiconductor memory circuits are divided into two categories: **random-access memory** (RAM) and **read-only memory** (ROM). Random-access memory is often considered a write-and-read memory. That is, you must record (write) information into the RAM before someone can access (read) the information. A RAM may be changed at any time by using the correct procedures; therefore, it is considered to be a volatile semiconductor memory.

A read-only memory is a nonvolatile semiconductor memory. The logic pattern of 1 s and 0 s is permanently programmed into the semiconductor material of an IC. If the power is removed from that IC, the memory remains intact. Read-only memories are used often in aircraft computer systems to remember the operational program and subroutines for each system.

There is a special type of ROM that can be altered by the user, but only under special conditions. **EAROM (electronically alterable read-only memory)** can be changed if desired. To change an EAROM, the operator must follow the correct procedures and "reprogram" the memory chip(s). A typical example of this type of ROM is used to store flight path information on an aircraft's flight management

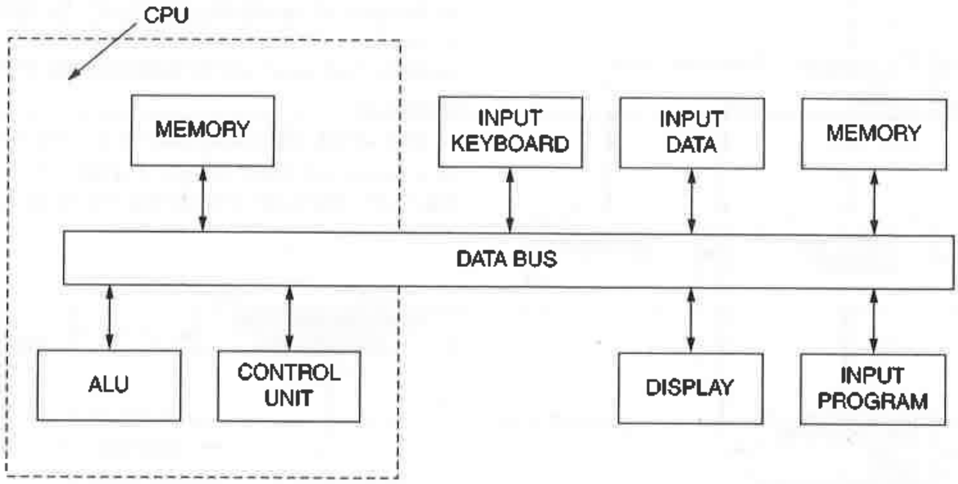


FIGURE 7-56 Data bus block diagram.

computer. Periodically the information must be updated. To do the updating, the new information is transferred to the EAROM from another "carry-on" computer, through a wireless download or a common flash drive storage device. During this update, the original data are lost and the new data stored in a read-only memory.

The Arithmetic Logic Unit

The **arithmetic logic unit** (ALU) is the "thinking" section of the CPU. That is, the ALU performs all the calculations and/or comparisons necessary to process the input data. The ALU received its name from the fact that it mainly performs arithmetic calculations using logic circuits. Of course, the ALU receives its coordination signals from the CCU. The resultant data from the ALU calculations are sent to the system's various output devices. The ALU is often thought of as the combination of logic circuits needed to process the computer program.

Data Transmission

All modern aircraft are highly computerized and contain hundreds of digital LRUs (line replicable units). Each of these LRUs and any computer subsystem or peripheral device must communicate using one or more digital data transmission systems. Commonly called a **data bus**, these data transfer systems connect various digital circuits using electrical or light energy. Copper wire is used for the transmission of electrical data and fiber optical cable is used to transmit digital light energy. At the time this text was written, fiber optical cable was still in limited use on civilian aircraft; however, two of the most recently designed commercial aircraft, the A-380 and the B-787, employ fiber optics for several main data connections. It is likely that aircraft designed in the future will continue to use digital light signals transmitted through fiber cable. There are two main advantages to optical data transmission; fiber cable weighs less than copper cable, and digital light signals are not susceptible to electromagnetic interference. Most digital communication data are transmitted in a **serial** form, that is, only one binary digit at a time. Transmission of data in serial form means that each binary digit is transmitted for only a very short time period. In most systems, the data transmission requires less than 1 ms. After one bit of information is sent, the next bit follows; this process continues until all the desired information has been transmitted. This type of system is often referred to as **time sharing**, because each transmitted signal shares the wires for a short time interval. **Parallel data transmission** is a continuous-type transmission requiring two wires (or one wire and ground) for each signal to be sent. Parallel transmission is so named because each circuit is wired in parallel with respect to the next circuit. One pair of transmitting wires may be used to handle enormous amounts of serial data. If the information signals were transmitted in parallel form, hundreds of wires might be required to perform a similar task.

When data is transmitted between various LRUs on the aircraft, the individual digital data bits (1s and 0s) are typically arranged into groups. Common names for these data groups are **words**, **bytes** or **message blocks**, or **datagrams**. Each group of bits is then transmitted through the data bus one bit at a time (in serial form); when transmission of the first group is complete, the second group will begin transmission, after completion of the second group, the third will begin and so on. This format allows a complete packet of information to be transmitted from one LRU to another in serial form. A data bus can be thought of as a conveyor belt that carries boxes. On the conveyor belt, only one box is sent at a time, followed by another, and another, like serial data transmission. Each box can be thought of as a data word containing multiple bits of digital data also transmitted in serial form.

Serial data transmission requires less wire than a parallel system; however, an interpretation circuit is needed to convert all parallel data to serial-type information prior to transmission. A circuit used to convert parallel data into serial data is called a **multiplexer**; and a circuit used to convert parallel data into a serial format is called a **demultiplexer**. Multiplexer and demultiplexer circuits are typically integrated into the input/output circuitry of an LRU. As illustrated in Fig. 7-57, parallel data are sent to a multiplexer, where they are converted into serial data and sent to the data transfer bus. The **data transfer bus** is a two-wire connection between the multiplexer and the demultiplexer. The demultiplexer receives the serial data and reassembles them into parallel form. In this example, the byte 10 100 is being received by the multiplexer in parallel form. Starting at the top and working down, the multiplexer transmits each digit individually. Bit number 0 is the first to be transmitted. Bit number 1 is the next digit transmitted, bit number 2 is next, and so on. This system is repeated until all the parallel data have been convened into serial form and have been individually connected to the data transfer bus. The demultiplexer receives a serial data input from the transmission bus and reassembles it into a parallel form. The output of the demultiplexer is identical to the input of the multiplexer (10 100). This example (Fig. 7-57) is very simple to help explain the concepts.

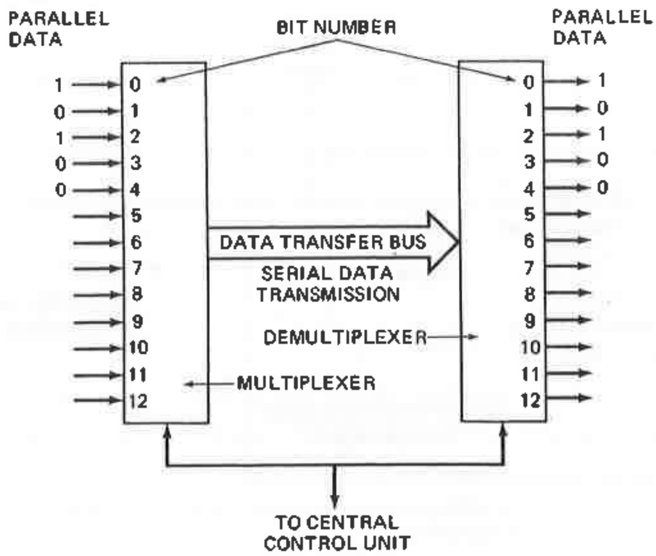


FIGURE 7-57 Data transfer system.

In many applications the individual bits would be replaced with data words or even word strings. Each word string could contain thousands of bits that are manipulated by the multiplexers and demultiplexer to allow for the serial transmission of data.

Some means of control must be used to coordinate the MUX/DEMUX arrangement. As shown in Fig. 7-57, the CCU is typically used to coordinate the transmission and reception of data. This control is essential to ensure that all serial data are transmitted and received at the proper time intervals. This system of serial data transmission may seem somewhat complex; however, the alternative, parallel data transmission, would require one wire for each data bit to be transmitted. Since thousands of bits of information are transferred among various airborne systems, serial data transmission techniques are the obvious choice.

The use of multiplexers and demultiplexers is necessary only when a change from serial to parallel (or vice versa) is required. In many cases serial data are transmitted to another component that can "read" serial data. In those cases no change in format is required. If the aircraft systems employ the use of fiber optical cable for data transmission, each LRU must incorporate a circuit to convert electrical energy into light energy and vice versa. Although light can be used to transmit digital data, electrical signals are necessary for the operation of digital circuits and computers. Figure 7-58 shows a simplified diagram of the elements needed for the use of fiber optical data transmission. The transmitting LRU must convert the electrical digital signal into a digital light signal. The actual light that travels through the optical cable is produced by an LED or a laser depending on the type of cable. It is critical to match the light wavelength to the optical fiber for proper data transmission. At the receiving LRU, another circuit is required to convert the incoming light into a digital signal. A light sensor, often a photo diode, is used to measure the incoming light and produce an electrical signal. Of course this is a simplified example and the actual circuitry is relatively complex, often containing amplifiers, buffers, and memory for data storage.

Data Bus Standards

Since digital aircraft systems were developed by different manufacturers and at different times in history, there are several data bus standards currently found on aircraft. A **data bus standard** can be thought of as a set of rules used to describe both the hardware and software of the data transfer system. In some cases, the data bus standard was developed by a specific manufacturer, such as Honeywell Corporation or Rockwell International and used primarily on their systems. Other data bus standards are established by industry-based groups and shared throughout the aviation and aerospace community. An openly shared standard allows all equipment developers to utilize common standards and simplifies development of new systems.

In order for two or more LRUs to communicate using digital signals, they must both conform to the same data bus standard. A data bus standard must define virtually every aspect of the digital data signals as well as structure of the data bus itself. Physical characteristics, such as, will the data bus be copper wire or fiber cable; and virtual characteristics, such as, voltage levels, transmission speed, and data word format must all be addressed by the standard. In some respects, a data bus standard establishes the rules for LRU communications; just as the English, Spanish, or Chinese language established the rules of communication between humans. This chapter will present introductory materials on common aircraft data bus standards; however, detailed explanations are beyond the scope of this text. Be sure to consult all current manufacturers' data and perform a thorough study of any data bus system prior to performing maintenance on digital aircraft systems.

ARINC Specifications

Aeronautical Radio Incorporated (ARINC) is a corporation established by foreign and domestic airlines, aircraft manufacturers, and transport companies. The purpose of this organization is to aid in the standardization of aircraft systems.

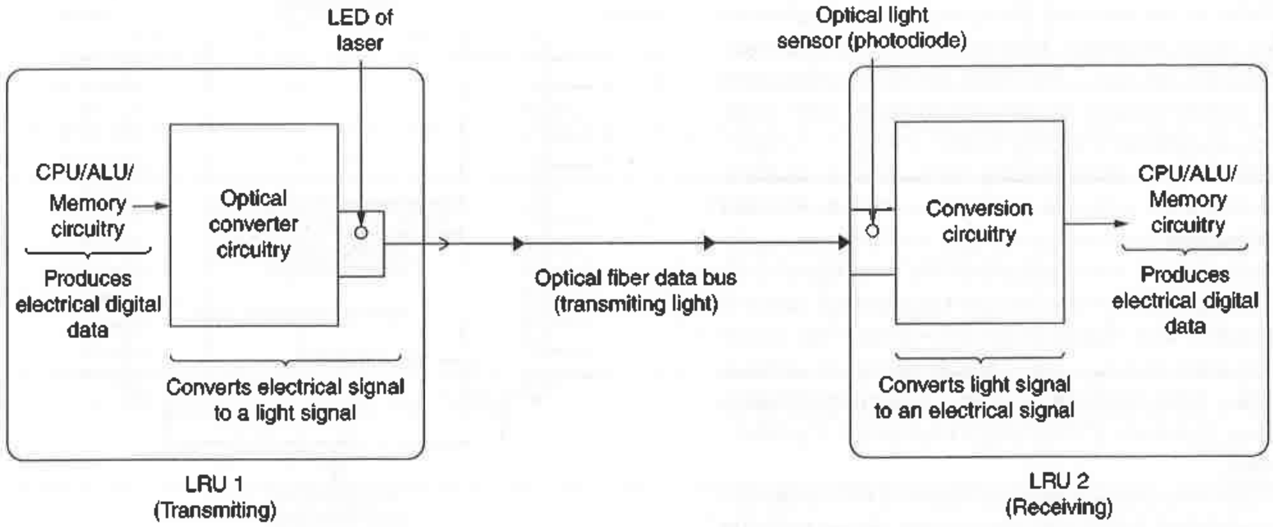


FIGURE 7-58 Optical conversion circuitry used for fiber-optic data transmission.

ARINC specifications have been established for digital flight data recorders (ARINC 573), inertial navigation systems (ARINC 561), digital information transfer systems (ARINC 429, 629, and 664), and various other aircraft communication and navigation systems.

ARINC 429 Data Bus Standard

ARINC 429 sets specifications for the transfer of digital data between aircraft electronic system components. An ARINC 429 data bus is a one-way communication link between a single transmitter and multiple receivers. The ARINC 429 system provides for the transmission of up to 32 bits of information in each byte or word. One of four-word formats must be used to conform to the ARINC 429 standards: **binary, binary-coded decimal** (BCD), **AIM**, or **discrete**. A synchronizing clock pulse is accomplished by a four-bit null between each word. A **null** is a signal that is equal to neither binary 1 nor binary 0. As shown in Fig. 7-59, ARINC 429 assigns the first 8 digits of a byte as the word label; digits 9 and 10 are a **source-destination indicator** (SDI), digits 11 through 28 provide the data information; digits 29 through 31 are the **sign-status matrix** (SSM), and bit number 32 is a **parity bit**. This format will change slightly between the different 429 word formats (see Fig.7-59).

There are 256 combinations of word labels in the ARINC 429 code. Each word is coded in an octal notation language and written in reverse order. The source-destination indicator serves as the address of the 32-bit word. That is, the SDI identifies the source or destination of the word. All information sent to a common serial bus is received by any receiver connected to that bus. Each receiver accepts only that information labeled with its particular address; the receiver ignores all other information.

The information data of an ARINC 429 coded transmission must be contained within the bits numbered 11 through 28. These data are the actual message that is transmitted by an LRU. For example, an airspeed indicator may transmit the binary message 0110101001. Translated into decimal form, this means 425, or an airspeed of 425 knots. The sign-status matrix (SSM) provides information that might be common to several peripherals. Examples of common information include north, south, plus, minus, right, left, east, and west. Using the SSM bits, fewer binary characters are required to represent this type of information than if each item were "spelled out" in the data segment of the word.

The **parity bit** of the ARINC 429 specification is used to check for errors in data transmission. The parity bit does not check for validity of data itself; this test is done by other circuitry in the transmitting and receiving LRUs. The ARINC 429 parity bit is assigned by the transmitting LRU just before the signal is sent to the data bus. ARINC 429 uses **odd parity,** meaning that the total number of bits set to digital 1 must be an odd number in order for the receiver to accept the data as valid. If the incoming data (bits 1-32) contain an even number of binary 1 bits, the entire 429 data word is ignored by the receiving LRU. The parity bit is assigned to the ARINC code prior to transmission. If an error occurs during data transfer, the parity bit will most likely be incorrect. The data receiver monitors the parity bit and identifies any errors. If an error is detected, the system's CPU will make any necessary adjustments and record the defect in a nonvolatile memory.

The parity bit test performed by all ARINC 429 receivers will determine if one or more data bits are lost during transmission. Data bits are low power electrical signals that turn on/off at very high speed. These signals are easily lost due to poor electrical connections or electromagnetic interference. It should be noted that the parity bit test is not foolproof; however, if several data bits are lost during transmission, other circuitry within the receiving LRUs are used to determine if the data is reasonable and valid.

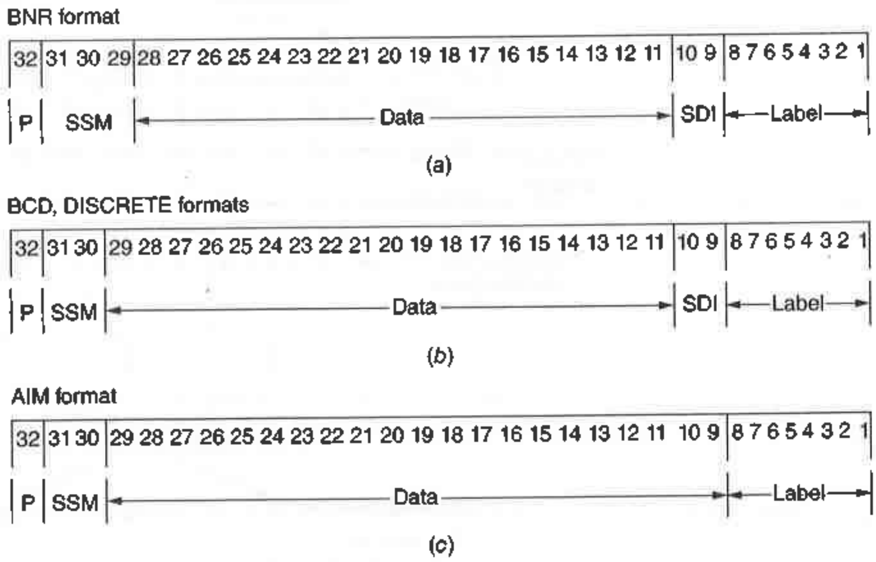


FIGURE 7-59 ARINC word formats: (*a*) binary (BNR); (*b*) binary coded decimal (BCD), discrete; and (*c*) AIM.

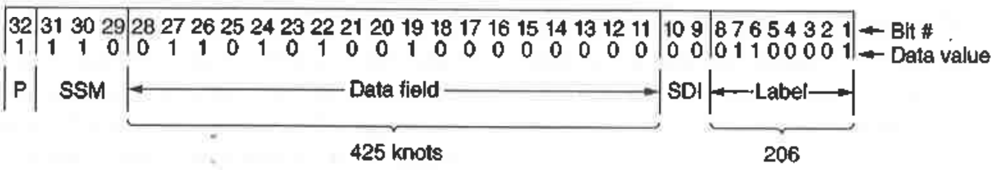


FIGURE 7-60 ARINC 429 data, computed airspeed.

Please note, the examples contained in this section of the text have been simplified for explanation purposes and should be used only for study of ARINC 429 not for actual aircraft maintenance or design.

Decoding the 429 Word Label

To help understand the ARINC 429 specification, please refer to Fig. 7-60 during the following discussions on decoding 429 data. The ARINC 429 standard assigns the **label** to the first eight bits of the 32-bit data transmission. The label is used to identify the type of information that is transmitted in the data field (bits 11-28). In this example, when the label is decoded, it is equal to 206. Since the label is an octal number, nothing higher than the number seven can exist and the label value must be stated as "two, zero, six" (not two hundred and six). As can be seen, the label is made up of 8 bits used to represent three octal digits. Bit numbers 1 and 2 create the first digit, bits 3, 4, and 5 create the second digit, and bits 6, 7, and 8 create the third digit of the label. To decode a binary label, one must first determine the decimal value of each bit then convert each binary group to its octal equivalent. As shown in the Fig. 7-61 each bit is set to a binary 1 or 0; if that bit is set to binary 1, it "counts"; if that bit is set to binary 0, it does "not count." All values set to binary 1 are added to create the octal digit. When all three octal digits are decoded, they are then placed in reverse order to determine the label. The digits are presented in reverse order so that during data transmission the most significant bit of the most significant octal digit is the first bit to be received by an LRU. This allows the receiving LRU to begin decoding the label as soon as data enters the circuitry.

According to the ARINC 429 specification, the label 206 is used to transmit computed airspeed data in the BNR format. The specification also contains details, such as the information necessary to decode or encode the SDI, the SSM, and data field. Of course, the ARINC specification provides the details for all 256 possible labels. Each label is assigned to a specific word format, such as, BNR, BCD, Aim, or Discrete. Although the label stays consistent, the specific details of

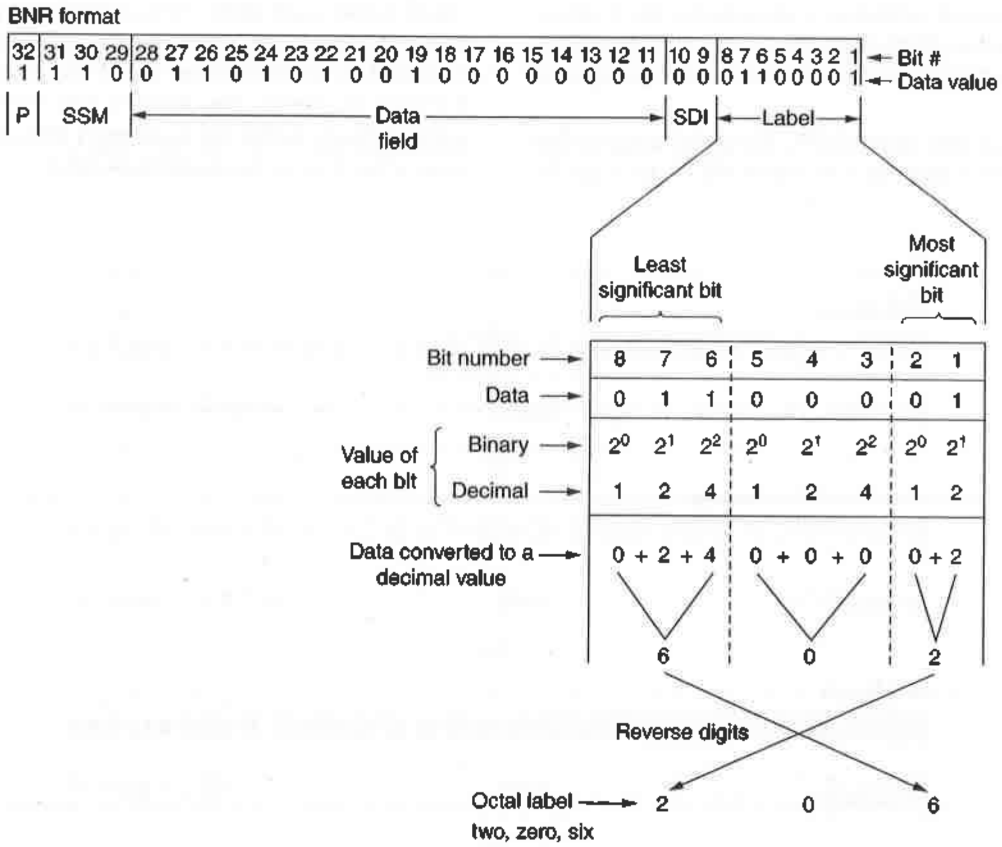


FIGURE 7-61 Decoded ARINC 429 label.

bits 9-32 change slightly between formats. To understand the procedures to decode/encode a 429 message, one must first use the octal label and the specification to determine what format is being used.

Decoding a BNR Data Field

The most popular data bus standard currently found on modern aircraft adheres to the ARINC 429 specification; and the BNR and BCD data formats are the most commonly used. This text will provide examples of decoding both BNR and BCD data. For a more in-depth study of this data bus, please refer to the ARINC 429 specification. During the following explanation of how to decode BNR data, refer to Fig. 7-62. The data field for any BNR message is contained in bits 11-28.The data can therefore contain a maximum of 18 bits; although some data will contain less. Whenever the transmitted data does not fill the entire data field, all unneeded bits are defined as **pad bits**. Pad bits are set to binary 0; however, some software designers utilize pad bits to carry additional information. This makes good use of data space that would otherwise go unused.

According to the ARINC specification, the label of 206 is assigned to the BNR format; the information is computed airspeed; the airspeed units are **knots**; there are 10 significant bits; the range of the data is 1024; and the resolution of the data is 1. The number of significant bits determines how much of the data field will contain actual data. As can be seen, ten bits (28-19) are usable data; the remaining data field bits (18-11) are pad bits set to binary 0. The range (in this case 1024) designates the maximum possible value of the decoded data; the resolution is defined as the smallest possible value of any data. Of course these values are assigned to the label 206; different values will be used for different labels defined by the ARINC 429 specification.

To decode the value for computer airspeed (label 206), first determine the values for bits 28-19. The value of bit 28 is the range divided by 2 (1024/2 = 512); the value of bit 27 is the range divided by 4 (1024/4 = 256); the value of bit 26 is the range divided by 8 (1024/8 = 128); and so on. In other words for BNR data, the range is divided in half starting with bit 28, divided in half again for bit 27, and this process repeats until all the significant bits are assigned a value. Once the bit values are determined, it is a simple matter of adding all bits set to binary 1. Bits set to binary 0 have a value of zero and may be ignored. In this example, bits 27, 26, 24, 22, and 19 are set to binary 1; therefore, 256 + 128 + 32 + 8 + 1 are summed to equal 425. In other words, this ARINC 429 word would be decoded to mean the computed airspeed is 425 knots.

The ARINC specification would also detail the meaning of the SDI and the SSM. In this case, for the label 206, the SDI data is set to binary 0, 0 for bits 9 and 10. This could mean that all LRUs connected to the data bus should read this label. The SDI set to binary 0,1 could mean that only the flight management computer should read this data and all other LRUs can ignore the message. The example shows the SSM set to binary 1,1, and 0 for bits 29, 30 and 31. This could indicate that the computed airspeed data is sent from the primary air data computer. The SDI and SSM values are always set specific to a given label number according to the ARINC 429 specification. Use the materials just presented in conjunction with the ARINC 429 specification or the aircraft manufacturers' data to decoding or encoding BNR data.

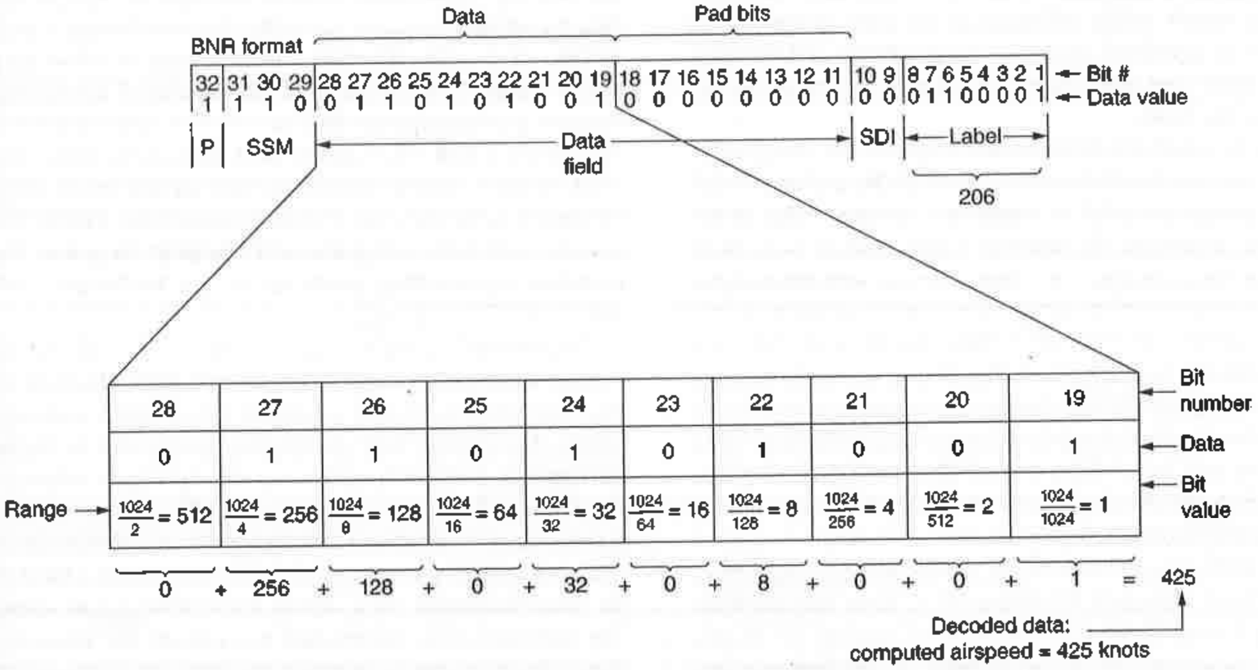


FIGURE 7-62 Decoded data: (BNR format) computed airspeed = 425 knots.

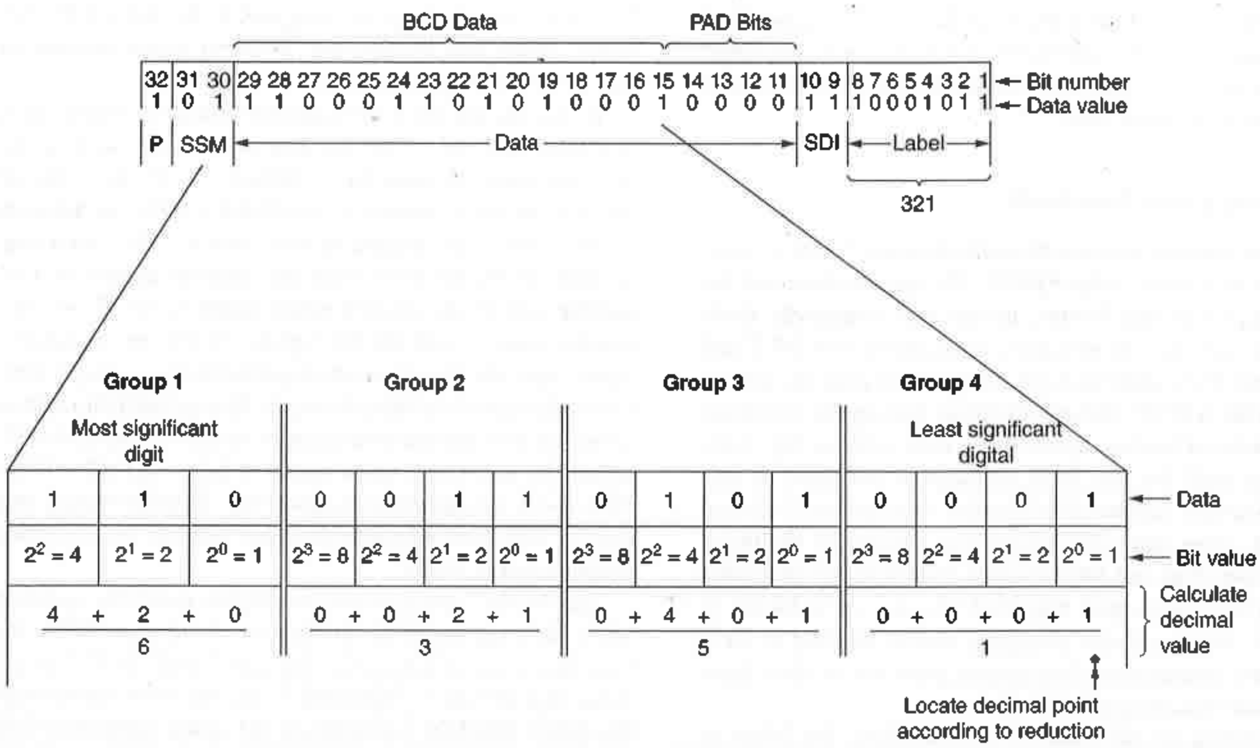


FIGURE 7-63 Decoded data: BCD format.

Decoding a BCD Data Field

Please refer to Fig. 7-63 during the following explanation on how to decode BCD data. The binary coded decimal (BCD) data field is contained in bits 11-29. Similar to BNR, the BCD specification will provide all the details needed to decode or encode the ARINC 429 data word. The details are provided according to the word label, in this case 321 (three, two, one; not three hundred and twenty one). Let's assume **fuel quantity** is assigned to label 321. In this case, the specification would define information on units (pounds), the number of significant digits (4), range (7999), and the resolution (0.0). The spec would also define meanings for the SDI and the SSM.

The data field of a BCD word is arranged into five groups: bits 11-14, bits 15-18, bits 19-22, bits 23-26, and bits 27-29. These groups are used to represent a decimal value of the data. To determine the decimal value, convert each BCD group as shown in Fig. 7-63. Here it can be seen that each bit is given a binary value arranged in a group of three or four bits to create a decimal digit. Once the decimal digits are calculated, the resolution is used to determine the location of the decimal point. In this example, the resolution is 0.0; this means the smallest possible value for fuel quantity is 1 gal, and there will be no digits to the right of the decimal point. In this example, the decoded data for label 321 states that the fuel quantity is equal to 6351 lb.

For BCD data the number of significant digits applies to the decimal value (not the binary bits). So in this example, four significant digits means the data will use bits 15-29, and bits 11-14 will be pad bits set to binary 0. For fuel quantity, it is likely the SDI would define which fuel tank is sending the information. For example, an SDI of 01 might mean the left main fuel tank, 00 the left auxiliary fuel tank, and so on.

The ARINC 429 Data Signal

As with most data bus standards, the ARINC 429 specification provides details on the electrical signals used to transmit the digital information. These details include the voltage levels, timing signals, and the related tolerance for these values (see Fig. 7-64). Here it can be seen that the ARINC 429 data bit actually contains two parts, the data (binary 1 or 0) and the clock pulse. The data will be a value of +10 V for a binary 1 and −10 V for binary 0. The polarity of the data bus reverses to change from +10 V to −10 V. A value of 0.0 V is considered a **null** value and is used for a clock pulse. The clock signal is used to provide accurate timing for all LRUs connected to the data bus. For these reasons the ARINC 429 signal is said to be a **bi-polar, self-clocking, data bus**. The tolerance of the voltage levels are +/− 1 V for binary 1 or 0 and +/− 0.5 V for the null.

Theoretically, a digital signal is either on or off and the voltage value must rise or fall instantaneously. However, in practical terms some time is needed for a voltage to change values. The ARINC 429 specification details this as timing tolerance as well as the frequency for the signal transmissions. The ARINC 429 allows for data transmission in two speeds; the low speed is 12 to 14.5 Kbits/sec. (**Kbits/sec** is read as **kilo-bits per second** or 1000 bits/second.) Most of the data transmitted using 429 is transmitted in low speed. The high-speed bus carries data at a rate of 100 Kbits/sec. The high-speed bus is typically reserved for flight-critical data that requires frequent updates.

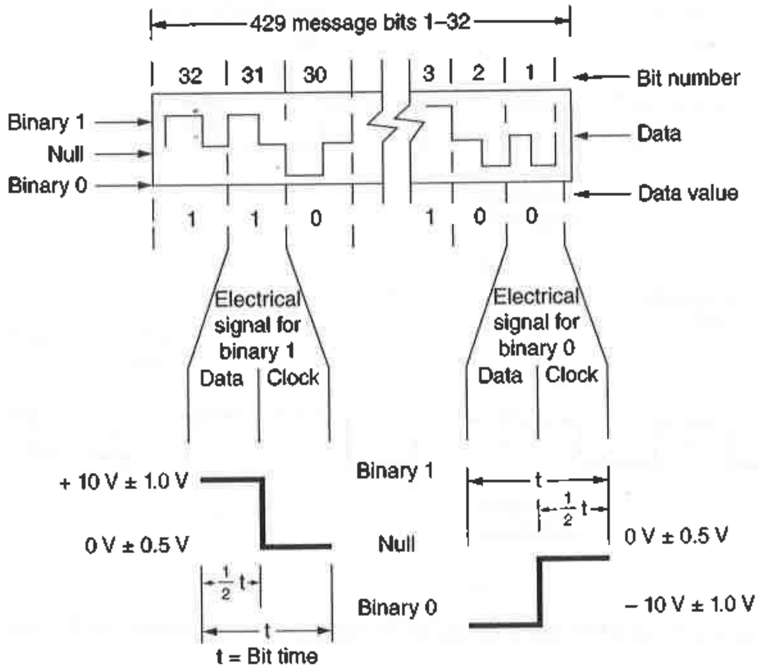


FIGURE 7-64 ARINC 429 data signal.

ARINC 629 Data Bus

ARINC 629 is another digital data bus format that offers more flexibility and greater speed than the 429 system. ARINC 629 permits up to 120 devices to share a **bidirectional serial data bus**, which can be up to 100 m long. The bus can be either a twisted wire pair or a fiber-optic cable. The Boeing Company, in developing the B-777, installed ARINC 629 in a two-wire format, as well as the fiber-optic format in limited use. ARINC 629 has two major improvements over the 429 system. First, there is a substantial weight savings. The 429 system requires a separate wire pair for each data transmitter. With the increased number of digital systems on modern aircraft, the 629 system will save hundreds of pounds by using one data bus for *all* transmitters. Second, the 629 bus operates at speeds up to 2 Mbits/s; the 429 is capable of only 100 kbits/s. Figure 7-65 shows simplified diagrams of the 429 and 629 bus structures. Here it can be seen that the 629 system requires much less data cable.

The ARINC 629 system can be thought of as a party line for the various electronic systems on the aircraft. Any particular unit can transmit on the bus or "listen" for information. At any given time, only one user can transmit, and one or more units can receive data. This "open bus" scenario poses some interesting problems for the 629 system: (1) how to ensure that no single transmitter dominates the use of the bus, (2) how to ensure that the higher-priority systems have a chance to talk first, and (3) how to make the bus compatible with a variety of systems.

The answer is found in a system called the **periodic aperiodic multitransmitter bus**. To understand this system, study the examples using four receivers/transmitters in Fig. 7-66. Here each transmitter can use the bus if it meets a certain set of conditions. First, any transmitter can make only one transmission per **terminal interval**. Second, each transmitter is inactive until the **terminal gap** time for that transmitter has ended. Third, each transmitter can make only one transmission; then it must wait until the **synchronization gap** has occurred before it can make a second transmission.

The **terminal interval** (TI) is a time period common to all transmitters. The TI begins immediately after any user starts a transmission. The TI inhibits another transmission from that same user until after the TI time period. A **periodic interval** occurs when all users complete their desired

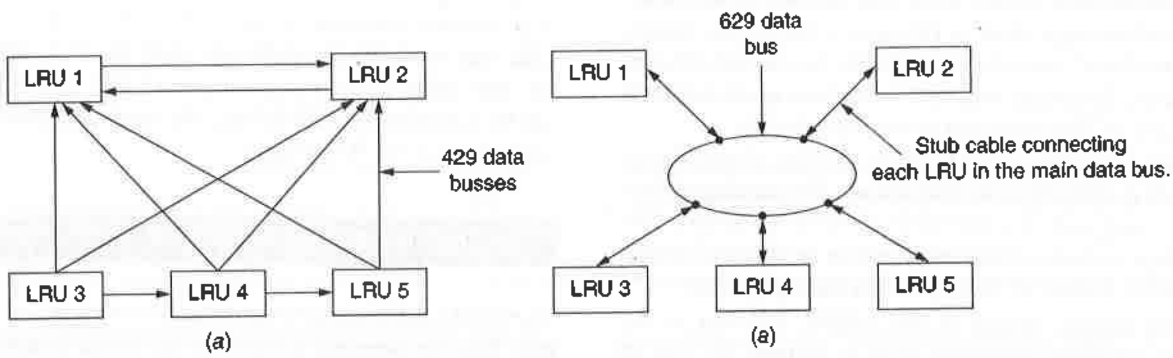


FIGURE 7-65 Typical data bus structures: (*a*) one-way ARINC 429; (*b*) two-way ARINC 629.

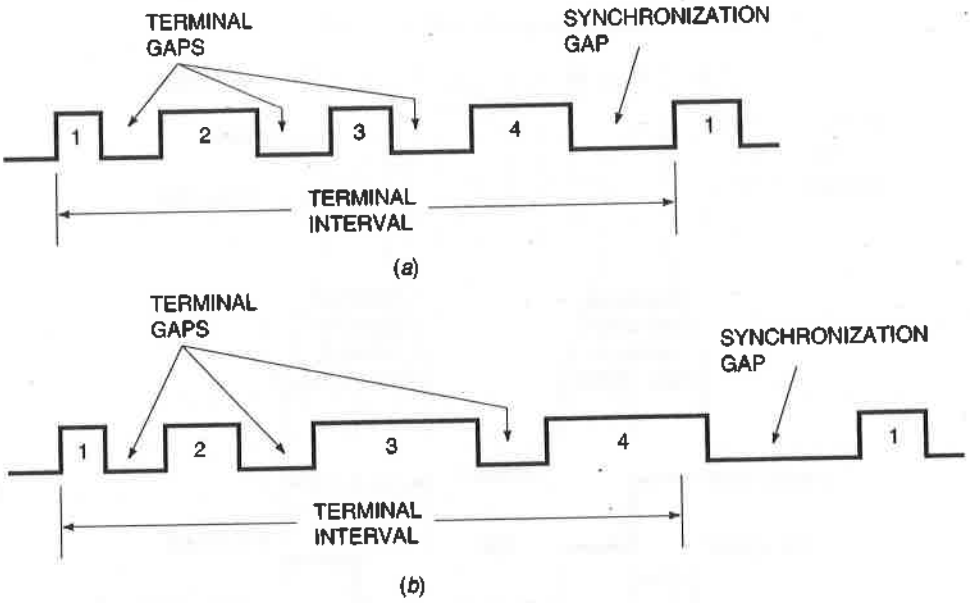


FIGURE 7-66 ARINC 629 bus structure: (a) a periodic interval; (b) an aperiodic interval caused by the extended message of user 3.

transmission prior to the completion of the TI. If the TI is exceeded **(aperiodic interval),** one or more users have transmitted a longer than average message (Fig. 7-66*b*).

The **terminal gap** (TG) is a unique time period for each user. The terminal gap time determines the priority for user transmissions. Users with a high priority have a short TG. Users with a lesser need to communicate (lower priority) have a longer TG. No two terminals can ever have the same terminal gap. The TG priority is flexible and can be determined through software changes in the receivers/ transmitters.

The **synchronization gap** (SG) is a time period common to all users. This gap can be thought of as the reset signal for the transmitters. Since the synchronization gap is longer than the terminal gap, the SG will occur on the bus only after each user has had a chance to transmit. If a user chooses not to transmit for a time equal to or longer than the SG, the bus is open to all transmitters once again. Keep in mind that the terminal and synchronization gaps are simply time periods where the bus is not transmitting data; the bus said to be **idle.** These can be thought of as a pause between messages and each LRU has to "wait" for a specific pause time before that LRU can transmit. Each LRU will be assigned a specific terminal gap and no two TGs can be the same for any given data bus. The synchronization gap will be longer than all TGs on that bus and determines the "idle bus time" needed to open the bus for the transmission by any LRUs. Of course, each LRU must once again wait until their specific TG has been met in order to transmit.

Any message transmitted by a bus user has a limited time in which it is allowed to be transmitted. The **message** transmitted is composed of a maximum of 16 word strings. The word strings contain a label word and up to 256 data words. Each word is limited to 16 bits of data and a parity bit.

Another unique feature of the **ARINC** 629 bus is the **inductive coupling** technique used to connect the bus to receivers/transmitters. As shown in Fig. 7-67, the bus wires

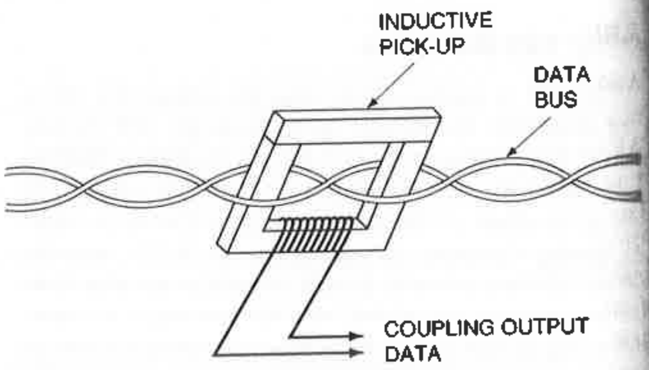


FIGURE 7-67 An example of inductive coupling in a bus system.

are fed through an inductive pickup, which uses electromagnetic induction to transfer current from the bus to the user, or from the user to the bus. This system improves reliability, since no break in the bus wiring is needed to form connections. The inductive coupling is basically a transformer although more complicated than the simple circuit shown in Fig. 7-67. The inductive coupling is known as a **current mode coupler (CMC)** and contains electronic circuitry to help monitor and control bus traffic. The CMC is a small LRU that connects the main 629 data bus to a stub cable; the stub cable then connects to each LRU. The stub cable can be a maximum of 75 ft long; the main data bus can be a maximum of 328 ft in length.

ARINC 664 DATA BUS

The latest ARINC data bus specification is known as **ARINC 664**. This bus standard is based on an Airbus Industries proprietary data bus known as **AFDX (Avionics Full-duplex**

Switched Ethernet). Although there are slight differences between AFDX and ARINC 664, for the most part they can be thought of as the same and this text will refer only to ARINC 664. The AFDX/664 data bus specification is currently used on the latest commercial aircraft: the Airbus A-380 and Boeing B-787. Also, similar Ethernet-type data bus standards are used by various manufacturers on proprietary systems such as the Garmin G-1000. The ARINC 664 bus is typically used as the "backbone" data transfer system and can easily transfer data created in other formats such as ARINC 429. The ARINC 664 standard is similar to the IEEE (Institute of Electrical and Electronics Engineers) 802.3 standard. ARINC 664 can transfer at two rates, 10 Mbits/s or 100 Mbits/s, and allows LRUs to both transmit and receive completely independently; hence making 664 approximately 1000 times faster than its predecessor ARINC 429 data transfer system. This allows for faster data transfer as well as decreases aircraft weight and improves efficiencies.

The ARINC 664 Hardware

The hardware component of the 664 standard consists of a network of **switches** that forward Ethernet frames to their appropriate destinations through a bidirectional data bus. The data connection can be either copper wire or fiber-optic cable, and of course, the system has multiple redundant components to improve reliability. The ARINC 664 switches are often referred to as "smart switches" because they contain elaborate circuitry and software to control the flow of data through the network. The switches use software to determine how data is routed to the various end systems. **End systems** are basically computerized LRUs which transmit/receive data in order to perform a variety of functions necessary to operate the aircraft. Figure 7-68 shows a simplified example of a system network. In this example, a flight management computer is an end system that transmits/receives data to/from the display management computer and four other end systems; each end system can also transmit and receive on the 664 bus. The system software and ability for a smart switch to make data routing decisions is often referred to as a **virtual link**. The link is considered virtual because the switch can make decisions concerning which direction (link) to send/receive data. Of course this is a very simple example; when hundreds of end systems are connected, the virtual link becomes much more complex. The ARINC 664 hardware, including the data bus, connectors, switches and LRU circuitry is often referred to as the **physical layer**.

ARINC 664 Data Flow and Message

Since the 664 data bus system is designed to allow data transfer from any end system to any end system at any time, a complex identification system must be transmitted with all data packets. A digital identifier used to direct all data packets within the network is known as the **virtual link ID**. The smart switches and the end systems of the network contain software that follow detailed instructions to ensure proper data flow according to the virtual link ID. In some respects this ID is similar to the label used in ARINC 429; however, it is much more complex. An ARINC 664 data bus will always contain two networks for each message being sent. The redundant network provides the improved reliability needed for aircraft safety.

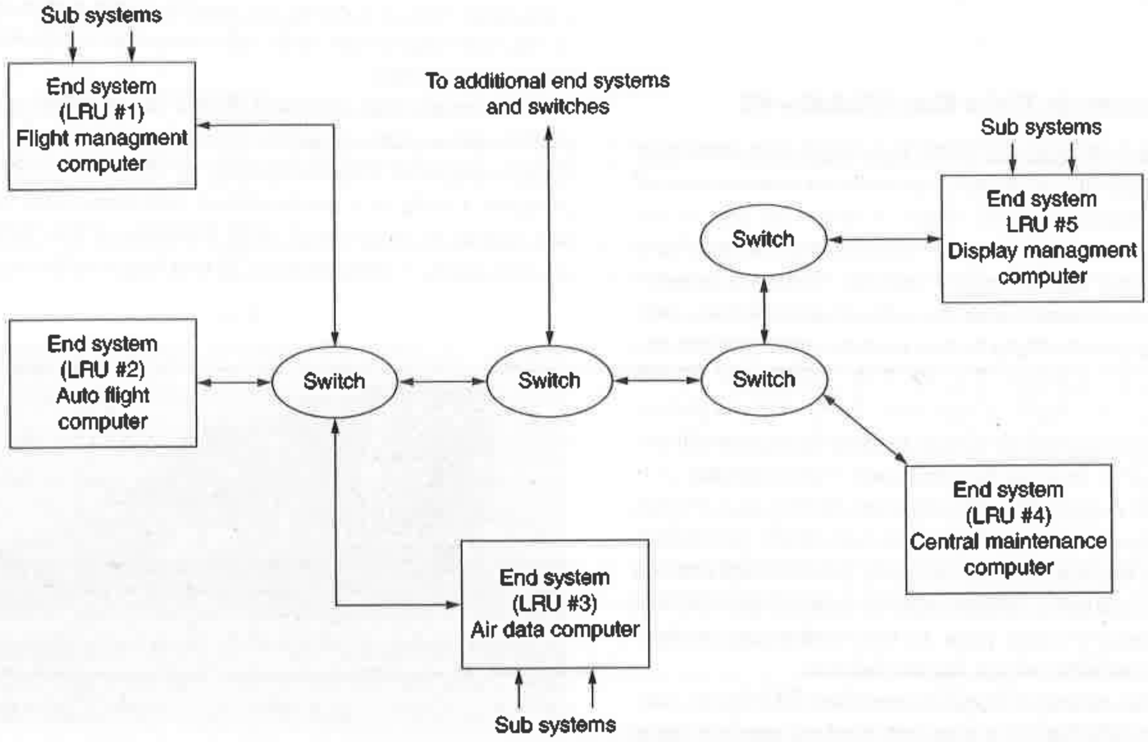


FIGURE 7-68 ARINC 664 network example.

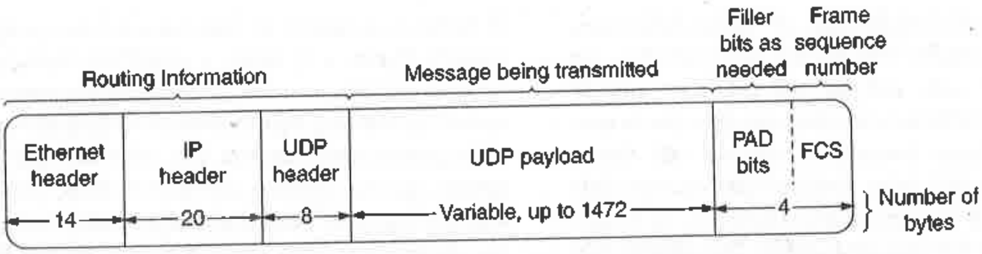


FIGURE 7-69 Simplified example of an ARINC 664 data transmission.

The complete message transmitted on the 664 data bus actually contains several **bytes, words,** or **word strings,** used for routing the message. The actual message is called the **UDP payload** which can contain up to 1472 data bytes. Figure 7-69 shows the basic structure of an ARINC 664 message. Here it can be seen that routing information is contained in three headers: the Ethernet header, the IP header, and the UDP header. The message follows the routing information and a sequencing number known as the frame sequence number (FCS) is added at the end of the data packet to ensure proper sequencing of the message.

In order to allow the 664 message to accommodate a variety of end users, the UDP payload data can be arranged in several different formats. The software engineers and aircraft designers can choose the desired format that best fits their particular message (UDP payload). For example, an ARINC 429 message can be carried within the payload section of the transmission. This allows the traditional 429-based equipment to easily transmit on a 664 data bus. Of course, the 429 data is simply contained in the message block of the transmission and all routing data must follow the 664 specification. Other common UDP payloads include messages written using **Boolean Algebra, Signed_32(64) integer, Float_32(64),** and **Opaque** data.

Other Common Data Bus Standards

Most aircraft built since the 1980s have employed some type of digital system that required a data bus for transmission of information between LRUs. Today it would be safe to say there are approximately 10 to 15 common data bus standards found on aircraft and aerospace vehicles. Some are proprietary specifications used solely by a single manufacturer; others have been standardized by one or more organizations and used on various systems. The **RS-232, ASCB,** and **CSDB** are data bus standards commonly found on corporate/commuter-type aircraft as well as modern light personal aircraft. As digital systems become more commonplace, it is likely that all modern aircraft will soon employ one or more data buses for communications between LRUs. All technicians should become familiar with any bus standard used on aircraft they maintain. Always refer to current specification and manufacturer's data prior to troubleshooting, maintenance, or installation of any digital data bus.

The **Recommended Standard number 232** (more commonly called **RS-232**) is a data bus standard used on many systems, including the popular Garmin integrated flight display systems. The RS-232 data bus standard was developed as a common interface between various units of standard personal computer system and adapted for aircraft use. Of course, the aircraft RS-232 systems use ruggedized hardware and redundant software to ensure the reliability and safety necessary for aircraft use. RS-232 is a serial data format that allows for full-duplex operations. Simultaneous transmission and reception of data is often referred to as **full-duplex** data transfer. RS-232 signals are represented by voltage levels with respect to the system ground. The specific voltage levels used to represent binary 1 and binary 0 may change between various RS-232 systems; however, as little as 3 V and as high as 15 V are typically acceptable.

The RS-232 standard requires a common ground between LRUs transmitting/receiving data. The connector used for termination of the data bus cable is typically one of two configurations: a 25-pin D-sub connector, or a 9 pin D-sub connector. A typical D-sub connector for aircraft use is shown in Fig. 7-70. This connector employs a metal backshell to provide mechanical support and completely shield the data bus termination points against electromagnetic interference from outside the cable. The socket's outer metal shell fits tightly against the plug's metal housing. This creates an electrically continuous screen covering the data bus cable and connector. Additional information on D-sub connectors can be found in Chap. 4 in this text.

The **commercial standard digital bus (CSDB)** is a standard found on many corporate and commuter aircraft that use digital equipment manufactured by the Rockwell Collins Corporation. CSDB is a unidirectional (one-way) data bus that can operate at a high speed of **50 Kbits/sec** or **12.5 Kbits/sec** for low speed. A maximum of 10 receivers can be connected

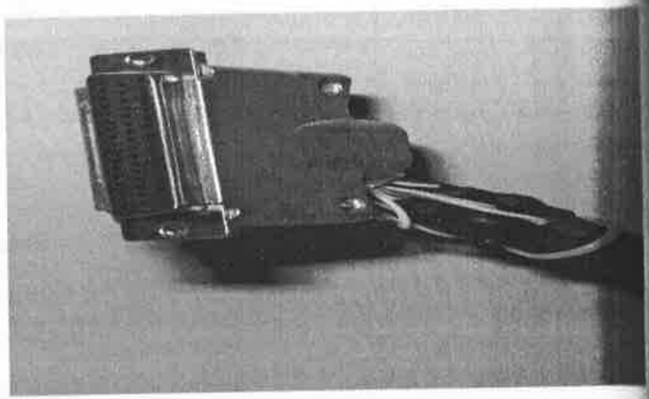


FIGURE 7-70 D-sub connector used for RS-232 data.

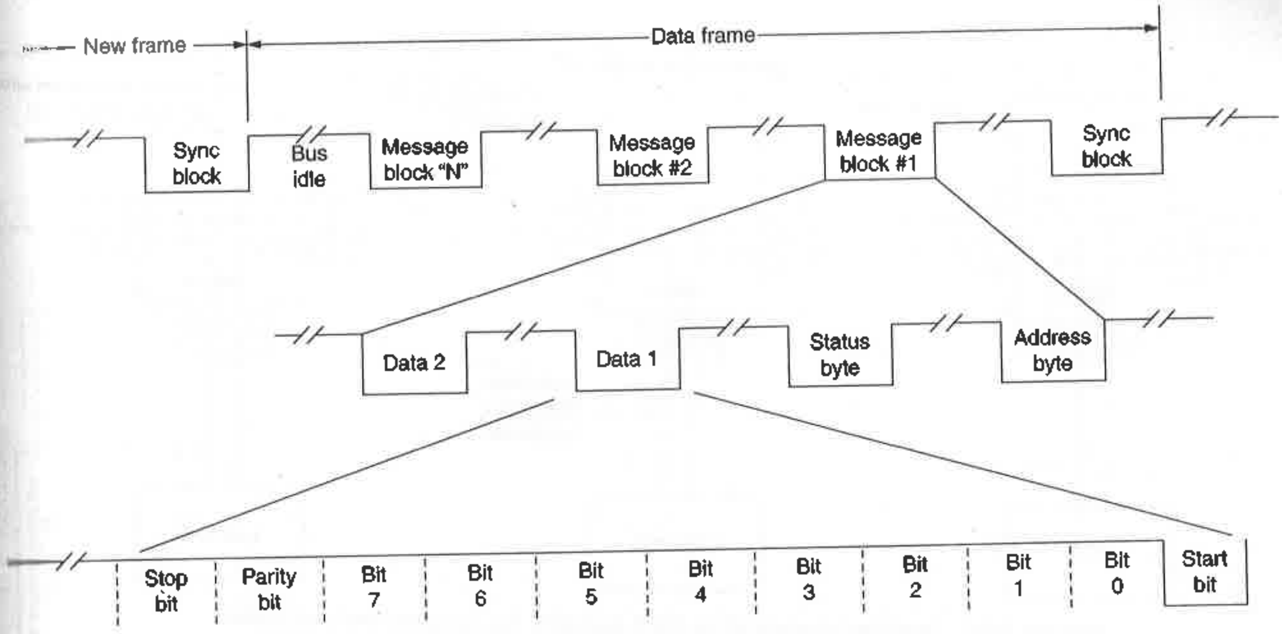


FIGURE 7-71 CSDB frame.

to each data bus, which is a twisted pair of shielded wire up to 150 ft long. CSDB adheres to a specification of the Electronics Industries Association standard RS-422A and has also been recognized as a standard aircraft data bus by the General Aviation Manufacturers Association (GAMA).

The CSDB standard states that the data signal will be a **non-return to zero** (NRZ) format where logic state 1 exists when bus line A is positive with respect to line B. Logic state 0 exists when bus line B is positive with respect to line A. As shown in Fig. 7-71 all CSDB transmissions are divided into different sections called **frames**. Each frame is allowed a fixed time interval for data transmission, and frame length is a function of the update rate required for that system. A **synchronization (sync) block** designates the beginning and ending of each frame. The sync block consists of a fixed number of bytes specific to that bus and programmed into the software. The actual CSDB message consists of a defined number of bytes. Each message is divided into an address byte, a status byte, and one or more data bytes. Each byte consists of 8 bits of data along with a start bit, a parity bit, and a stop bit. The parity bit is used for a quick validity test of the data; similar to the parity bit used in ARINC 429.

The **avionics standard communication bus (ASCB)** operates at 0.667 MHz as a bidirectional data bus that requires multiple bus controllers to coordinate bus transmissions. Since ASCB allows for data transmissions in both directions (bidirectional), a bus controller is used. One or more LRUs, the **bus controller**, must be connected to the bus to control bus activity. Typically, ASCB employs two pairs of data bus cable and three bus controllers as seen in Fig. 7-72. During operation, one bus controller is active and the other two operate in standby mode. This configuration provides the redundancy needed to ensure flight safety. Each LRU connected to the buses can transmit only on command of the active bus controller. The controller software sends a request signal on both data buses to a specific LRU address. The subsystem will then respond to the request with its own message. All transmission requests from the bus controller occur in a given sequence and at specific time intervals according to controller software. Critical systems may be accessed more frequently in order to update those systems more rapidly.

All ASCB data is transmitted in a non-return to zero (NRZ) format at 0.667 MHz using a standard digital format.

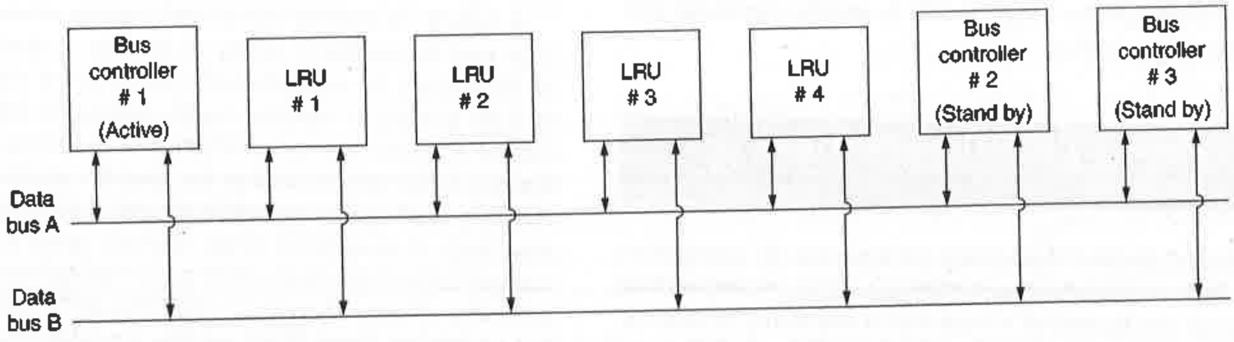


FIGURE 7-72 ASCB bus structure.

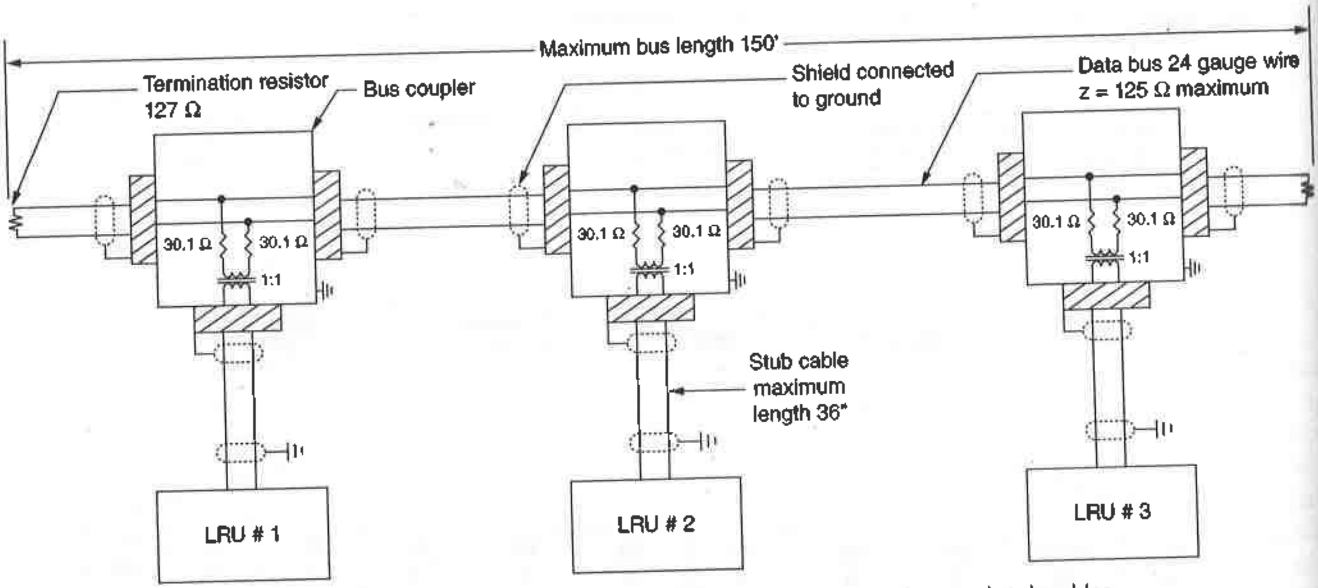


FIGURE 7-73 Simplified example of an ASCB data bus, bus couplers, and stub cables.

A signal of + 5 V is used for a binary 1, 0 V for binary 0, and there is no change in voltage level during each bit period for timing purposes. An acceptable tolerance for signal loss during transmission is approximately 0.5 V (allowing + 4.5 V to reach the receiver). A greater signal loss will most likely cause an error in data transmission. ASCB data transmissions contain an address at the beginning of each message. All receivers on the bus can choose to accept or ignore a given message through analysis of the address. The data from any LRU will be transmitted using a specified format according to the software program; the receiving LRU will decode the data accordingly.

The ACSB data bus is a two-wire, 24-gage, shielded cable with a maximum impedance of 125 Ω +/– 2 Ω, and maximum capacitance is 12 +/– 2 picofarads. All bus cable shielding must be terminated to ground at each end of the cable. Each wire pair must contain a termination resistor of 127 Ω, +/– 1/4 Ω. Figure 7-73 shows a simplified example of how each LRU is connected to the bus through a stub cable and a transformer/coupler assembly. (An actual aircraft ASCB data bus would contain more than three LRUs; including multiple bus controllers.) The bus coupler is basically a simple transformer with a one-to-one ratio; therefore, it does not change the voltage or current value of the data signal. The maximum bus length is 150 ft, and the maximum stub cable length is 36 in.

TROUBLESHOOTING DIGITAL CIRCUITS

With the advent of digital logic circuits came the introduction of **logic troubleshooting techniques**. This troubleshooting system can be applied to both digital and analog circuits, as well as hydraulic, pneumatic, and other mechanical systems. A logic troubleshooting sequence simply employs a flowchart of "logical" faults and repairs for a given system.

Figure 7-74 shows a typical flowchart for troubleshooting an avionics system. This system "asks" a yes or no question and directs the technician to the correct means of repair. The increased use of LRUs has made this troubleshooting method feasible. Since any given system contains only a limited number of replaceable parts, a relatively simple flowchart can identify most defective components.

Built-in Test Equipment

Built-in test equipment (BITE) systems are used in conjunction with many digital circuits. BITE systems are designed to provide **fault detection, fault isolation,** and **operational verification after defect repair**. Fault detection is performed continuously during system operation. If a defect is sensed, the BITE initiates an appropriate control signal to isolate any defective component(s). In order to repair the defective system, the line technician can utilize the BITE to identify faulty components or wiring. After the appropriate repairs have been made, the system should be run through a complete operational check. The BITE will once again monitor the system and verify correct operation if the system has been properly repaired.

A typical commercial airliner may contain several BITE units used to monitor a variety of systems. A Boeing 757 or 767 aircraft, for example, utilizes built-in test equipment systems in order to monitor electric power, environmental control, auxiliary power, and flight control systems. Seven separate BITE units located in the aircraft's electric equipment bay or aft equipment center are used to accomplish this task. Each of these BITE boxes receives inputs from several individual components of the system being tested. Other individual systems also contain their own dedicated built-in test equipment. These BITE systems are relatively simple,

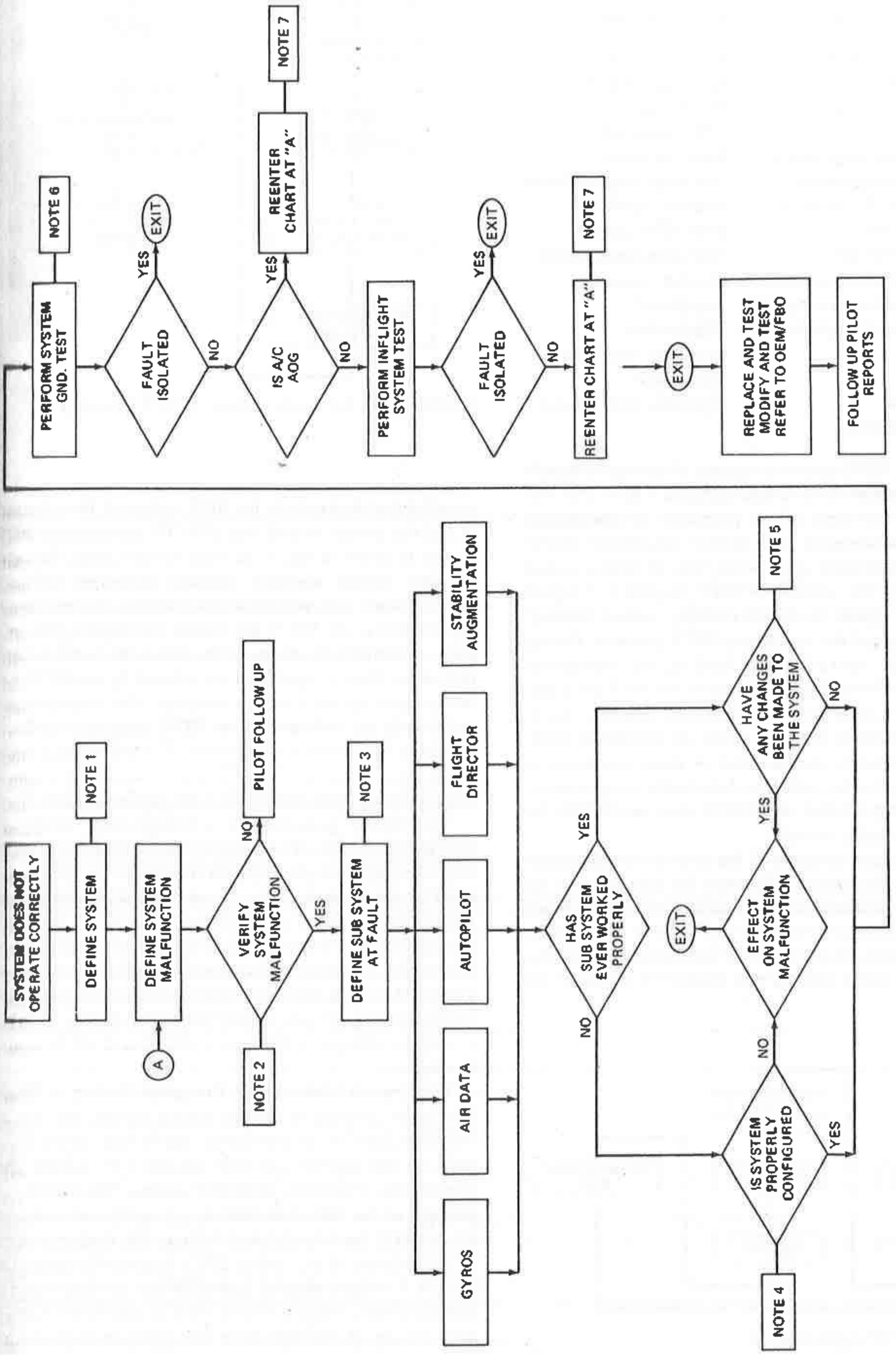


FIGURE 7-74 A typical troubleshooting flowchat. (*Sperry Corporation.*)

and each is usually contained within a line replaceable unit of the system being monitored. Systems that employ dedicated built-in test equipment include the following:

- Engine indicating and crew alerting
- VHF communication radios
- HF communication radios
- ARINC communication addressing and reporting
- Inertial reference
- Air data computer
- Electronic flight instruments
- Flight management computer
- Radio distance magnetic indicator
- Lighting
- Fuel quantity
- Fire and overheat
- Selective calling
- Passenger address
- Weather radar
- ATC transponder
- Radio altimeter
- Automatic direction finder
- Antiskid-autobrake
- Instrument landing
- VHF omnirange receiver
- Distance measuring equipment
- Window heat
- Proximity switch electronic unit
- Hydraulic management

A complex BITE system is capable of testing thousands of input parameters from several different LRUs. The system performs two types of test programs: an **operational test** and a **maintenance test.** Normal operational checks start with initialization upon acquisition of system power (see Fig. 7-75), The operational BITE program is designed to check input signals, protection circuitry, control circuitry, output signals, and the operational BITE circuitry. During normal system operation, the built-in test equipment monitors a watchdog signal initiated by the BITE program. The watchdog routine detects any hardware failure or excessive signal distortion that may create an operational fault. If the BITE program detects either of these conditions, it automatically provides isolation of the faulty component(s); initiates warning, caution, or advisory data; and records the fault in a nonvolatile memory.

The maintenance program of the built-in test equipment is entered into the system only when the aircraft is on the ground and the maintenance test routine is requested. When requested, the maintenance BITE will exercise all input circuitry and software routines of the system being checked. The corresponding output data are then monitored, and faults are

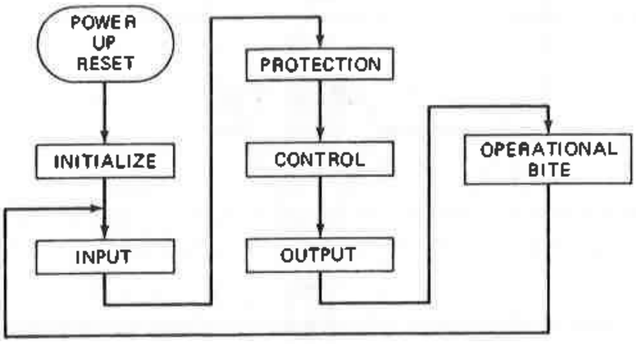


FIGURE 7-75 BITE flow diagram.

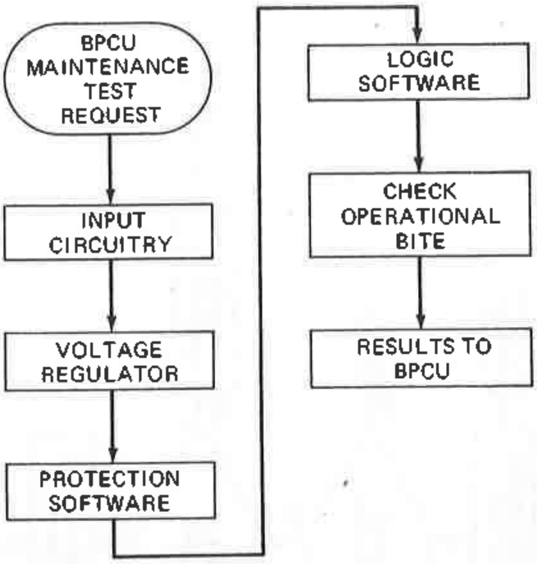


FIGURE 7-76 Bus power control unit BITE flow diagram.

recorded and displayed by the BITE system. A flow diagram of the bus power control unit (BPCU) maintenance BITE routine is shown in Fig. 7-76. This routine checks the input circuitry, voltage regulator circuitry, protection software, logic software, and operational BITE system. The test results are returned to the BPCU for storage and display. The software, or operating programs, of the system are tested through utilization. That is, input data are initiated by the BITE and manipulated by the software program. The corresponding output data are evaluated by the BITE program in order to determine the system's performance. If a discrepancy in the output data is detected, the BITE system considers the operational software faulty and provides the appropriate indication.

The second generation of self-diagnostics equipment incorporates the use of a centralized monitoring system. The faults detected through several BITE systems could be monitored in one location. These systems are highly integrated and can be thought of as a clearing house for all the BITE data collected by the various LRUs containing BITE. Most commercial, corporate and commuter aircraft built during the 1990s and beyond have some type of centralized system for troubleshooting aircraft malfunctions. The Boeing 747-400 is a perfect example of this type of aircraft and will be examined here.

The **Central Maintenance Computer System (CMCS)** is found on a variety of modern Boeing aircraft. The Boeing 747-400 CMCS is accessed from one of four central locations on the aircraft and will present both inflight and ground tests of virtually all digital systems. The CMCS is a manager of the individual built-in test equipment and does not perform the actual circuit testing; the testing is done by the software of the various LRUs located throughout the aircraft. A **control display unit (CDU)** is an alphanumeric keyboard and a display screen used to access the CMCS data. On the B-747-400 there are typically four control

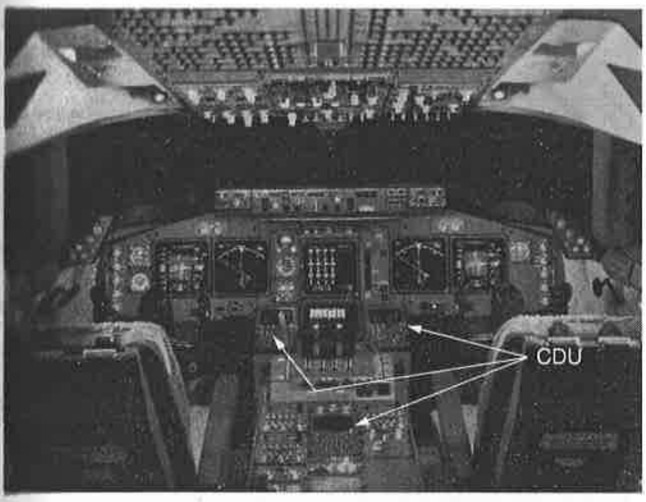


FIGURE 7-77 Control display units on a Boeing 747-400 flight deck (*Boeing Corporation.*)

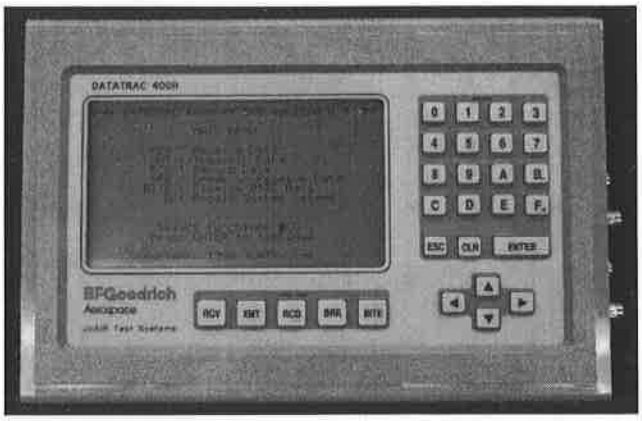


FIGURE 7-78 A typical data bus analyzer.

display units (CDUs), three located on the center console of the flight deck and one located in the main equipment bay. The flight deck of a 747-400 containing the CDUs is shown in Fig. 7-77. A printer may also be located on the flight deck to provide a written report of the fault data when needed and a software data loader can be used to download faults to a disc or flash drive. The aircraft can also send fault data during flight to a ground-based maintenance facility using ACARS equipment. ACARS will also answer all maintenance data requests from the ground facility. **ACARS** is a system designed to send digital messages from the aircraft during flight to the airline's ground facilities. An ACARS message is similar to a text message sent from a common cell phone.

Third generation maintenance and diagnostic systems have become more integrated and allow for wireless communications of troubleshooting data. Modern diagnostic systems have also become common place on light aircraft as they too become more integrated with digital systems. Today's aircraft can monitor systems, analyze faults, and automatically download maintenance information through the use of wireless systems such as cellular, Wi-Fi, or satellite technologies. These automated troubleshooting systems improve aircraft maintainability and enhance safety. Chap. 13 of this text will present a more detailed look at the design and operation of modern aircraft diagnostic systems.

Data Bus Analyzers

The **data bus analyzer** is a common carry-on piece of test equipment used to troubleshoot digital systems. There are many types of data bus analyzers, but their basic purposes are quite similar. Bus analyzers are used (1) to receive and review transmitted data or (2) to transmit data to a bus user. Before using any analyzer, one must first be sure that the bus language is compatible with the bus analyzer. For example, the **DATATRAC 400H** shown in Fig. 7-78 can monitor, simulate, and record data transmissions for avionics equipment using ARINC 429 data formats.

When monitoring a system, the analyzer captures a stream of data being transmitted between digital devices. The recorded data can then be displayed by the analyzer for evaluation. If inconsistencies are detected, the transmitter or the data bus system is faulty. Some data bus analyzers are capable of reading several transmission lines, or **channels**, at one time. This allows for comparisons to be made that might expedite troubleshooting.

For the DATATRAC 400H there are three basic modes of operation:

Receive This allows the technician to select specific labels to evaluate or to receive all incoming data. Hexadecimal, decimal, or binary format may be selected for the data display.

Transmit The data bus analyzer is capable of sending digital data in order to simulate communications between avionics equipment or sending analog data using a D/A converter and driver.

Record A particular data label and record rate are selected, and the avionics bus analyzer collects information sent to this address. All the data can then be displayed in a numerical format. Some avionics bus analyzers have the capability of displaying the information in a graphic mode.

In most cases, the data analyzer must be connected to the system at the connector plug of an LRU. For example, if you plan to receive data transmitted to the generator control unit (GCU), you must unplug the GCU from the bus and connect the analyzer to the data bus cable. If the correct connections are made and the test equipment is properly adjusted, the analyzer will display all messages sent to the GCU. On some aircraft a specific connector is available to allow for direct connection into the data bus system. Figure 7-79 shows a carry-on bus analyzer connected to

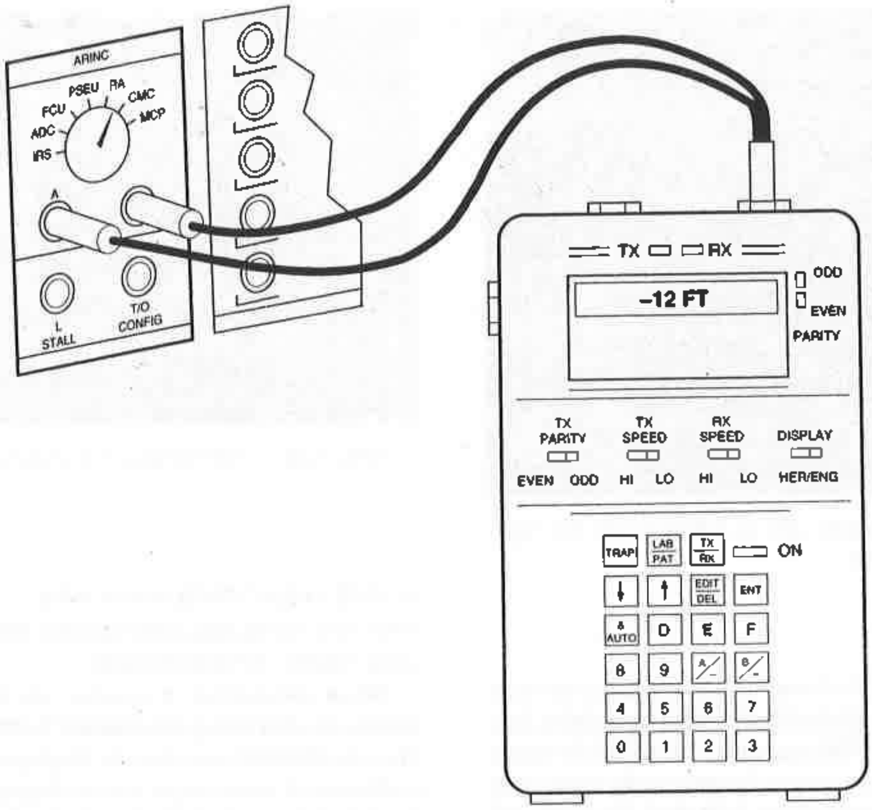


FIGURE 7-79 Example of a bus analyzer installed on a transport-category aircraft.

the data bus. In this case the technician is monitoring the radar altimeter (RA). *Note:* The selector is set for RA, and the analyzer indicates −12 ft.

Other carry-on-type data bus analyzers are computer based; that is, a circuit card and/or proper software are installed into a personal computer to create a data bus analyzer. In this case, the computer is often capable of storing and transmitting multiple packets of data in a serial format. With the correct hardware/software arrangement a personal computer can be used to analyze data or replace LRUs during system testing. This type of troubleshooting will help to quickly and easily detect defective LRUs or data bus problems.

Measurement of Logic Levels

There are two common instruments used to measure logic levels: the **logic probe** and the **logic monitor**. A logic probe measures one point in a circuit to determine its logic level (high or low). A logic monitor is capable of measuring the logic levels of an entire integrated circuit. That is, every pin of an 1C may be simultaneously tested for its logic level through the use of a logic monitor.

A typical logic probe is shown in Fig. 7-80. The tip of the probe is touched to any connection in the logic circuit in order to detect its logic state. For example, a signal of + 5 V or greater activates the HIGH logic LED indicator, and a signal of less than + 5 V activates the LOW indicator. The actual voltage levels for a response of HIGH or LOW may vary between logic probes. Most logic probes will respond to a digital pulse of 50 ns or longer. This quick response rate is well beyond the capabilities of most voltmeters. The logic probe is therefore a vital instrument needed to test any rapidly changing digital signal.

Appropriate switch adjustments allow many logic probes to test both diode-transistor logic (DTL) and transistor-transistor logic (TTL) ICs. All logic probes must be connected to a reference signal; therefore, each contains a separate lead that must be connected to the logic circuit's power source.

Logic monitors use a special test clip that connects to each lead of an integrated circuit. A typical logic monitor and various test clips are shown in Fig. 7-81. The logic monitor pictured contains 16 LEDs. Each LED represents one of the connection pins of the IC being tested. When a connection pin of the IC is at a HIGH logic level, its corresponding LED will illuminate. If the IC connection is at a LOW logic level, its LED will not illuminate. Both TTL and DTL integrated circuits can be tested by most logic monitors. Many monitors also contain an adjustment that allows the operator to set the desired voltage thresholds. This adjustment determines the voltage level required to indicate a logic HIGH on the monitor's LEDs.

Many variations of logic probes and logic monitors are currently available. Be sure to familiarize yourself with any equipment used to test digital circuits. Most ICs are

FIGURE 7-80 A logic probe. (*Global Specialties, an Interplex Electronic Company.*)

very delicate; any unnecessary voltage may damage the circuit being tested.

High-Energy Radiated Electromagnetic Fields (HERF)

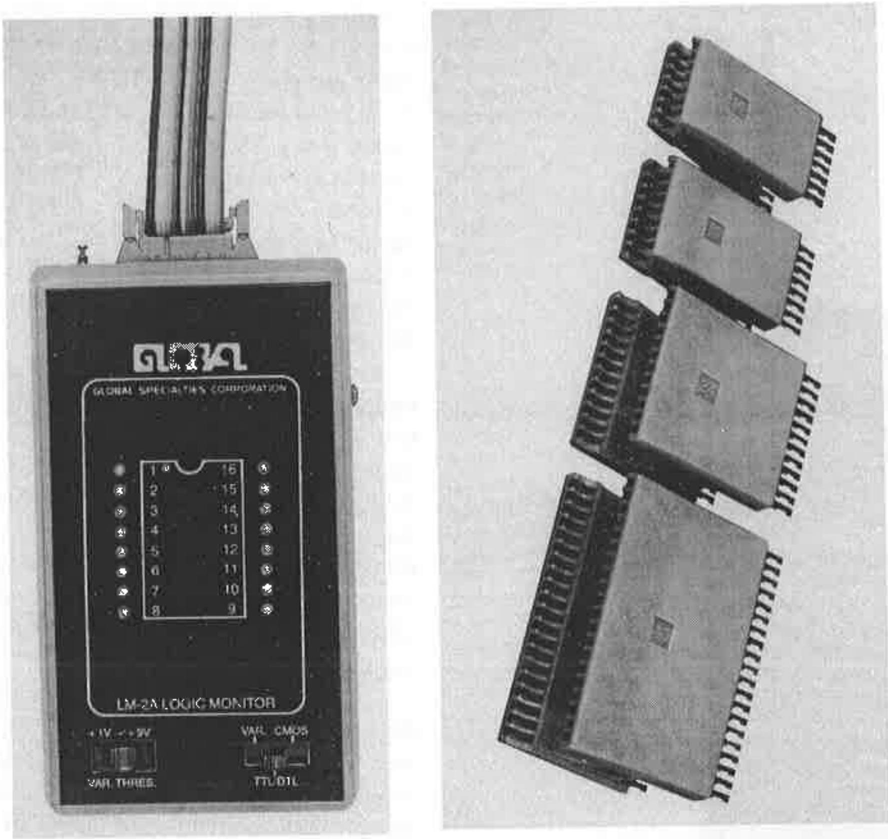
Today's digital aircraft systems communicate through the movement of thousands of bits of digital data. These data streams operate at extremely low power levels and can easily be overridden by a more powerful signal. This is the underlying concept that makes radiated energy from electromagnetic fields so troublesome. **High-energy radiated electromagnetic fields** (HERF) are emitted by virtually every radio broadcast tower in the world. Every FM transmitter, every TV station antenna, and every radar station emits electromagnetic energy. This radiated energy can and will induce a current into a nearby conductor. If the conductor happens to be a data bus and if the induced current is strong enough, the possibility exists that the data on the bus can be lost. For an aircraft, this loss of data can be catastrophic.

Recent FAA standards require all new equipment to undergo HERF testing. These tests are used to ensure that the electronic components used on modern digital systems will not fail when subjected to high-energy electromagnetic fields. An aircraft might be subjected to such high-energy fields if it flies too close to a powerful radio transmitter or perhaps if it is struck by lightning. There is concern that even indirect lightning (lightning that comes close to but does not hit the aircraft) could cause digital system failure.

Composite structures, which block less magnetic energy than conventional aluminum aircraft, also complicate the issue. Today's standards for HERF testing may be adequate or may be increased; but if aircraft continue to rely on low-energy digital circuits, the threat of HERF will remain. Modern aircraft incorporate extensive shielding as the primary means to protect circuits from the effects of HERF. Shielded cable, specialty connectors with shielded backshells, shielded LRUs, and even aluminum cages specially designed to surround sensitive components are all techniques used to protect modern electronics. Each of these techniques relies on the principle of surrounding the sensitive parts with a "shield" of metal connected to ground. So, whenever performing maintenance near electronics equipment on digital aircraft, pay particular attention to grounding straps and bonding jumpers. There must always be a good clean connection to ground for any shielding to be effective.

Electrostatic Discharge–Sensitive (ESDS) Components

Many digital electronic devices are susceptible to damage from the discharge of static electricity. These components are known as **electrostatic discharge–sensitive** (ESDS) parts. Since digital circuits are manufactured from extremely small silicon chips, they can be damaged by the discharge of static voltages as low as 100 V. During movement for everyday activities, a technician can easily generate well over 1000 V. If this voltage is discharged into an ESDS component, the part will be damaged. There are several simple steps a technician can take to avoid damaging ESDS parts. Each step ensures that the sensitive components are never subjected to high levels of static electricity. The damage-prevention techniques are discussed in Chap. 13 of this book.



(a) (b)

FIGURE 7-81 A logic monitor: (a) the indicator; (b) the IC test clips. (*Global Specialties, an Interplex Electronic Company.*)

REVIEW QUESTIONS

1. What is a *digital circuit*?
2. Give an example of where a digital circuit would be found on an aircraft.
3. What electrical component made digital circuits practical?
4. What are computer peripheral devices?
5. Explain the difference between a digital signal and an analog signal.
6. Explain the binary number system.
7. What two symbols make up the binary number system?
8. How is the decimal number 12 represented in the binary number system?
9. List some common designations of binary 1 and 0.
10. Describe the decimal number system.
11. How is binary 10110 represented in the decimal system?
12. How is binary 1000110 represented in the decimal system?
13. What is the hexadecimal value of the decimal number 12?
14. Define the terms *bit* and *byte*.
15. Describe the binary-coded decimal system.
16. Describe the octal notation system.
17. Describe the hexadecimal number system.
18. What is the decimal equivalent of the octal notation number 101 001 000 101?
19. Define the term *logic gate*.
20. What is a truth table?
21. What is the major function of an exclusive or gate?
22. Explain the positive logic concept.
23. What is a digital waveform of a logic gate?
24. Explain the process of photolithography.
25. Explain the manufacturing process used to produce integrated circuits.
26. Define the term *microprocessor*.
27. What are the four categories of ICs?
28. What is a logic family?
29. Describe the TTL logic family.
30. Describe the advantages of CMOS logic family devices.
31. What is the DIP standard?
32. How are the connections of an IC identified?
33. What are adder circuits?
34. What is the function of a digital clock?
35. Describe the operation of a flip-flop circuit.
36. What is the function performed by latch or flip-flop circuits?
37. Describe the function of a central processing unit.
38. What are the two major categories of memory circuits?

39. Give an example of how ROMs are used.

40. What is the function of the arithmetic logic unit?

41. Explain the process used to transmit digital data.

42. Explain the functions of a multiplexer and a demultiplexer.

43. Describe a nonvolatile memory.

44. Which ARINC standards are used for transmission of digital data?

45. What is the purpose of the parity bit in the ARINC 429 code?

46. What is the ARINC 629 code?

47. Explain the concepts of the ARINC 664 data bus standard.

48. What is the purpose of the source-destination indicator of the ARINC 429 code?

49. Explain the concept of logic troubleshooting techniques.

50. What are logic diagrams?

51. Describe the operation of a typical built-in test equipment system.

52. What are two common instruments used to test logic levels?

53. Explain the different data formats used by the ARINC 429.

54. Explain how the ARINC 429 word table is decoded.

55. What is the relationship between the ARINC 664 and the AFDX data bus standard?

56. Describe the *virtual link* and *physical layer* as they apply to the ARINC 664 specifications.

Electric Measuring Instruments 8

INTRODUCTION

The fundamental units of electrical measurement are the ampere, volt, ohm, and watt. To measure electrical values in terms of these units, certain instruments are required.

The common electric measuring instruments are the **ammeter, voltmeter, ohmmeter**, and **wattmeter**. The unit measured by each of these instruments is clearly indicated by its name. There are many electric measuring instruments in addition to those mentioned above. Each variation employs the basic principles that will be discussed in this chapter. For example, the operation of an engine temperature gauge may operate similar to a common volt meter. Fundamentals of how instruments function can help all aircraft technicians.

Digital and analog are the two general types of meters currently in use in modern aircraft and related test equipment. Analog meters utilize an infinitely variable scale upon which a specific value is indicated. A typical analog meter might contain a scale ranging from 0 to 100. The actual indicator position has an infinite number of possibilities within this range. Digital meters and instruments contain only a finite number of possible indications. A typical digital meter might have a scale from 0 to 100 with only 100 possible readings.

The digital system is usually more accurate, even though it allows for fewer possible indications. This is because the digital system gives indications in precise figures that are easily read without error. Digital meters and instruments have also proved to be more durable and reliable than analog systems. Although there are many commonalities between digital and analog meters, digital meter systems will be discussed in a separate section of this chapter.

METER MOVEMENTS

The basic principle of many electric instruments is that of the **galvanometer**. This is a device that reacts to minute electromagnetic influences caused within itself by the flow of a small amount of current. A simple galvanometer is shown in Fig. 8-1. It consists of a magnetized needle suspended within a coil of wire. When a current is passed through the wire, a magnetic field is produced, and the magnetized needle attempts to align itself with this field. Practical galvanometers cannot be constructed as simply as the one described above, but they all operate because of the reaction between magnetic and electromagnetic forces.

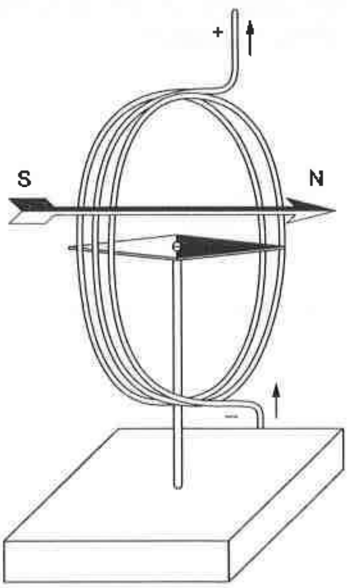


FIGURE 8-1 A simple galvanometer.

Any device that is designed to indicate a flow of current, particularly a very small current, and which operates on the principle of two interacting magnetic fields can be called a galvanometer. A permanent magnet pivoted so that it can turn in response to the influence of a current-carrying coil, or a current-carrying coil placed in a magnetic field and pivoted so that it can turn in response to the field produced by a current flow, can be used as a galvanometer. In any event, the rotating part must be balanced by a spring that will tend to hold it in the zero position when there is no current flow.

The most common types of electric measuring instruments employ a moving coil and a permanent magnet. This arrangement is known as the **d'Arsonval** or **Weston** movement and is illustrated in Fig. 8-2. The coil, consisting of

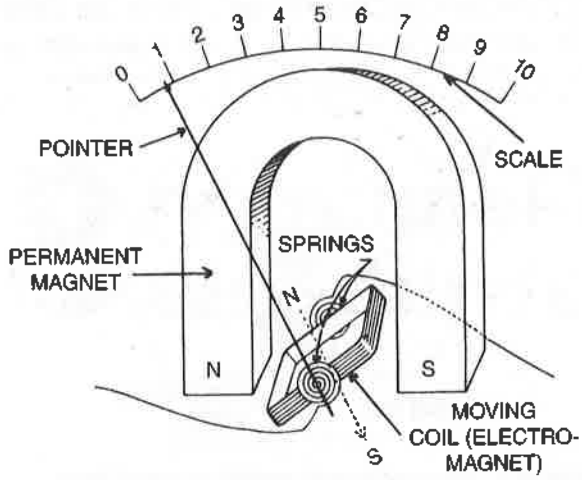


FIGURE 8-2 D'Arsonval or Weston meter movement.

fine wire, is pivoted and mounted so that it can rotate in the magnetic field of the permanent magnet's poles. When a current flows in the coil, a magnetic field is produced. The north pole of this field is repelled by the north pole of the permanent magnet and attracted by its south pole. As shown in Fig. 8-2, this will cause the coil to rotate to the right. The magnetic force causing the rotation is proportional to the current flowing in the coil and is balanced against a coil spring. The result is that the distance of rotation will increase as the current flow in the coil increases. The needle attached to the coil moves along a scale and indicates the amount of current flowing in the coil.

It is quite apparent that the d'Arsonval movement, used alone, is not suitable for the measurement of alternating current. Such current would produce rapid reversals of polarity in the moving coil that would cause the needle only to vibrate. Under these conditions, no indication could be obtained.

A movement similar to the d'Arsonval movement, but suitable for ac measurements, employs an electromagnet in place of the permanent magnet. This is called a **dynamometer** movement (see Fig. 8-3). The moving coil can be connected in either series or parallel with the electromagnet circuit.

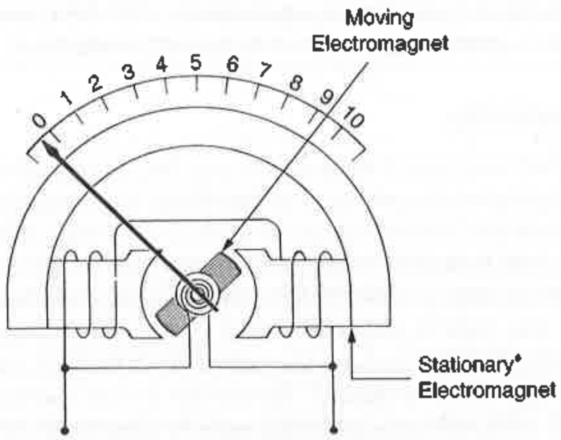


FIGURE 8-3 Dynamometer movement (front view).

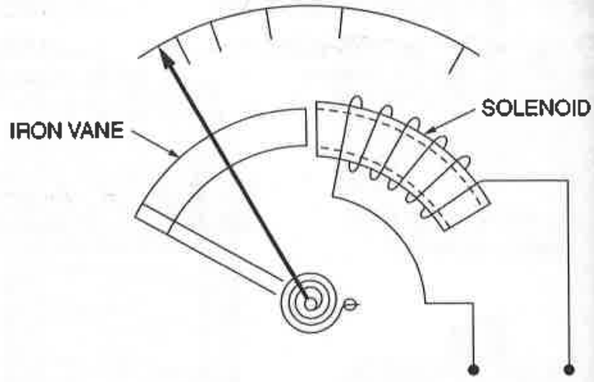


FIGURE 8-4 Iron-vane movement (front view).

When a movement of this kind is used, the indicating needle will always move in the same direction, regardless of the direction of the current through the instrument. This is because the polarity of both the moving coil and the electromagnet changes when the current direction changes; hence, the direction of torque (twisting force) remains the same. The movement will therefore operate with alternating current.

Another type of movement used with alternating current is illustrated in Fig. 8-4. This is called an **iron-vane** mechanism, and, as the name implies, it employs an iron vane through which electromagnetic forces act to move the indicating needle. The iron vane is attached to a pivoted shaft and is free to move into the coil whenever the coil is energized.

Also mounted on the shaft is the indicating needle; hence, the vane and the needle move together in response to a current flow in the coil. The movement of the vane and needle assembly is balanced by a coil spring that holds the needle in the zero position when no current is flowing.

Construction Features

Because some meter movements must respond to currents as small as a few millionths of an ampere, electric meters must be constructed with the utmost care and precision. Some of the moving parts are extremely accurately machined and finished. For this reason such instruments must be handled with great care to prevent shock or vibration damage, which would result in a loss of accuracy.

Because of the sensitivity required of electric meter movements, it is necessary that the pivot shaft bearings be as nearly frictionless as possible. This is accomplished by using jewel bearings similar to those used in fine watches. Figure 8-5 shows three different types of jewel bearings. For electric measuring instruments, the V-jewel bearing is typically used because it produces the least friction.

Although the moving elements of instruments are designed to be of the lowest possible weight, the extremely small contact area between the pivot and jewel results in the large stresses for which the bearing must be designed. For example, a moving element weighing 300 milligrams (mg) [0.00066 lb], resting on the area of a circle 0.0002 in. [0.0005 cm] in diameter, produces a force of about 10 tons/in.^{2} [1406 kg/cm^2]. From this it can be seen that if an instrument is dropped or jarred,

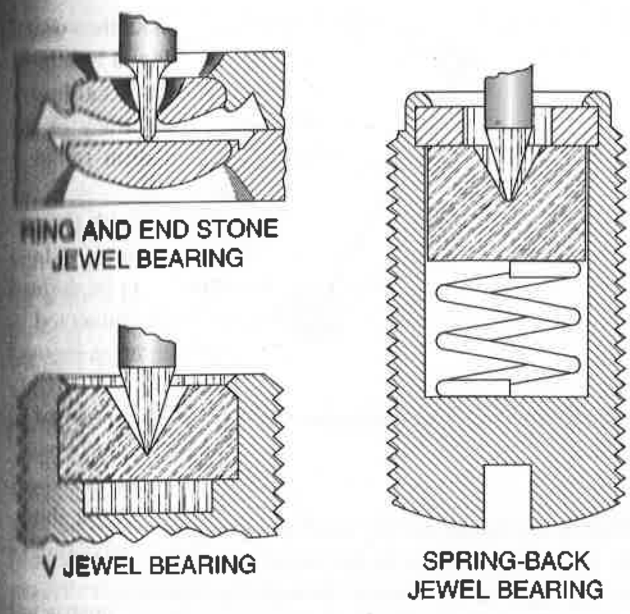


FIGURE 8-5 Jewel bearings.

the bearing stresses can easily be increased to the level where permanent damage is done.

Some instruments are designed to withstand rather severe shocks, and these are supplied with spring-back jewel bearings such as that shown in Fig. 8-5. This construction permits the pivot shaft to move axially when it is subjected to shock, with the result that the stresses are greatly reduced.

Taut-Band Movement

A rather ingenious development in instrument movements has largely eliminated the friction problems and the need for pivoted bearings. In this instrument movement, the moving coil is suspended on a taut band held by spring tension in the instrument frame. The taut band is a high-strength and very flexible material. This type of unit is called a **taut-band movement**. Figure 8-6 shows the construction of an instrument utilizing the taut-band suspension for the moving coil.

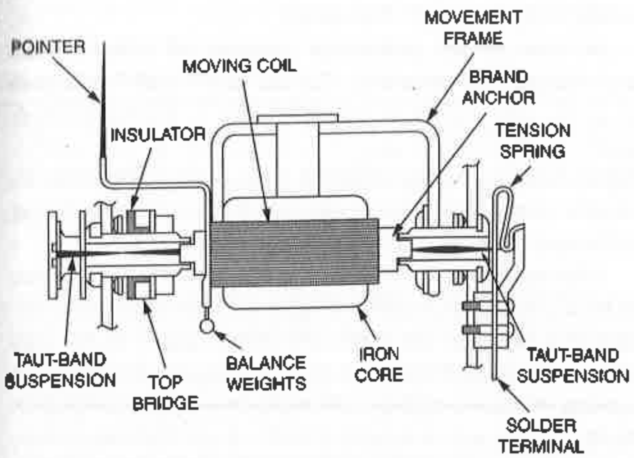


FIGURE 8-6 Taut-band movement (side view).

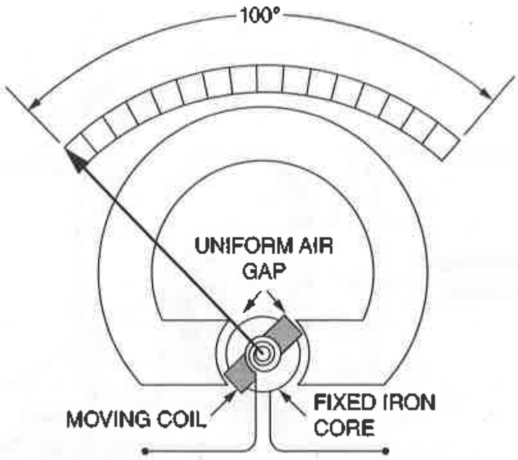


FIGURE 8-7 Iron core used to provide a uniform field (front view).

It can be seen that the taut-band instrument is not nearly as sensitive to shock as the type having jewel bearings, because shocks are taken up by the elasticity of the taut band. The band is not subject to corrosion because of the material from which it is made. Since there are no parts rubbing against one another as in a bearing, the friction is eliminated, and the movement can respond to extremely small magnetic influences. For this reason, the movement can be designed for very high sensitivity.

Design for Uniform Scale

Since the magnetic force acting upon a magnetic substance is inversely proportional to the distance between the magnet and the substance acted upon, instruments using the magnetic principle do not have a uniform scale unless special construction features are incorporated. In the Weston meter movement a uniform scale is obtained by placing a cylindrical iron core inside the moving coil (see Fig. 8-7). This arrangement results in a uniform magnetic field in the air space between the core and the poles. The coil rotates in the cylindrical space a distance proportional to the amount of current flowing in the coil windings.

It is apparent from a study of a typical instrument diagram that there is a limit to the range through which the indicating needle can act. In a conventional meter movement, such as that in Fig. 8-7, this range is approximately 100°. Some meters require a greater range and must be specially constructed.

Sensitivity

As previously stated, some meters must be constructed with a high degree of sensitivity. This **sensitivity** is determined by the amount of current required to produce a full-scale deflection of the indicating needle. Very sensitive movements may require as little as 0.00005 A to produce a full-scale deflection. This value is commonly called 20 000 Ω/V, because it requires 20 000 Ω to limit the current to 0.00005 A when a voltage of 1 V is applied. Movements having a sensitivity of 1000 Ω/V are commonly used by electricians when the power consumed by the instrument is of no consequence.

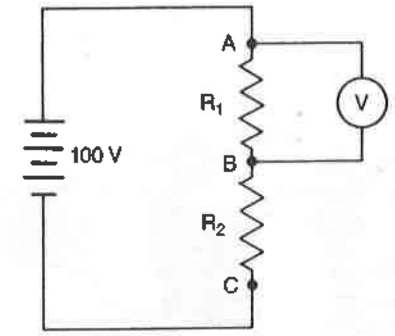


FIGURE 8-8 Demonstration of a need for high sensitivity in a voltmeter.

In electronic work, where very small currents and voltages must be measured, instruments of very high sensitivity are required. Electronic measuring instruments, such as the volt-ohm meter (VOM), the multimeter, or the digital multimeter (DMM), are normally used for the measurement of resistance, currents, and voltages in electronic circuits. These instruments are designed to isolate the measuring circuit from the circuit being measured; hence very little loading is applied to the circuit being measured.

To understand the importance of sensitivity in an instrument for testing certain values where current flow is very small, it is well to consider a specific example. In the circuit in Fig. 8-8, a 100-V battery is connected across two resistors in series. Each resistor has a value of 100 000 Ω, making the total resistance of the circuit 200 000 Ω. Since the two resistors are equal in value, it is obvious that the voltage across each will be 50 V. If we wish to test this voltage by means of a voltmeter that has a 1000-Ω/V sensitivity, we will discover that a large error is introduced into the reading.

Assume that the voltmeter has a range of 100 V and that it is connected across R_1, between points *A* and *B*. Since the voltmeter has a sensitivity of 1000 Ω/V, its total resistance will be 100 000 Ω. When this is connected in parallel with R_1 the resistance of the parallel combination becomes 50 000 Ω, and the total resistance of the circuit is now 150 000 instead of 200 000 Ω. With the resistance between *A* and *B* 50 000 Ω and the resistance between *B* and *C* 100 000 Ω, the voltage drop will be 33.3 V between *A* and *B* and 66.7 V between *B* and *C*. It is apparent, then, that the voltmeter used would not be satisfactory for this test.

If we connect a voltmeter with 20 000-Ω/V sensitivity across R_1, we will obtain a much more accurate indication of the operating voltage. The voltmeter has an internal resistance of 2 000 000 Ω, and this resistance, combined in parallel with R_1, will produce a resistance of 95 238 Ω. This resistance in series with the 100 000 Ω of R_2 will produce a voltage drop of approximately 48.7 V across R_1 and 51.3 V across R_2. The reading of the voltmeter is then 48.7 V, which is probably as accurate as necessary for normal purposes.

THE AMMETER

Most of the electric measuring instruments in use today require very little current to produce a needle movement or digital indication. A resistance is used to restrict the current applied to the meter's sensitive circuitry when a relatively high voltage or current is being measured. If calibrated resistors are used for the restriction, the accuracy of the meter remains high, and the meter's indication range is extended.

When a resistance is connected in parallel with the terminals of a meter, it is called a **shunt resistance**. A shunt resistance, also called an **instrument shunt**, can be defined as a particular type of resistor designed to be connected in parallel with a meter to extend the current range beyond some particular value for which the instrument is already competent. In general, the word *shunt* means "connected in parallel." The shunt resistor can be thought of as a "bypass" for a current flow, allowing most of the current to bypass the sensitive meter movement and travel through the shunt. A meter designed to measure multiple current/voltage ranges may contain several shunts.

A simple ammeter with low capacity can be constructed by using relatively large wire in the moving coil. If the wire is large enough to carry the full amperage of the circuit in which the meter is used, it is not necessary to incorporate a shunt resistance.

A typical ammeter circuit with a shunt resistance is shown in Fig. 8-9. If we assume that a current of 0.01 A causes a full-scale deflection of the indicating needle and that the resistance of the movement is 5 Ω, we can calculate the voltage required to produce a full-scale deflection. By applying Ohm's law, we find this to be 0.05 V. This instrument can be made to measure almost any current value by using a shunt resistance of the correct value. Suppose that it is necessary to use the ammeter where the current range is from 0 to 30 A. Since 30 A must flow through the parallel combination of the meter and the shunt resistance and only 0.01 A can flow through the meter, then 30 − 0.01 A, or 29.99 A, must flow through the shunt resistance. We know that 0.05 V across the meter provides a current of 0.01 A; hence, we must find a

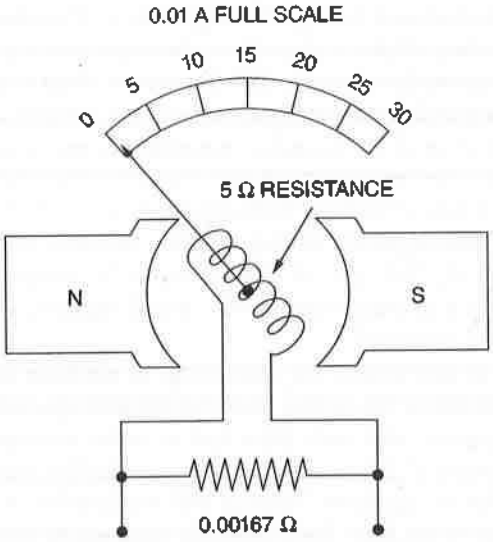


FIGURE 8-9 Ammeter circuit.

resistance that will cause a voltage drop of 0.05 V when a current of 29.99 A is flowing through it. By Ohm's law,

$$R = \frac{0.05}{29.99} = 0.00167\ \Omega$$

If we wish to use the same meter movement for a range of 500 A, the value of the shunt resistance can be determined as for a 30-A range. Since 0.01 A will flow through the instrument at full-scale deflection, 499.99 A must flow through the shunt. The resistance of the shunt must be such that 499.99 A will cause a voltage drop of 0.05 V. This value is obtained by dividing 0.05 by 499.99. The required resistance is found to be approximately 0.0001 Ω. It is very difficult to construct a resistance of exactly 0.0001 Ω, and temperature changes also cause some variations; hence, practical ammeters for high amperage employ a movement less sensitive than that described above.

Greater accuracy can be obtained with a sensitive movement by incorporating a series resistance into it. For example, if a resistance of 995 Ω is connected in series with the movement, then the value of the shunt resistance can be increased to approximately 0.02 Ω. This will provide much greater accuracy because the higher resistance of the shunt reduces the error factor. Typical external ammeter shunts are shown in Fig. 8-10.

Milliammeters, which are used to measure current values in thousandths of amperes, do not necessarily require shunt resistance. If the instrument has a sensitivity of 100 Ω/V, it has a range of 0 to 10 milliamperes (mA) without a series or shunt resistance. A shunt resistance can be incorporated to increase the range to any desired value. To measure current in units smaller than the milliampere, a **microammeter** is used. One microampere (μA) is one-millionth of an ampere. An ammeter with a sensitivity of 20 000 Ω/V has a full-scale deflection of the indicating needle with a current of 50 μA through the movement. Such a meter can be used to measure current in a range of 0 to 50 μA.

An ammeter designed to measure a wide range of values may contain internal shunts. Each internal shunt is typically controlled through the meter's range switch. When the meter is measuring a high-current circuit, the range switch is placed in the appropriate position, and the correct shunt resistor is added in parallel to the ammeter circuit. If a different current range is desired, the switch is repositioned, and a different shunt is connected in parallel with the meter movement.

Those ammeters used to measure only a narrow range of current flows typically employ external shunts as illustrated in Fig. 8-10. This type of shunt is typically constructed of a thin piece of metal of a specific size designed to create a calibrated resistance.

The proper method for connecting an ammeter in a circuit is shown in Fig. 8-11*a*. Note that the ammeter and shunt are in parallel with each other and in series with the load. An ammeter of the proper type uses a negligible amount of power for its operation; hence it will not interfere with the operation of the load. The instrument must not be connected in parallel with the source of power. The ammeter and its shunt are designed to offer as little resistance as possible in a circuit; hence, if they are connected in parallel with the power source, they will act as a direct short circuit. This will not only prevent the operation of the circuit but also in most cases cause irreparable damage to the instrument and to the power source.

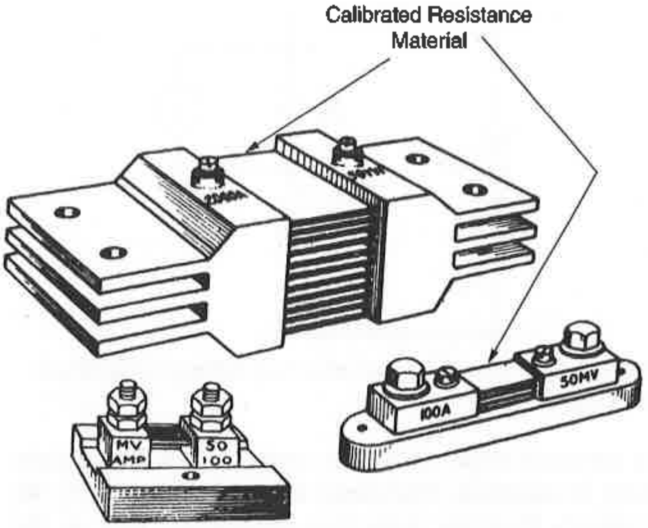


FIGURE 8-10 External ammeter shunts.

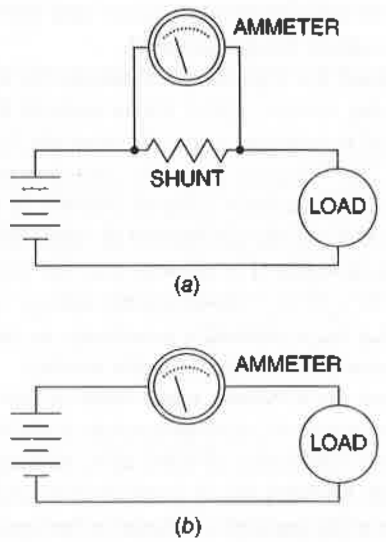


FIGURE 8-11 Ammeter connected in a circuit: (a) with an external shunt and (b) with an internal shunt.

An ammeter requiring no shunt, or containing an internal shunt, is illustrated in Fig. 8-11*b*. In this circuit the ammeter is still connected in series with the load, and no external shunt is required.

If the current in a portion of a circuit is to be measured, the ammeter must be placed in series with that portion of the circuit. As illustrated in Fig. 8-12, the ammeter will measure only the current that flows through the meter. The current that bypasses the meter through a different portion of the circuit will not be measured. In this illustration, the meter

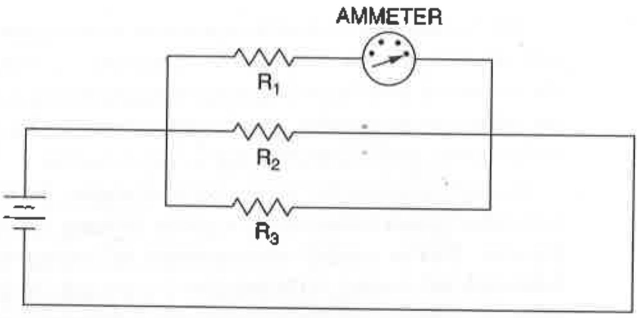


FIGURE 8-12 Ammeter connected to measure the current through R_1.

measures only the current through R_1, not the current of the entire circuit.

An ammeter of the correct capacity and type can be used to determine how much current a particular load in an aircraft will draw. If it is desired to find out how much current flows in a starter circuit, it is merely necessary to disconnect one of the power cables to the starter motor and connect the ammeter between the starter cable and the terminal on the starter motor. Care must be taken to see that the ammeter is connected with the correct polarity. In a system with a negative ground, the positive (+) terminal of the ammeter is connected to the power cable from the starter relay, and the negative (−) terminal of the ammeter is connected to the power terminal of the starter motor. It is also important to install a meter capable of measuring the maximum anticipated current flow of the circuit. In the case of a starter motor, this may be several hundred amperes.

The ammeter used to check the current in a light aircraft's starter system should have a range up to approximately 500 A. After the ammeter is properly connected with wire as large as the starter cable, the starter switch can be closed. It will be noted that there is a very high surge of current at first, and this rapidly falls off to a much lower value.

When connecting an ammeter, or any other meter, in an electric circuit, it is always essential to choose a meter with a range high enough to ensure that the meter is not overloaded. If the maximum current flow of the circuit is unknown, always install a meter of very high indicating range. If a very low indication is measured by this test, a lower-range meter can be installed to more accurately determine the circuit's current flow. When a meter containing internal shunts is used, this matter becomes very simple. Always install the meter with the range selector set to the highest value. Then, if necessary slowly move the selector switch to a lower value in order to achieve a needle indication at approximately mid-scale.

THE VOLTMETER

A **voltmeter** of the moving-coil type actually measures the current flow through the instrument; but since the current flow is proportional to the voltage, the instrument may be

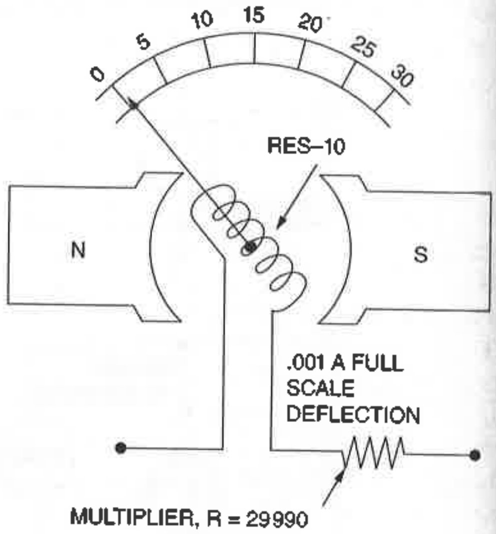


FIGURE 8-13 Voltmeter circuit.

marked in volts. The meter movement is adapted to the measurement of voltage by the use of series resistance.

Figure 8-13 shows a schematic diagram of a voltmeter circuit. Assuming that the meter movement has a full-scale deflection at a current of 0.001 A and an internal resistance of 10 Ω, it is easily determined that 0.01 V is the maximum that can be applied to the instrument without the addition of a series resistance. If we wish to give the instrument a range of 0 to 30 V, we use Ohm's law to find the required series resistance. Since the current through the instrument must be 0.001 A for a 30-V reading, we proceed as follows:

$$R = \frac{30}{0.0001} = 30000\,\Omega$$

Since the internal resistance of the movement is 10 Ω, this value must be subtracted from the total required resistance. The series resistance required is then 29 990 Ω.

Voltmeters usually have the necessary series resistance built into the instrument itself. The range of such an instrument can be increased by the use of additional series resistances called **multipliers**. Resistances of this type are used with test instruments when the instrument must be capable of measuring a wide range of voltages. For example, to double the range of a voltmeter, it is necessary merely to add a series resistance equal to the total resistance of the instrument.

The proper method of connecting a voltmeter with an internal multiplier is shown in Fig. 8-14*a*. The meter is connected in parallel with the power source being measured. Figure 8-14*b* shows a voltmeter and an external multiplier connected in a circuit. The meter is in series with the multiplier, and the multiplier and voltmeter are in parallel with the power source being measured. Almost all voltmeters contain internal multiplier resistors and it is very rare to find a voltmeter using an external resistance.

As stated in the discussion of Ohm's law, parallel resistances have equal voltage drops. Since a voltmeter is a resistance,

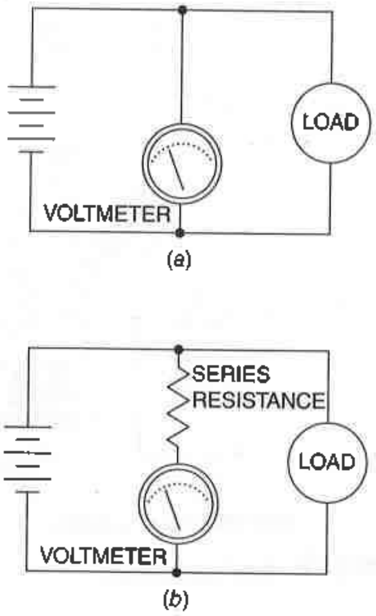


FIGURE 8-14 Voltmeter connected in a circuit: (*a*) with an internal multiplier and (*b*) with an external multiplier.

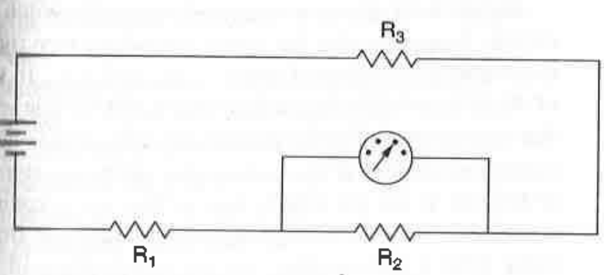


FIGURE 8-15 Voltmeter connected to measure the voltage applied to R_2.

It must be placed in parallel with any item whose voltage is to be measured. When measuring the voltage in a portion of a circuit, the voltmeter must be placed in parallel with the portion to be measured. Figure 8-15 illustrates the connections necessary to measure the voltage available to R_2. The voltmeter in parallel with R_2 will measure the voltage drop across R_2 and not the voltage of the entire circuit.

If the resistance of a voltmeter is too low, it disturbs the conditions of the circuit, and an accurate reading cannot be obtained. This is particularly true in circuits having a low current flow, such as electronic circuits. In such circuits it is necessary to use very sensitive (high-resistance) instruments.

Since a voltmeter has sufficient resistance so that it can be connected in parallel with the power supply, there is no damage to the instrument if it is connected in series with the load. The only effect is to prevent the operation of the circuit.

Voltmeters are used in airplanes so that the pilot, or another member of the crew, can be kept informed concerning the operation of the electric system. They are not usually installed in small airplanes with single generator systems, but where it is necessary to operate two or more generators in parallel, the voltmeter is essential to aid in balancing the output of the generators.

The voltmeter is a valuable instrument for troubleshooting and checking electric and electronic circuits. In every case, the technician must be sure that the voltmeter being used is of the correct range and that it is the proper type for the current in the circuit, whether alternating or direct current.

If a particular electric unit is not functioning, the first step is to determine whether electric power is being delivered to the unit. This is quickly accomplished by testing with the voltmeter. In a system with negative (−) ground, the positive probe or alligator clip connected to the voltmeter is touched to the terminal of the unit being checked, and the negative probe is touched to the metal of the airplane. If power is reaching the test point, the voltmeter should read system voltage.

Circuits can be tested while "hot," that is, with power on, or they may be tested by connecting the voltmeter with the power off and then turning the power on and observing the response of the voltmeter. In testing hot circuits, care must be taken to avoid causing short circuits by allowing some metal object to bridge between the terminal being tested and the metal of the aircraft. The test leads of the voltmeter should be well insulated, and the test probes or alligator clips should be insulated except at the points where electrical contact is to be made.

On large aircraft where high voltage (100 volts and up) circuits are to be tested, great care must be taken to avoid contacting hot parts of circuits with the bare hands or any other part of the body. Severe shocks will occur at any time that a circuit is completed through the body. Working procedures established by the company operating large aircraft are usually such that the danger of shock is minimized. **The potential for bodily damage and even death must not be ignored when testing high-voltage circuits. Always follow all safety precautions established by the aircraft or equipment manufacturer.**

For testing the normal operating circuits of an aircraft's electrical system, the sensitivity of the test voltmeter need not be high. A voltmeter with a sensitivity of 1000 Ω/V will usually suffice.

A voltmeter of high sensitivity must be used when testing delicate circuits, that is, circuits that operate on very low voltage or very low current. In cases where a short-term or changing voltage is to be measured, the speed of the test meter is also an important consideration. An accurate reading can only be obtained if the voltmeter can respond quickly enough to measure the voltage before it changes.

THE OHMMETER

The **ohmmeter**, as its name implies, is an instrument for measuring resistance. To make the meter movement capable of measuring resistance directly, it is necessary merely to provide a source of electric power and a suitable resistance. Remember, the test instrument responds only to current through the meter's coil; but since current is a function of a circuit resistance, a galvanometer can be used as an ohmmeter, as long as power is supplied to the circuit.

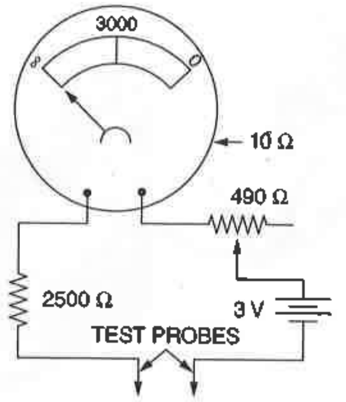


FIGURE 8-16 A simple ohmmeter circuit.

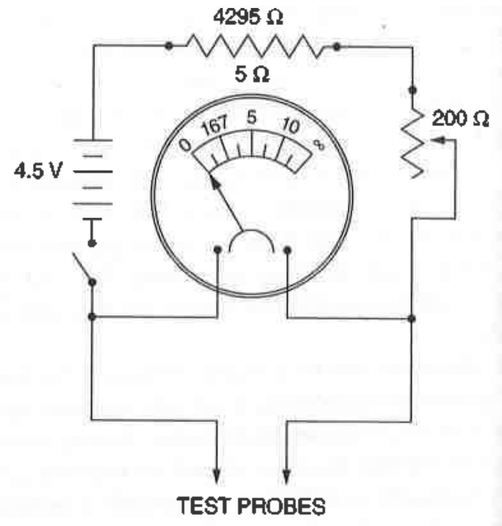


FIGURE 8-17 Ohmmeter for testing low resistance.

Figure 8-16 is a schematic diagram of a simple ohmmeter circuit. The principle of operation follows Ohm's law, and a 3-V battery (two 1.5-V AA cells in series) provides the power necessary for operation. The meter movement has a sensitivity of 1000 Ω/V and an internal resistance of 10 Ω. The total series resistance throughout the circuit must be 3000 Ω to provide a full-scale deflection of the indicating needle when the emf of the power source is 3 V. This is attained by placing a 2500-Ω fixed resistance and a 490-Ω variable resistance in series with the battery and the meter movement. The variable resistance makes it possible to compensate for the lowering of the battery voltage over a period of time.

When the test probes are in contact with each other, the indicating needle moves to the full-scale position. This point is marked zero because it indicates that there is zero resistance between the test probes. If a resistance of 3000 Ω is placed between the test probes, the needle travels halfway across the scale. This point on the scale is marked 3000 Ω. If the test probes are separated, that is, placed to measure the resistance of the air between them, the indicating needle remains at the extreme left side of the scale. This point is marked infinity (∞) because the resistance of the air is so great that no measurable current passes through the circuit; hence, for practical purposes, the resistance is infinite.

The range of resistance readings on the scale of the ohmmeter described above is from zero to infinity, but the practical range is from approximately 100 to 30 000 Ω. The scale divisions for the very high resistances are so close together that the probability of error increases tremendously as the value of the reading becomes higher. The basic range of the ohmmeter can be changed by the use of resistances as multipliers. For higher resistances, it is necessary to use a higher voltage or a more sensitive movement. In either case, the current-limiting resistance must be increased.

An ohmmeter designed for the measurement of very low resistances must be connected so that the resistance to be measured acts as a shunt resistance across the test probes. A circuit for this type of ohmmeter is shown in Fig. 8-17. The meter movement is connected in series with a battery, a switch, a fixed resistor, and a variable resistor. If we assume that the meter has an internal resistance of 5 Ω and that 1 mA will produce a full-scale deflection, then a total circuit resistance of 4500 Ω will provide for a full-scale deflection when a 4.5-V battery (three 1.5-V AA cells in series) is used to power the instrument. To test a resistance, the switch is closed and the indicating needle moves to the extreme right of the scale; that is, it indicates infinite resistance. If we place a 5-Ω resistor between the test probes, the needle will take a position at half scale. This is because 0.5 mA is now passing through the meter and 0.5 mA through the resistor. If a 15-Ω resistor is placed between the probes, the indicating needle will take a position three-fourths the distance from the zero end of the scale. This is because 0.75 mA will be flowing through the meter and 0.25 mA through the resistor.

To measure the resistance of any electric item such as a resistor, coil, or length of wire, it is necessary merely to connect the test probes of the ohmmeter to the terminals of the item being tested. Before the test is made, the ohmmeter should be adjusted so the scale reading is zero when the probes are connected together and infinity when the probes are separated. This is done by adjusting the meter's resistance to compensate for any variance in battery voltage. The meter's resistance is changed by adjusting a variable internal multiplier. Over time, even if a battery is not used, its voltage decreases. To obtain accurate indications, one must always "zero" an analog ohmmeter prior to use. Most digital ohmmeters do not require this zeroing adjustment. Typically, an ohmmeter contains several internal multipliers, which can be connected to the circuit by using the meter's range selector. The range selector switch can be adjusted to allow one instrument to accurately measure several different resistances. The range of the ohmmeter used should be such that the indicating needle will move to a point in the center two-thirds of the scale when the unit being tested is connected to the test probes. With some instruments, the manufacturer may suggest a different portion of the scale as providing the most accurate results.

An ohmmeter will not be damaged by measuring a resistance while the meter is set on the wrong scale; however, the meter indication may be less accurate or difficult to read.

In testing units connected in a circuit, all electric power in the circuit must be turned off. It is good practice to disconnect or remove power sources from a circuit or unit when testing portions of the circuit with an ohmmeter. Electric power in a circuit being tested with an ohmmeter will usually cause damage to the instrument and will certainly prevent a correct reading of resistance values. It is often necessary to isolate one side of a unit from a circuit to prevent other parts of the circuit from affecting the reading. If a unit is tested while it is still connected to the circuit, an inaccurate reading is likely.

The ohmmeter can be a useful instrument for testing or checking electric components. It not only measures resistance but also is an excellent **continuity tester**. Testing continuity is the process whereby the meter is used to determine if the circuit has a complete *(continuous)* current path. Continuity tests are often performed on items such as lightbulbs or relays to determine if the item has a continuous path or an open circuit. An open circuit means there is a disconnection somewhere inside the unit and it will not function.

To use an ohmmeter as a continuity tester, it is necessary merely to contact the terminals of the circuit being tested with the test probes of the ohmmeter. This is illustrated in Figure 8-18, which shows how a section of circuit wiring can be checked. Usually, the wiring for a number of circuits is included in a bundle called a **harness**, and it is not possible to inspect the individual wires visually. The particular circuit to be tested can be identified at each end by means of coding on the wire and in the circuit diagram provided in the aircraft maintenance manual. After the wire to be tested is identified, the probes of the ohmmeter are touched to the two terminals of the wire simultaneously. If the wire is in good condition, the ohmmeter will read near the zero resistance point.

Although the procedure described above is valid, it often becomes difficult to perform. For example, if the wire to be checked is routed from the wing tip to the instrument panel, the ohmmeter test leads will be too short to connect to both ends of the suspect wire. A voltage check, with the system power on, is typically the easiest way to troubleshoot an open wire. Troubleshooting techniques are discussed in Chap. 13. An ohmmeter is best used to test the continuity of a component such as the switch illustrated in Fig. 8-19.

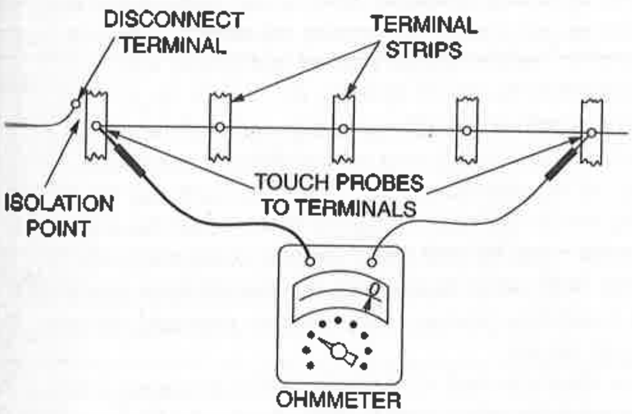


FIGURE 8-18 Use of an ohmmeter as a continuity tester.

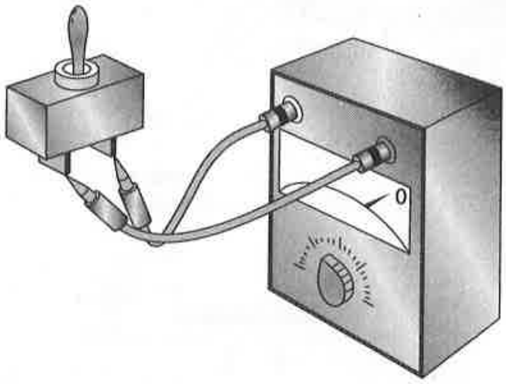


FIGURE 8-19 Measuring the continuity of a switch.

The ohmmeter should indicate near zero resistance (less than 1 Ω) when the switch is turned on and infinite resistance when the switch is turned off.

AC MEASURING INSTRUMENTS

Since the basic electrical meter is designed to measure direct current, the measurement of alternating current (ac) requires some meter design modifications. Specifically the alternating current being measured must somehow be converted to direct current for measurement. In most cases the conversion of the ac to dc (known as rectification) creates a slight loss of electrical signal. To ensure proper accuracy, any meter measuring alternating current must compensate for the energy lost during rectification; this is true for both moving-coil and digital ac meters. The most common means to measure alternating current using a moving-coil meter is to simply rectify the alternating current prior to sending the electrical signal to the meter movement; these are often called **rectifier meters**. The iron-vane and dynamometer may also be used to measure alternating current; however, these meters are less common.

The iron-vane movement and the dynamometer were discussed earlier in this chapter. These movements are satisfactory for alternating current of relatively low frequencies within a range of 15 to 1000 Hz. For frequencies of over 150 Hz, the dynamometer-type movements must have corrections applied.

One of the most common instruments for use with relatively low-frequency alternating currents is a dc meter movement connected in a circuit with a full-wave rectifier, as shown in Fig. 8-20. An instrument such as this is often called a **rectifier instrument**. A full-wave rectifier is used to change the alternating current to direct current and is discussed in great detail in Chap. 6. When such a meter is used for both ac and dc measurements, two scales are usually provided. This is because the movement of the needle, when measuring ac values, is proportional to the average value of the current rather than the effective value.

When a rectifier-type meter is used to measure high frequency alternating current, the error increases in proportion

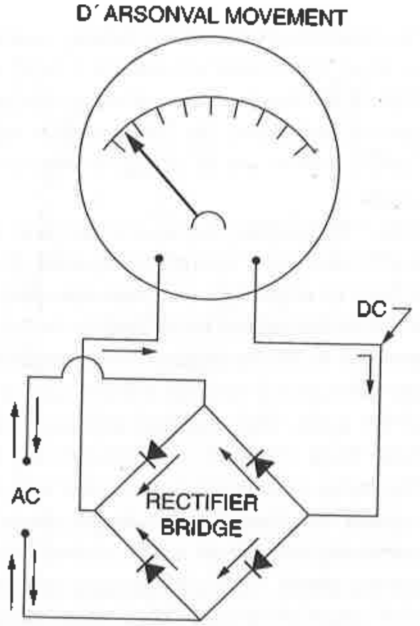


FIGURE 8-20 Rectifier-type meter.

FIGURE 8-21 An inductive pickup meter.

to the frequency. This error is caused by the capacitive effect of the rectifier elements. At extremely high frequencies, the rectifier will pass a substantial amount of current in both directions; hence, the current will flow through the instrument in both directions.

The result is that the current in one direction is reduced by the current in the opposite direction. There are ways to compensate for this effect and accurately measure high frequency alternating current. The most common means is to reduce the high frequency being measured prior to sending the signal to the rectifier. The frequency can be reduced by an additional circuit located inside a specially designed high-frequency ac meter.

Inductive Pickups

Many ac meters use the principle of electromagnetic induction to measure the current and frequency of a circuit. These meters contain a test probe called an **inductive pickup** or a **current transformer** that wraps around one wire of the circuit to be tested. A meter employing an inductive pickup is shown in Fig. 8-21. An inductive pickup receives its current from the electromagnetic wave that forms around any wire carrying a current. If this magnetic field is constantly changing, as in an ac circuit, a voltage/current will be induced into the inductive pickup. The pickup then sends a signal to the measuring instrument, which measures the circuit's current flow. Inductive pickups are commonly used for ac ammeters and wattmeters. They can also be used on circuits operated by a pulsating direct current.

The Wattmeter

Wattmeters are not frequently used by the aircraft maintenance technician, but a short discussion of the principles of such meters will aid in the understanding of the measurement of electric power.

The unit for the measurement of electric power is the watt. One watt is the power expended when a current of 1 A is flowing under the pressure of 1 V. In an electric circuit, the power in watts is equal to the product of the voltage and the amperage. This is true in dc circuits and in ac circuits when the voltage and current are in phase.

Since electric power involves both amperage and voltage, the wattmeter must be capable of multiplying these values. A schematic diagram of a wattmeter connected in a circuit is shown in Fig. 8-22. The construction of the instrument is similar to that of a dynamometer movement, but the circuits for the magnetic field and the moving coil are separate. One of the windings must provide a field proportional to the current in the circuit, and the other must produce a field proportional to the voltage. Since the current winding

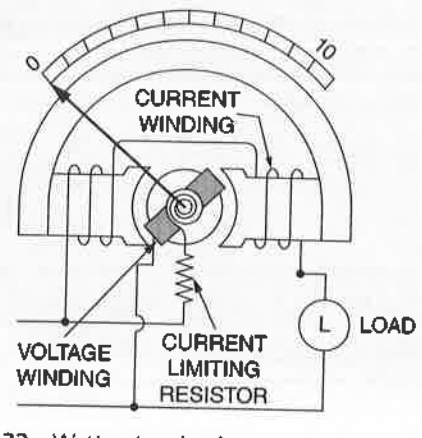


FIGURE 8-22 Wattmeter circuit.

must be heavy enough to carry the current of the circuit, the current coil is stationary. The moving coil carries the voltage because this winding must have a high resistance and is relatively light in weight.

The current circuit is connected in series with the load circuit, and the voltage circuit is connected in parallel with the load circuit. A current-limiting resistor is connected in series with the voltage coil. When the circuits are connected in this manner, the strength of the stationary field is proportional to the load current, and the strength of the moving-coil field is proportional to the voltage across the load. The indicating needle moves a distance proportional to the product of the voltage and the amperage; hence the scale can be marked directly in watts.

THE MULTIMETER

In practice, the functions of a voltmeter, ohmmeter, and ammeter (or milliammeter) are usually combined in an instrument called a **multimeter or volt-ohm-milliammeter** (VOM). This combination instrument makes it possible to take a wide range of electrical measurements with just one basic instrument. One type of analog multimeter is shown in Fig. 8-23. This instrument will measure ac and dc voltage up to 1000 V, resistance from zero to infinity, and dc current from zero to 10 A. One meter movement is used to provide all the indications by means of the various scales on the dial. For each type of indication, the instrument is adjusted by means of a rotary switch and by plugging the test leads into the proper jacks.

FIGURE 8-23 A typical analog multimeter. (*Simpson Electric Co.*)

When using a multimeter, the technician must follow the instructions provided in the instrument manual. In testing an unknown voltage or amperage, it is important that the meter range be set above the highest level likely to be encountered. It is good practice to set the highest range available to start and then adjust downward until the reading falls in the upper one-third of the scale. This practice will avoid damage to the instrument from overload and provide for maximum accuracy. The meter movement is provided with automatic protection against overload. When voltages above the 30-V range are tested, the technician must exercise care in order to avoid electrical shock. This is particularly important in the 300- to-1000-V range. Additional information on meter usage is contained in Chap. 13.

DIGITAL METERS

Digital meters have become commonplace in modern aircraft. They are lighter, more reliable, and generally less expensive than analog meters. Digital meters, used as bench-top or portable multimeters, are also commonly employed by aircraft technicians. A **digital multimeter** (DMM) is shown in Fig. 8-24. In many cases the DMM is considered more accurate than the analog meter because of its display of precise numerical values. Digital displays require less interpretation by the operator; therefore, there is less chance for error. Since the display of a digital meter is a solid-state device, there is no sensitive meter movement that can be damaged during rough handling; hence making digital meters more accurate and more reliable. In a digital multimeter; the signal under test is converted to a voltage, then amplified, and sent to a microprocessor for signal analyze. The microprocessor converts that signal and sends the information to the digital display which will then create an image of the value being measured.

Digital meters use one or more integrated circuit (IC) chips to process input data, initiate displays, and perform any required calculations. Light-emitting diodes or liquid crystals are used for displays on most digital meters. When measuring voltage, the DMM sends the input signal (from the test leads) through an analog-to-digital converter. The digital signal is then compared with an internal reference voltage by means of the meter's microprocessor. The microprocessor interprets the signal and sends output data to the numerical display. When current is measured, a resistor is placed in series with the load inside the meter. The voltage drop over the resistor is measured, and the microprocessor converts the information into the proper signals for the numerical display. When measuring resistance, the meter supplies a reference voltage to the resistance being measured. A current flow results. This current is measured by the meter to determine

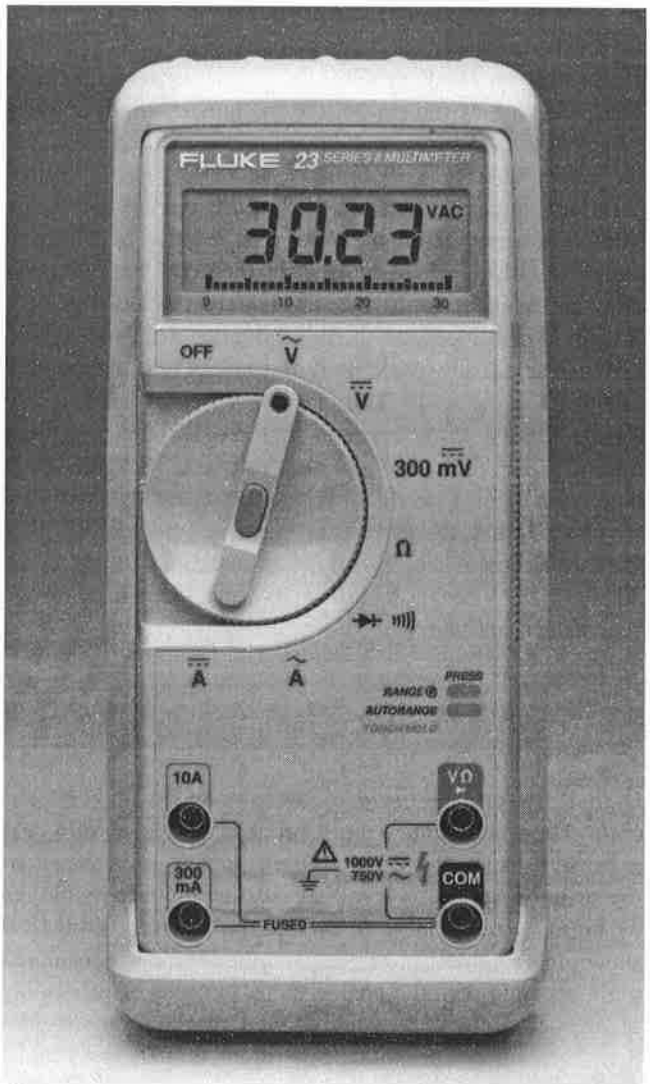


FIGURE 8-24 A typical handheld digital multimeter. *(Reproduced with permission, John Fluke Mfg. Co.)*

the load resistance. The meter's internal batteries supply the voltage needed to measure resistance.

The resolution of a digital meter will determine how small a measurement the meter can make. In other words, a meter with high resolution may be able to measure down to 1 mV (0.001 V); a meter with poor resolution may only be able to measure down to 0.1 V. One limiting factor of a meter's resolution is the number of *digits* on the meter display. Typically, handheld DMMs have between 3 and $4\frac{1}{2}$ counts. A 3-digit meter can display up to three full digits (0 to 9). A $4\frac{1}{2}$-digit unit can display four full digits and one $\frac{1}{2}$ digit (1 or blank). The $\frac{1}{2}$ digit is located at the far left of the display. For example, a 3-digit display could indicate up to 999 V; a $3\frac{1}{2}$-digit display could indicate up to 1999 V.

Many digital meters incorporate a diode test function. During a diode test the meter supplies a voltage to the test probes. If the diode is operating correctly, the meter will indicate the voltage drop across the diode when the red probe is connected to the anode and the black probe is connected to the cathode of the diode. The voltage drop should be approximately 0.3 or 0.7 V, depending on the type of diode. When the meter probes are reversed, the meter should indicate an open circuit. Most digital meters incorporate an easy-to-use continuity tester. The meter selector switch must be set to the correct position to perform the continuity test. In most cases, the DDM will contain a digital beeper that will sound when the circuit is continuous (below a certain resistance value, approximately 1 Ω). If the circuit or component exceeds this preset resistance value, the circuit is considered open (not continuous) and the beeper will not sound. This allows the technician to determine continuity without actually having to look at the meter display, a very handy feature when troubleshooting aircraft systems and components. The continuity tester is used to ensure that a circuit, or component, will allow *continuous* current flow. To allow current flow, the circuit, or component, must have a complete circuit from one contact to another. Figure 8-25 shows a DDM used to perform a continuity test on a common navigation light bulb. If the bulb is operational, the DDM will sound a beep tone, and the meter display will indicate the lamp's resistance, indicating a continuous current path through the lamp. If the bulb is defective (open), the DDM peeper will not sound and the meter display will indicate an open circuit.

Modern digital multimeters often have an embedded computer, or microprocessor, which provides a wealth of convenience features. Measurement enhancements available for digital meters include

1. **Auto-ranging,** which selects the correct range for the quantity under test so that the greatest number of significant digits are displayed by the meter. For example, a four-digit multimeter would automatically select an appropriate range to display 1.234 instead of 0.012. Other factors being equal, an auto-ranging meter will have more circuitry than an equivalent nonauto-ranging meter, and so will be more costly, but will be more convenient to use. An auto-ranging meter may respond relatively slowly when compared to a nonauto-range meter, and the meter may fluctuate when measuring signals that are unstable. For these reasons, many meters allow the user to turn on/off the auto-range feature.

2. **Auto-polarity** correction is a feature for measuring direct-current. If the meter leads are connected to the circuit

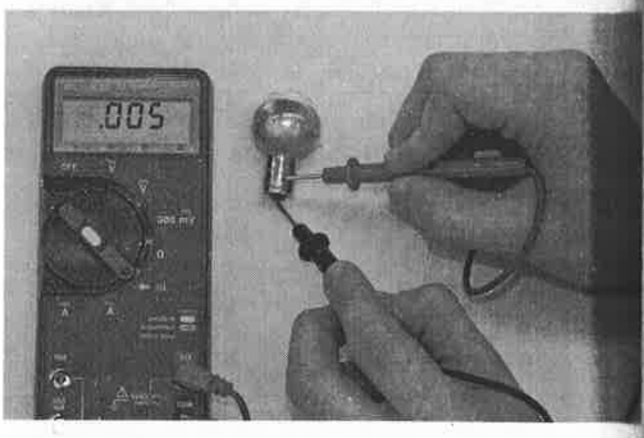


FIGURE 8-25 A digital meter used to test the continuity of a light bulb.

with the incorrect polarity, the internal circuitry of the meter will automatically make the correction.

3. **Sample and hold**, which will latch the most recent reading for examination after the instrument is removed from the circuit under test.

4. **Current-limited tests** for voltage drop across semiconductor junctions. This feature allows the user to test diodes and a variety of transistor types. This is also referred to as **a semiconductor test function**.

5. A **graphic representation** feature uses a bar graph display to show a more specific image of the signal being tested.

Safety Precautions

Whether you are using an analog meter or a digital meter, always follow the manufacturer's safety instructions for the test equipment and the equipment being tested. Always check your meter test leads to ensure that their insulation is in good condition. Be extremely cautious when testing high-voltage or high-current circuits, and connect and disconnect test leads with the circuit's power turned off. Always disconnect the *hot* (red) test lead first, and connect the hot lead last. Never test any circuit while standing in water or wearing wet shoes and clothes. Large metallic jewelry can easily create a short circuit. Be careful with metal watchbands, bracelets, rings, and necklaces; if connected between + and − voltages, they can quickly heat up and cause severe burns. Don't assume anything; always double-check to make sure the voltage is off. Never work alone.

Frequency Counters

When testing circuits, it is often important to know the frequency of the alternating current. **Frequency counters** are instruments used to "count" the electrical pulses of a given voltage. Most frequency counters can measure not only the frequency of an alternating current but also the frequency of a pulsating direct current, a square waveform, or a triangle waveform. Frequency counters are connected in parallel to the circuit being measured. This allows the instrument to monitor the circuit's voltage.

A typical frequency counter will change the incoming waveform into a standard square wave with the same frequency as the input signal. The frequency of the standard wave is then compared with a frequency of known value that is generated by the frequency counter. This comparison allows the instrument to determine the value of the measured frequency.

Some type of time gate circuit must be used in a frequency counter. Since the waveform being measured is constantly changing, the test instrument must measure the input for a given length of time (gate time). Frequency counters therefore measure an average frequency. A typical gate time is 1 s.

THE OSCILLOSCOPE

The oscilloscope is one of the most important measuring instruments used in analyzing complex electronic circuits.

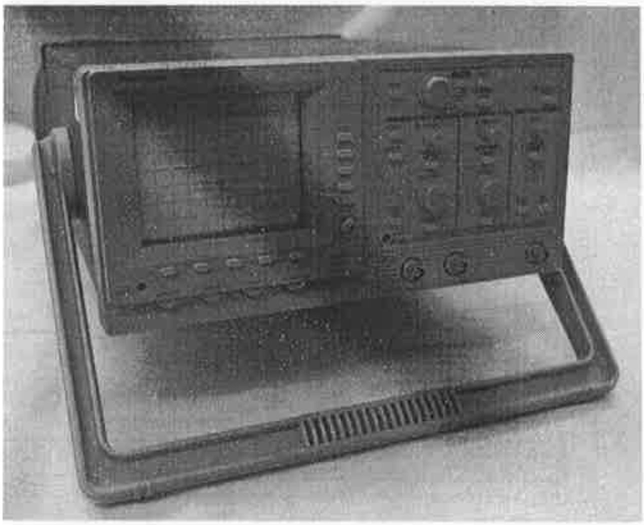


FIGURE 8-26 Typical oscilloscope.

The oscilloscope is a sophisticated voltmeter with a two-dimensional graph display that can be used to measure the voltage (amplitude) and frequency (time) of an electrical signal. This allows the operator to view voltage or frequency changes over time; therefore, either a constant or a changing signal can be measured. With a multitrace oscilloscope, it is possible to compare two separate signals. An oscilloscope is typically used to analyze signals that change too fast to be monitored by a common multimeter. Measurement of a rapidly changing signal is often necessary when troubleshooting radio or digital circuitry. A typical oscilloscope is shown in Fig. 8-26.

Most electrical signals can be easily connected to an oscilloscope with either test probes or cables. Nonelectrical phenomena such as sound or temperature can be measured by using specialized probes which contain **transducers**. A transducer is a calibrated device that measures one form of energy and converts it into a voltage. A microphone is a type of transducer that converts sound waves into electrical signals. Examples of various waveforms on an oscilloscope screen are shown in Fig. 8-27.

The general purpose of a typical oscilloscope is to measure an electrical signal, analyze that signal, and use processor circuitry to convert the information into an image that can be viewed by the technician. The image must be a graphical representation of the electrical signal being measured. This becomes a relatively complex task because the oscilloscope is capable of measuring a wide range of electrical signals. The functional blocks of a typical oscilloscope are shown in Fig. 8-28. Here it can be seen that an oscilloscope **probe** is often used for connection to the circuit being measured. The input block may contain protection circuitry, amplifiers, and signal reduction (attenuation) circuitry. The **vertical section** controls the voltage level (vertical axis) shown on the oscilloscope display, and the **horizontal section** controls the time value (horizontal axis) shown on the oscilloscope display. The **trigger section** is used to synchronize the signal in order to create a steady display. This is needed because the scope can measure such a

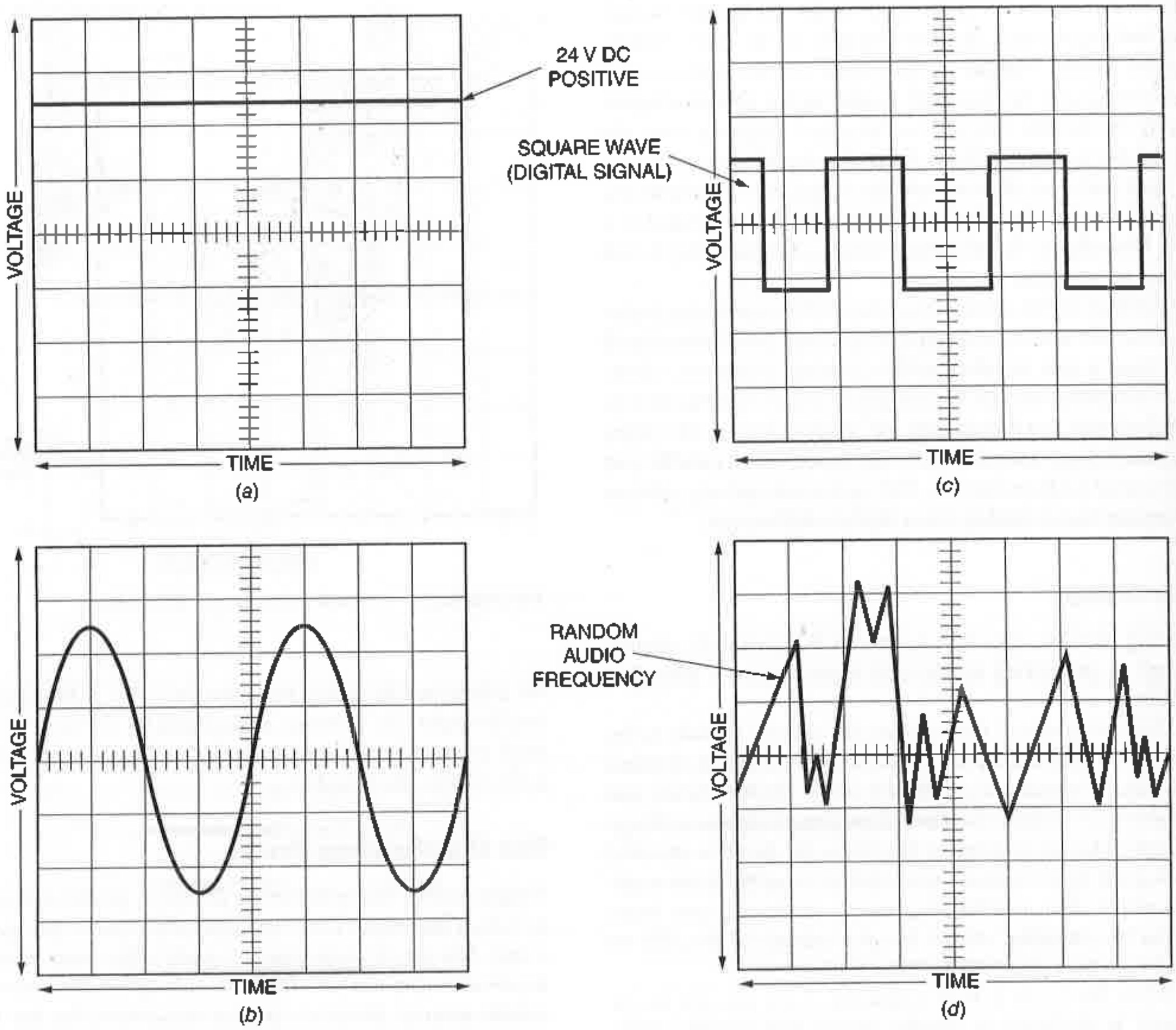


FIGURE 8-27 Various waveforms shown on an oscilloscope screen: (*a*) positive 24 V dc; (*b*) ac sine wave; (*c*) square wave for a digital signal; (*d*) audio frequency sound wave.

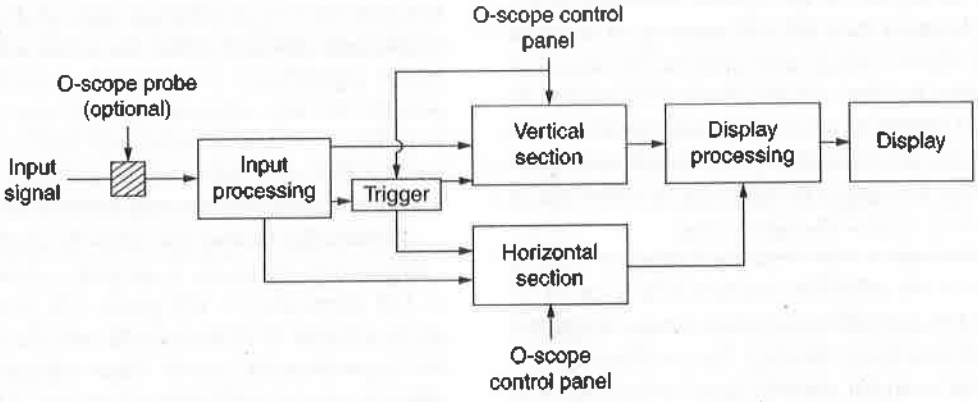


FIGURE 8-28 Diagram of the basic functional blocks of an oscilloscope.

wide range of dynamic signals; some stable, some unstable. The information is eventually sent to an output processor which performs any conversion needed to "paint the picture" on the oscilloscope display. The two common displays for an oscilloscope are the cathode ray tube (CRT) and the flat panel liquid crystal display (LCD).

Oscilloscope categories

Oscilloscopes are often categorized by the circuitry used to process the waveform information. **Analog oscilloscopes** utilize analog circuitry for process and display of the input signal and typically have a CRT display. Analog oscilloscopes were very popular until the early 2000s, when most technical and engineering facilities changed to the more modern digital scopes. **Digital oscilloscopes** employ microprocessor circuitry for analysis and display of the electrical signal being monitored. Digital oscilloscopes typically have the capability to process higher frequency signals than do analog scopes, and typically can hold the values of a waveform in a digital memory for display at a later time or download to a PC. Virtually all digital scopes utilize a flat panel LCD, and many are portable.

Another recent advancement in oscilloscope technologies consists of a specialized signal acquisition circuit board used to create a user interface with a personal computer, tablet-type computer, or even a smart phone. Some of these devices are designed as a circuit card for addition to your PC; some are stand-alone and connect to the device with a parallel port or external USB connection. This option can turn any modern computer-based display into a digital oscilloscope.

The Display

Analog oscilloscopes that utilize a CRT create the display image by projecting an electron beam against a phosphor screen.

The movement of the beam on the screen is produced by two sets of deflection plates inside the CRT; one set of plates controls the horizontal movement of the electron beam, and the other set controls the vertical movement. When a voltage is applied to one or more of the plates, the beam is attracted toward the positive plates and repelled away from the negative plates. The resulting movement of the electron beam across the phosphor screen leaves a tracing of the path on the screen for a short time.

When the beam is held stationary, a dot appears on the screen. If the beam is rapidly moved horizontally across the screen, a **sweep** line appears. If a signal or voltage to be measured is applied to the input of the oscilloscope, then it will indirectly be applied to the vertical deflection plates of the CRT. The beam of the CRT will move up or down on the screen as the signal voltage goes positive (increases) or negative (decreases) in value. As the signal goes positive in voltage, the beam moves upward on the screen, and as the signal goes negative, the beam moves downward. Any signal that varies in voltage will appear as some type of waveform on the screen, depending on how the signal varies.

The LCD has become a very common display on modern oscilloscopes due to the reliability and low cost of the LCD. In general, both LCD and CRT scopes have similar functional characteristics and operations circuitry. The oscilloscope processor must output a digital control signal containing both vertical and horizontal data to the LCD. The LCD then converts those digital signals to an image of the electrical signal being measured by the oscilloscope. Greater detail of the operation of LCDs is discussed in Chap. 6 of this text.

The graticule is the grid of lines, with the major divisions spaced at 1-cm intervals. The graticule is typically painted on the face of the CRT or on a faceplate that is then installed on the LCD or CRT display. The graticule is used as a reference for voltage and frequency measurements (Fig. 8-29). On some oscilloscopes, the graticule is displayed by the LCD or CRT itself as part of the image produced. In this case, there is no need of graticule faceplate.

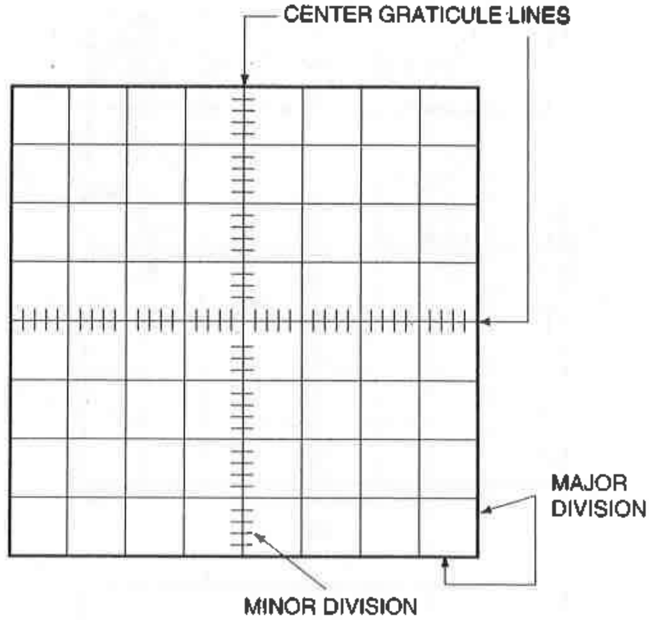


FIGURE 8-29 A typical oscilloscope graticule.

The Oscilloscope Probe

Simply defined the **oscilloscope probe** (or **probe**) is a means by which the circuit to be tested is connected to the oscilloscope. The use of open-wire test leads (like those found on a typical multimeter) are likely to pick up interference from outside sources; therefore, they are not suitable for low-level signals. Open-wire test leads also have a high inductance and are not adequate for measurement of high frequencies. Using an oscilloscope probe connected with a shielded cable test lead will help to eliminate these problems. Coaxial cable (a specialty shielded cable) has lower inductance, but it has higher capacitance; consequently, a probe is used to compensate for any mismatch in inductance, capacitance, or impedance. A typical probe will load a circuit being measured with a capacitance of about 110 pF and a resistance of 1 MΩ. A typical oscilloscope probe is shown in Fig. 8-30.

To minimize loading and allow the oscilloscope to measure a larger range of signals, some probes contain a switch for 1X or 10X attenuation. A **10X probe** will attenuate the input signal by a factor of 10 through the use of a high-resistance and low-capacitance RC circuit. Other value probes are also available for certain applications; however, 1X and 10X probes are the most common. The coaxial cable, which connects the probe to the oscilloscope, must be of certain value impedance, and therefore its design and length are critical.

There are special high-voltage probes which are physically larger than a common low voltage probe. Current probes are also available which utilize an inductive pickup and do not require a direct connection to the circuit being measured. An inductive pick-up requires that the wire be

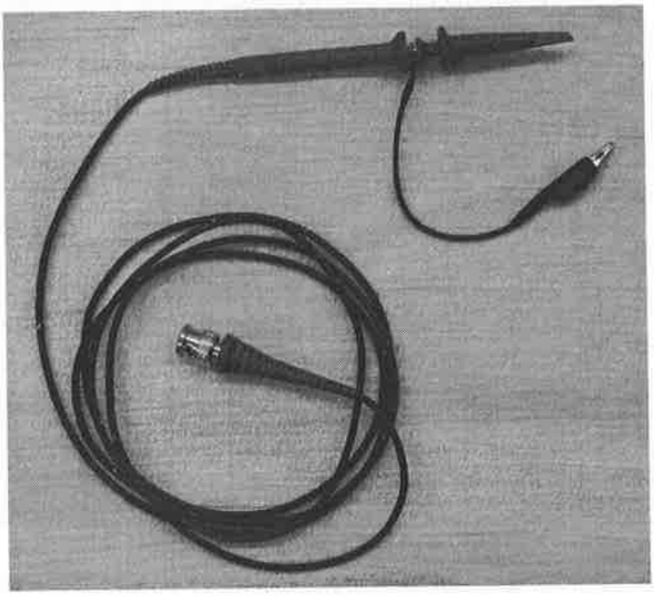


FIGURE 8-30 A typical oscilloscope probe.

passed through a hole in the probe. The process of electromagnetic induction is then used to transfer the measured signal to the probe. This type of probe can only be used for testing alternating current or voltage.

The Vertical Section

The display represents an electrical signal as a waveform. The vertical displacement of the electrical signal is called the ***y axis*** and represents the voltage level of the waveform being measured. The waveform's change over time is represented horizontally on the LCD or CRT and is called the ***x axis***. The vertical control section for the oscilloscope supplies the information for the y-axis display. On CRT oscilloscopes the input signals are converted into deflection voltages that are used by the display section to deflect the electron beam. On LCD scopes, the vertical information is sent to the LCD processor circuit. The vertical section also provides internal signals for the trigger section of the oscilloscope.

Triggering is accomplished by synchronizing the sawtooth generator that produces the horizontal sweep with the signal waveform that is being measured. If the sawtooth generator does not start and stop at the same point in time on the signal waveform, then an out-of-synchronization condition will occur. An out-of-sync condition will generate an instable display. This will create multiple waveforms on top of each other or the signal will appear as a moving waveform. In order to synchronize the sawtooth generator with the input signal, a **trigger pulse** is applied to the sawtooth generator. The trigger pulse can come from the vertical section or from an external source.

The Horizontal Section

The horizontal processor function controls the horizontal sweep rate and allows the operator to choose the amount of input signal to be displayed. The horizontal section contains a sweep generator that produces a sawtooth waveform, or ramp, that is used to control the scope's sweep rates. The sweep generator is calibrated in time and often called the **time base**. By adjusting the **sweep time**, or rate at which the image moves horizontally across the display, it is possible to choose the amount of input signal viewed by the operator. The sweep time value must also be known in order to determine the frequency of the measured signal. Most modern scopes will allow the operator a manual adjustment of the horizontal sweep rate as well as an automatic feature that will set the sweep rate to best measure the incoming signal.

The Trigger Section

The oscilloscope draws a waveform on the LCD or CRT using information from the vertical and horizontal processor sections, which provide reference signals. The trigger section determines when the oscilloscope should start to "draw" the waveform. The waveform shown on the display is constantly being "redrawn." If the oscilloscope did not start to redraw the waveform at the same point each time, the display would not make much sense.

The trigger section ensures a stable display by recognizing a particular voltage point on the input waveform. Once this point is recognized, the sweep generator is activated, and a new waveform is drawn in the correct spot on the display.

Operations and Safety

Specialized instruments are essential in the troubleshooting and testing of electronic circuitry. However, if they are not used properly, great damage can be done to them and/or to the circuitry. Operators of these instruments must make sure they know how the instruments are to be connected, and they must make sure that the voltage to be tested is not above the range of the instrument. They must also be aware of the effects the test instrument has on the circuit itself. It has been pointed out that a common voltmeter will often produce effects that make the readings erroneous. The same can be true for oscilloscopes or other instruments.

Many electronic test instruments have been developed for special purposes. Operators of any instrument must thoroughly understand all operating procedures before connecting the instrument to the circuit. They should always read and be sure they understand the manufacturer's instructions before using any test instrument.

Almost all tests performed with an oscilloscope will be made to a live (hot) circuit. This creates the potential for electric shock or even electrocution. Always take extreme precautions and read all safety materials for the equipment being used or tested. In general, when using an oscilloscope always follow these guidelines: (1) limit any exposure to high voltage. Any value above approximately 100 V is potentially dangerous. (2) When testing inside equipment, be aware of any electrical connections containing high voltage and use caution to avoid these points whenever possible. (3) Whenever possible, tests should be performed at properly insulated work stations which should include an insulating floor pad,

(4) Keep one hand away from the circuitry and electrical grounds at all times. Many technicians work with only one hand and keep the other hand away from any electrical ground. (5) Remember even equipment that is turned off may have hot electrical connections inside the case; unplug or disconnect power to be completely safe. (6) Whenever possible work with someone nearby who can help in case of any emergency. These precautions may save your life; always take extreme caution whenever working with live circuits.

REVIEW QUESTIONS

1. Describe the differences between digital and analog meters.
2. Give three general classifications of electric measuring instruments.
3. Explain the operation of a galvanometer.
4. Describe the d'Arsonval or Weston meter movement.
5. Describe the type of pivot bearing most commonly used in electric instrument movements.
6. Explain a meter sensitivity of 20000 Ω/V.
7. What is the reason for using a very sensitive instrument to test voltages in a circuit?
8. When are meter shunts required?
9. Explain the difference between a meter circuit connected as an ammeter and one connected as a voltmeter.
10. What important precaution must be observed when connecting an ammeter in a circuit?
11. How must a voltmeter be connected with respect to a load in order to determine the voltage applied to the load?
12. What is a common instrument used to measure low-frequency alternating current?
13. Explain the operation of a thermocouple.
14. What are frequency counter instruments used for?
15. What is the function of a wattmeter?
16. What are inductive pickup-type meters?
17. Describe a multimeter.
18. What are some of the advantages of a *digital multimeter*?
19. Explain what safety precautions must be taken when measuring circuits using a multimeter.
20. List and explain the important operations to be performed before connecting a multimeter for a test.
21. What is an oscilloscope?
22. What is the purpose of the trigger circuit in an oscilloscope?
23. What is an oscilloscope probe?

Electric Motors 9

INTRODUCTION

An electric motor is a device that changes electric power to mechanical energy. Electric motors can be classified in many ways; the number of different types of motors is so great, however, that it would be impossible to describe them with simple classifications. Two broad classifications would describe the type of electrical power required to operate a motor: alternating current (AC) or direct current (DC). Typically ac motors are found on large commercial aircraft because these planes employ ac generators and an adequate supply of power. For the most part, dc motors are found on light aircraft which have dc generators and a dc power distribution system. Another type of motor which has been recently developed requires a computer control circuitry. These motors often use high-strength permanent magnets and a microprocessor to control multiple electrical windings. DC motors are described in part by the type of internal winding they have. There are **series-wound, shunt-wound,** and **compound-wound** motors, named according to the relationship between the field coil connections and the armature winding. Motors of all types are usually rated according to horsepower. Usually, the data plate will also show the voltage and amperage. Additional information on dc motors include rpm, type of duty, and some other points descriptive of the motor design.

AC motors are classified according to horsepower, phase, operating frequency, and type of construction. Usually, the power factor is also stated. In any event, all the characteristics of a motor must be considered in making a selection for a particular duty.

Electric motors are used in aircraft and spacecraft for many purposes. Among the many units and systems requiring electric motors are engine starters, controls valves, landing gear, flaps, trim tab, flight controls, servos, fuel pumps, hydraulic pumps, vacuum pumps, gyrostabilizing units, and navigation devices. It is not intended that this text cover the details of all electric motors, but a thorough explanation of motor theory and functions will be given. This should enable the student to gain an understanding of any motor installation found on modern aerospace vehicles.

MOTOR THEORY

Magnetic Attraction and Repulsion

The function of an electric motor is to change electrical energy into mechanical energy. The electrical energy is input to the motor as either alternating or direct current and the mechanical energy output creates a rotational force, or torque. All electric motors found on aircraft operate on the principle of magnetic attraction and repulsion. Through the study of magnetism it is known that *like* magnetic poles repel each other and *unlike* magnetic poles attract each other. Figure 9-1 shows the basic

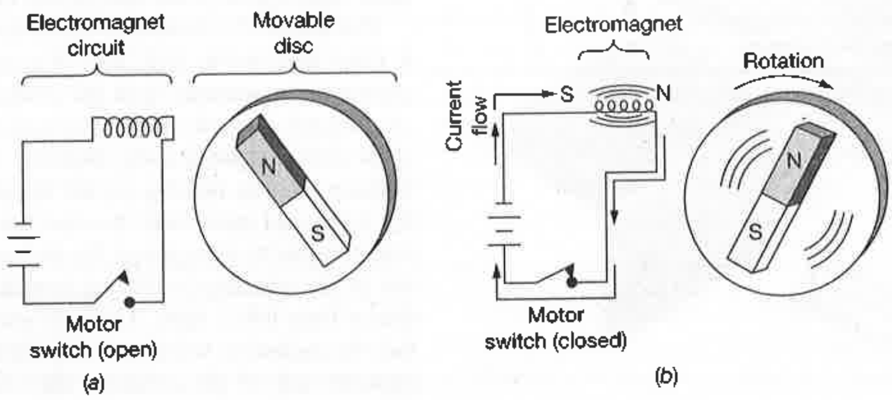


FIGURE 9-1 Operating principles of an electric motor: (a) switch open/no current flow/no rotation, (b) switch closed/current flow/rotation.

operating principles of all electric motors. In this example, a coil of wire is mounted near a disk that can easily rotate; on the disk is mounted a permanent magnet. The coil is placed near the north pole of a permanent magnet (Fig. 9-1*a*). If the switch is closed, current will flow through the coil creating an electromagnet. The coil is designed so the force of the electromagnet opposes the force of the permanent magnet; the two north poles repel. Therefore, when the switch is closed and the motor turned on, a torque is produced and the disk will rotate. Of course the rotation of this simple motor will stop when the south pole of the permanent magnet aligns with the north pole of the stationary electromagnet. Although not practical, this example does represent the basic operating principles of all electric motors.

Another principle that defines the operation of a typical motor is the fact that any conductor which carries current will produce a magnetic field. If this conductor is placed within another magnetic field as shown in Fig. 9-2, the conductor will move due to the interaction of the electromagnetic and magnetic fields. When designing a motor it becomes very important to know the relationships between the direction of current flow and the polarity of a magnetic field.

The direction in which a current-carrying conductor in a magnetic field tends to move may be determined by the use of the **right-hand motor rule**. This rule is applied as follows: *Extend the thumb, index finger, and middle finger of the right hand so that they are at right angles to one another, as shown in Fig. 9-3. Turn the hand so that the index finger points in the direction of the magnetic flux and the middle finger points in the direction of the current flowing in the conductor. The thumb will then point in the direction of the conductor movement.*

Any coil of wire will have magnetic polarity when a current is passed through it. If a soft-iron core is placed in the coil, the result is an electromagnet. In this example the field, or field magnet, is a stationary permanent magnet and the armature is the rotating permanent magnet. If this electromagnet is placed between the poles of a field magnet and is free to rotate, the flux of the electromagnet will react with the flux of the

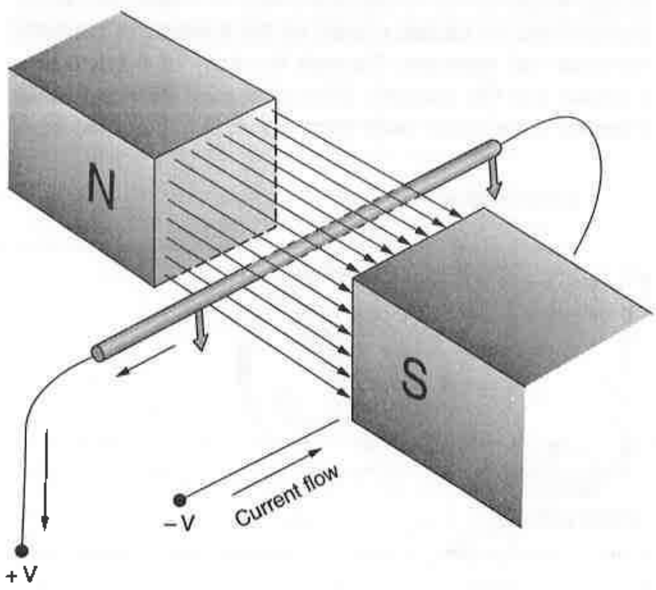


FIGURE 9-2 Current-carrying conductor in a magnetic field.

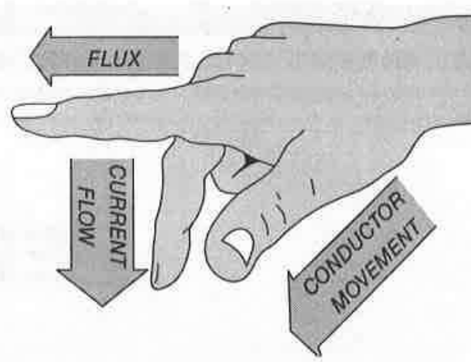


FIGURE 9-3 Right-hand motor rule.

field magnet and produce torque will cause the electromagnet to turn (see Fig. 9-4*a*). The north pole of the electromagnet is attracted by the south pole of the field magnet and repelled by the north pole. The electromagnet will continue to rotate until it is lined up with the field. At this point, it would naturally stop because the conditions of repulsion and attraction would be satisfied. In an electric motor, however, the armature polarity is reversed through the action of the **commutator**. The commutator is a switching device that reverses the connections to the armature coil (see Fig. 9-4*b*). It will be noted that the flux reversal takes place just before the armature becomes aligned with the field, thus causing the armature to continue to rotate as it attempts to line up with the new conditions (Fig. 9-4*c*). The flux reversal in the armature takes place each time the armature becomes nearly aligned; hence it continues to rotate for as long as electric energy is applied.

A simple motor of the type described above does not deliver a smooth flow of power, because the torque is high when the armature is at right angles to the field poles. There is also no torque at the moment the armature is in line with the field poles. In order to have the motor deliver smooth power, the armature is provided with additional coils so that there will always be a high torque. Figure 9-5 shows a motor with four armature poles. With this arrangement, the torque on one set of poles will increase as the torque on the other set decreases, and the motor will deliver a reasonably smooth power output. The addition of more coils will provide still smoother power. If the motor had four field poles, the sides of the armature coils would be spaced a distance of one-fourth the circumference of the armature. Most modern motors will contain four or more poles.

The action of a drum-wound armature in a magnetic field is illustrated in Fig. 9-6. This diagram represents a cross section of an armature with the conductors in the armature slots shown as small circles. The cross in a small circle indicates current flowing away from the observer, and the dot indicates current flowing toward the observer. By applying the right-hand motor rule, the direction of the torque on the armature can be determined. For example, the current on the left of the armature is flowing into the page, and the field flux is from left to right. The right-hand rule then indicates that the conductor would move up through the field. On the opposite side of the armature, the conductor would move down through the field, and the armature would turn in a clockwise direction.

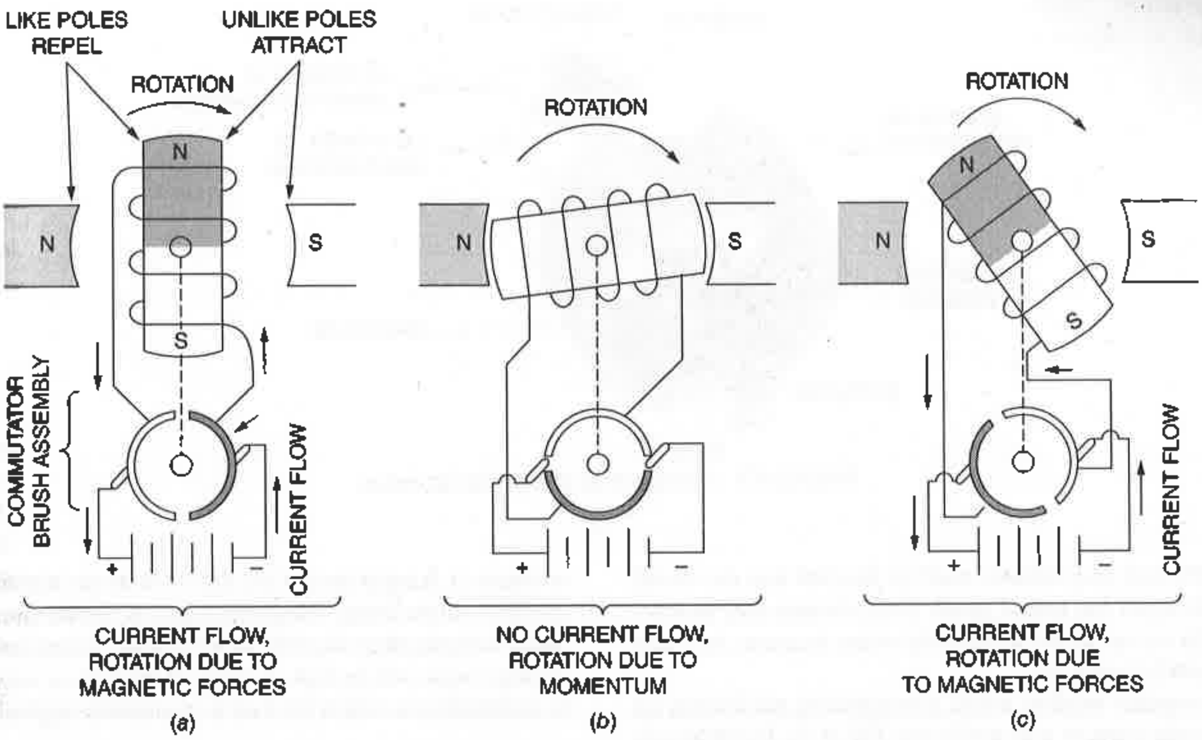


FIGURE 9-4 Principle of the dc motor.

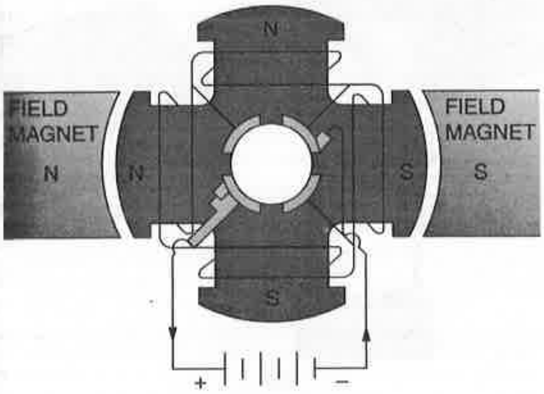


FIGURE 9-5 DC motor with a four-pole armature.

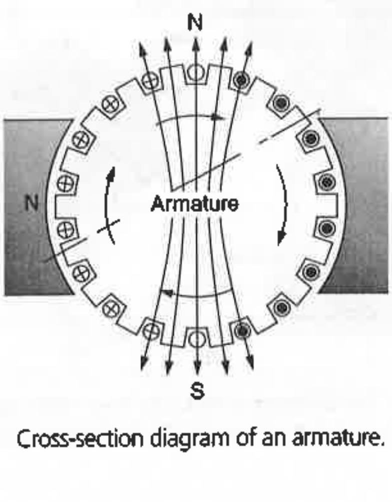


FIGURE 9-6 Cross-section diagram of an armature.

The action of the commutator continually switches the input current to new sections of the armature winding so that the top of the armature is always a north pole; hence, the armature continues to rotate in an effort to align itself with the field poles.

Counter EMF and Net EMF

It has been pointed out in previous discussions that a conductor moving across a magnetic field will have an emf induced within itself. Since the conductors in the armature of a motor are cutting across a magnetic field as the armature rotates, an emf is produced in the conductors. This induced emf opposes the current being applied to the armature from the outside source. This induced voltage is called **counter emf**, and it acts to reduce the amount of current flowing in the armature. The **net emf** is the difference between the applied emf and the counter emf.

Counter emf plays a large part in the design of a motor. Motors must be designed to operate efficiently on the net emf, which is only a fraction of the applied emf; hence, the resistance of the armature coils must be relatively low. Before a motor gains speed, the current through the armature is determined by the applied emf and the armature resistance. Since the armature resistance is low, the current is very high. As the speed of the motor increases, the counter emf builds up and opposes the applied emf, thus reducing the current flow through the armature. This explains the facts that there is a large surge of current when a motor is first started and that the current then rapidly falls off to a fraction of its initial value.

With some electric motor installations, the starting current is so high that it would overheat and damage the wiring or the

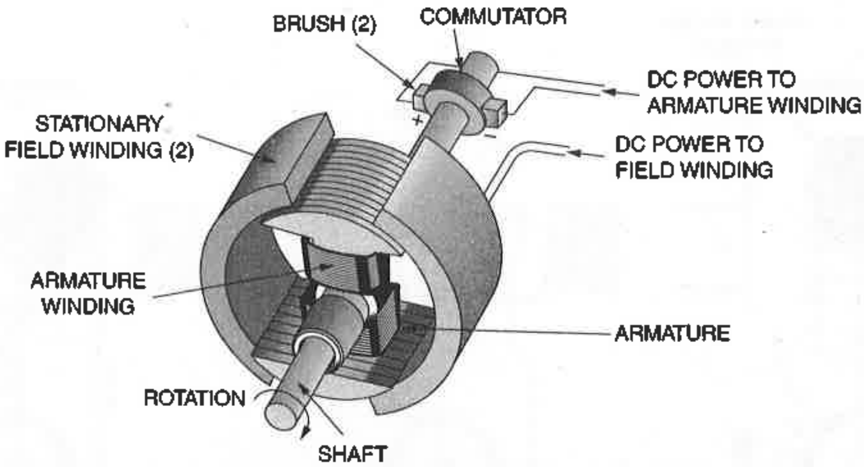


FIGURE 9-7 Components of a simple dc motor.

armature, and so resistance must be inserted into the circuit until the motor has gained speed. The resistance may be automatically cut out as the speed of the motor increases, or it may be controlled manually.

An armature winding, a field, a commutator, and brushes are all essential parts of a dc motor (see Fig. 9-7). The field may be produced by a permanent magnet or by an electromagnet. The electromagnetic field is almost always employed because such a field lends itself to a wide range of operation. The armature receives current through the commutator and brushes and becomes an electromagnet. The magnetic forces of the armature and field interact to produce a rotational force.

Types and Characteristics of DC Motors

A variety of dc motors are found on most modern aircraft. For example, the dc starter motor is used on virtually all aircraft except some antique and large commercial planes. There is a wide variety of dc motors; however, they each share one commonality: there must be at least two magnetic fields in each motor. One magnetic field is the **stator** (or stationary component) and one magnet is the **rotor** (the rotating component). DC motors can be constructed with one permanent magnet and one electromagnet; these are called **permanent magnet motors**. These motors are simple in design; however, they are generally low power. The permanent magnet is typically designed as the stator of the motor. DC motors can also be designed with an electromagnet for both the rotor and the stator; these motors are called **electromagnet motors**. Since they produce the most torque and horsepower, electromagnet dc motors are by far the most common on a typical aircraft. Figure 9-8 shows the basic difference between a permanent magnet motor and an electromagnet motor.

Three common electromagnet dc motors are series-wound, shunt-wound, or compound-wound, depending on the arrangement of the field windings with respect to the armature circuit (see Fig. 9-9).

In a **series motor**, the field coils are connected in series with the armature, as shown in Fig. 9-9*a*. Since all the current used by the motor must flow through both the field and the armature, it is apparent that the flux of both the armature and the field will be strong. The greatest flow of current through the motor will take place when the motor is being started; hence, the starting torque will be high. A motor of this type is very useful in installations in which the load is continually applied to the

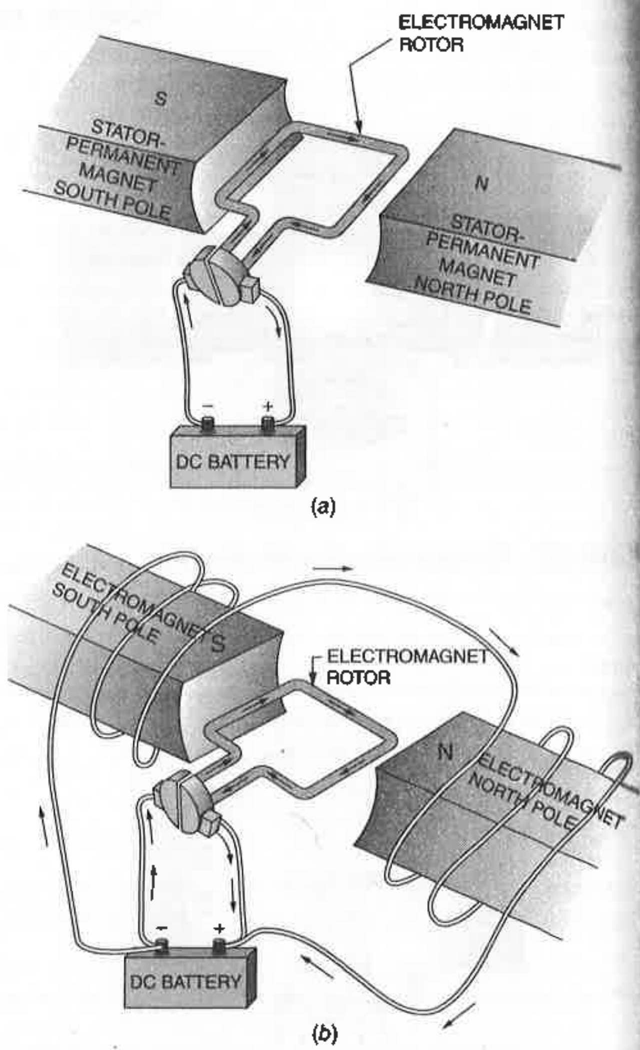


FIGURE 9-8 The difference between two motor types: (*a*) permenant magnet motor, (*b*) electromagnet motor.

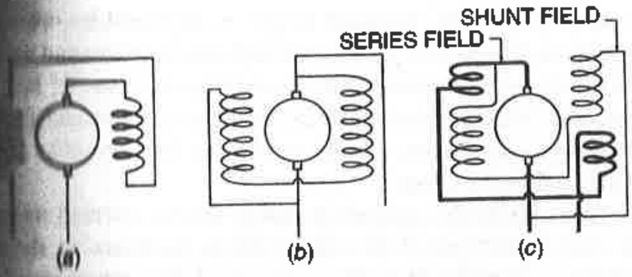


FIGURE 9-9 Schematic diagrams of different types of dc motors: (*a*) series wound, (*b*) shunt wound (parallel), (*c*) compound wound.

motor and in which the load is heavy when the motor starts. In aircraft, series motors are used to operate engine starters, landing gear, and similar equipment. In each case, the motor must start with a fairly heavy load; the high starting torque of the series motor is particularly well suited to this condition.

If a **series** motor is not connected mechanically to a load, the speed of the motor will continue to increase for as long as the counter emf is substantially below the applied emf. The speed may increase far above the normal operating speed of the motor, and this may result in the armature flying apart because of the centrifugal force developed by the rapid rotation. A series motor should always be connected mechanically to a load to prevent it from "running away."

The reason for the increase in speed when a series motor is not driving a load can be understood if the behavior of the field in such a motor is considered. As the speed of the motor increases, the counter emf increases. As the counter emf increases, however, the field current decreases. Remember that the field is in series with the armature and that since the counter emf causes the armature current to decrease, it must necessarily cause a decrease in the field current. This weakens the field so that the counter emf cannot build up sufficiently to oppose the applied voltage. A current continues to flow through both the armature and the field, and the resulting torque increases the armature speed still further.

In a **shunt motor** the field coils are connected in parallel with the armature (see Fig. 9-9*b*). The shunt motor is often called a parallel wound motor. The shunt field coil must have sufficient resistance to limit the field current to that required for normal operation because the counter emf of the armature will not act to reduce the field current. Since the voltage applied to the field at operating speed will be practically the same as the voltage applied to the motor as a whole, regardless of counter emf, the resistance of the field must be many times the resistance of the armature. This is usually accomplished by winding the field coils with many turns of fine wire. The result of this arrangement is that the motor will have a low starting torque because of a weak field.

As the armature of a shunt motor gains in speed, the armature current will decrease because of counter emf, and the field current will increase. This will cause a corresponding increase in torque until the counter emf is almost equal to the applied emf, at which time the motor is operating at its normal speed. This speed is almost constant for all reasonable loads.

When a load is applied to a shunt motor, there is **a slight** reduction in speed. This causes the counter emf to decrease and the net emf across the armature to increase.

Since the resistance of the armature is low, a slight rise in net emf will cause a comparatively large increase in armature current, which in turn increases the torque. This prevents a further decrease in speed and actually holds the speed to a point only slightly less than the no-load speed. The current flow increases to a level sufficient to hold the speed against the increased load. Because of the ability of the shunt motor to maintain an almost constant speed under a variety of loads, it is often called a **constant-speed motor**.

Shunt motors are used when the load is small at the start and increases as the motor speed increases. Typical loads of this type are electric fans, centrifugal pumps, and fuel boost pumps.

When a motor has both a series field and a parallel field (Fig. 9-9*c*), it is called a **compound motor**. This type of motor combines the features of series and shunt motors; that is, it has a strong starting torque like the series motor but will not overspeed when the load is light. This is because the shunt winding maintains a field that allows the counter emf to increase sufficiently to balance the applied emf. When the load on a compound motor is increased, the speed of the motor will decrease more than it does in a shunt motor, but the compound motor provides speed that is sufficiently constant for many practical applications.

Compound motors are used to operate machines subject to a wide variety of loads. In aircraft they are used to drive hydraulic pumps, which may operate from a no-load condition to a maximum-load condition. Neither a shunt motor nor a series motor would satisfactorily fulfill these requirements.

Brushless DC Motors

The three motors just described, **series**, **shunt**, and **compound**, each use a set of contacts called **brushes** to make the electrical connections to the rotating electromagnet. The brushes ride on a contact called the commutator as will be described later. There are disadvantages to brushes; first and foremost they wear out and must be replaced periodically; also brushes often arc or create sparks that can disturb nearby sensitive electronics equipment or radio circuits. Some modern dc motors are designed without brushes; these are called **brushless dc motors**. In this motor, the mechanical "rotating switch" or brush/commutator assembly is replaced by an external electronic switch synchronized to the rotor's position. Brushless motors are typically 85 to 90 percent efficient or more, whereas dc motors with brush/commutator arrangements are typically 75 to 80 percent efficient.

The brushless dc motor uses a permanent magnet external rotor and a three phase electromagnet used as the driving coils. Some type of position sensor(s) is needed along with a control circuit to activate the three electromagnets. The sensors are used to determine the position of the rotor and associated stationary electromagnets. The stator coils are activated, one phase after the other, controlled by the electronics as cued by the sensors.

Modern dc brushless motors range in power from a fraction of a watt to many kilowatts. Larger brushless motors up to about 100 kW rating are used in electric vehicles. Brushless dc motors are commonly used where precise speed control is necessary; they have several advantages over conventional motors and they are as follows:

Compared to most motors, they are very efficient, running much cooler which leads to much-improved motor life.

Without a commutator to wear out, the life of a dc brushless motor can be significantly longer compared to a dc motor using brushes and a commutator. Commutation also tends to cause a great deal of electrical and RF noise; without a commutator or brushes, a brushless motor may be used in electrically sensitive devices like audio equipment or computer equipment.

The motor sensors that provide rotor location information can also provide a convenient tachometer signal for closed-loop control applications. The tachometer signal can be used to derive an "OK" signal as well as provide running speed feedback.

The motor can be easily synchronized to an internal or external clock, leading to precise speed control.

Brushless motors have virtually no chance of creating a spark, unlike brushed motors, making them better suited to environments with volatile chemicals and fuels.

They are also acoustically very quiet motors which is an advantage if being used in equipment that is affected by vibrations.

Another type of brushless motor has no permanent magnets, and the rotor has no electric current flows. Known as **switched reluctance motor (SRM)**, the torque comes from a slight misalignment of the magnetic poles of the rotor with poles of the stator. The stator is fed direct current through an electronic control circuit. The rotor aligns itself with the magnetic field of the stator, while the stator windings are sequentially energized. The magnetic flux created by the stator windings follows the path of least magnetic reluctance; therefore, flux will flow through the closest pole. Through precise alignment of the stator and rotor poles, the magnetic flux travels from the stator into the rotor pole and creates torque. As the rotor turns, different windings will be energized, keeping the rotor turning. This is done by switching the poles on and off at the right time using an electronic control circuit.

MOTOR CONSTRUCTION

Characteristics of Aircraft Electric Motors

The power-to-weight ratio of aircraft electric motors must be high; that is, a small motor must deliver a maximum amount of power for a minimum of weight. A commercial motor may weigh as much as 100 lb/hp [60.8 kg/kW], but for aircraft purposes there are motors that weigh less than 5 lb/hp [3 kg/kW]. Reduced weight is attained by operating the motors at high speeds and high frequencies and with relatively high currents. This necessitates the use of heat-resistant insulation and enamels in the armature and field windings and perhaps ram air or cooling fans to help dissipate the motor's heat.

Some fractional-horsepower motors used in aircraft rotate at over 40 000 rpm [4138 rad/s] with no load and at about 20 000 rpm [2069 rad/s] with a normal load. Since horsepower means the rate of doing work, it is apparent that a motor turning at 20 000 rpm develops twice the power of a similar motor turning at 10 000 rpm [1035 rad/s]. To reduce the effect of centrifugal force on the armature of the motor rotating at a very high speed, the armature diameter is made to be relatively small compared with its length.

Continuous- and Intermittent-Duty Motors

Many electric motors used in aircraft are not required to operate continuously. Because the heat developed in a short time is not sufficient to cause any damage, a motor in this type of service is designed to deliver more power for its weight than a motor used for continuous service. If such a motor were used continuously, it would overheat and burn the insulation and thus become useless. Motors designed for short periods of operation are called *intermittent-duty motors,* and those that operate continuously are called *continuous-duty motors.* The type of duty for which a motor is designed is sometimes stated on the nameplate, and if it is not on the nameplate, the type of duty can be found in the manufacturer's specifications.

Reversible DC Motors

On light aircraft, motors used for the operation of landing gear, flaps, cowl flaps, and other applications must be designed to operate in either direction and are therefore called **reversible motors**. Reversible 28-V dc motors are also found on transport-category aircraft; they are used for controlling various fuel and hydraulic valve assemblies.

The voltage polarity applied to the field and armature windings of any motor will determine that motor's direction of rotation (clockwise or counterclockwise). To reverse the rotation of a dc motor containing an electromagnetic field, the polarity of the voltage applied to the field or the armature must be reversed. This will reverse the magnetic field of one of the two coils and change an attractive force into a repulsive force (or vice versa), hence reversing the motor's rotation. Reversing a motor by this method would require a complex external circuit such as that illustrated in Fig. 9-10.

Another method to reuse a dc motor provides a double field winding known as a **split field**. A schematic diagram of the circuit for a split-field motor is shown in Fig. 9-11. Note that a separate circuit is provided for each field winding. This makes it possible to change the direction of the motor at will by placing the switch in the desired position. The motor is reversed by changing field polarity in relation to the armature polarity when the different field windings are energized.

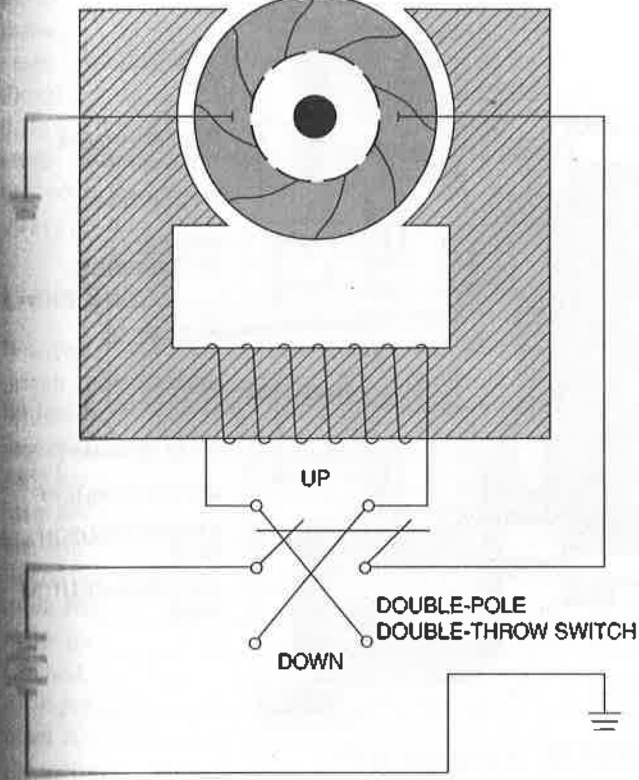


FIGURE 9-10 Reversing a dc motor with external switching.

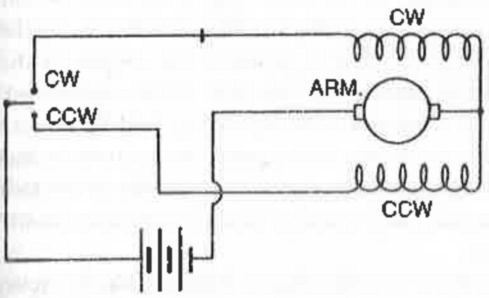


FIGURE 9-11 Circuit schematic for a reversible motor with two field windings.

The separate field coils of a reversible motor are usually wound either in opposite directions on the same pole or on alternate poles. Since the field coils are in series with the armature, they must be wound with wire of a size large enough to carry the entire motor current. Remember that the entire load current passes through both the field and the armature.

The brushes in a reversible motor are usually held in box-type holders in line with the center of the motor shaft. With this arrangement the brushes are perpendicular to a plane tangent to the commutator at the point of brush contact, and the brushes will wear evenly regardless of the direction of motor rotation. On small motors the field and brush housing is sometimes made in one piece. The brush holders are inserted through openings at the end of the housing and are insulated from the housing by composition bushings. Each brush assembly consists of the brush, a helical spring, a flexible connector inside

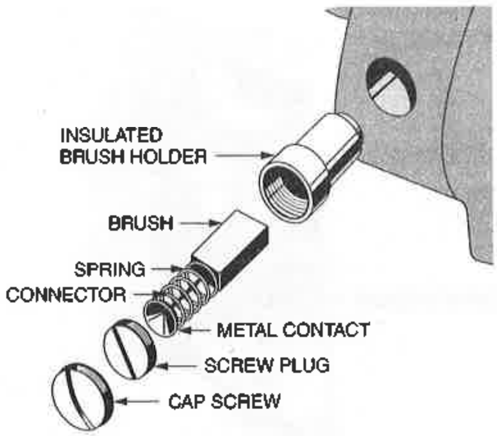


FIGURE 9-12 Brush and holder assembly for a small motor.

the spring, and a metal contact. When a brush is installed in the motor, it is held in place by a screw plug (see Fig. 9-12).

On some light-duty dc motors the field coil is replaced by a permanent magnet. To reverse the rotation of this type of motor, one need only reverse the polarity of the applied voltage. This will reverse the magnetic field of the armature (not the field); therefore, the motor will reverse its direction of rotation. Permanent-magnet reversible motors are commonly used to power light aircraft flap systems.

Reversible dc motors are controlled directly by single-pole double-throw (SPDT) switches or indirectly by relays controlled by similar switches. The use of relays or solenoids is dictated by the amount of current that the motor draws while in operation. Any motor requiring more than 20 to 30 A will typically be controlled (turned on/off) using a relay or a solenoid. A starter motor circuit using a solenoid is shown in Fig. 9-13. Here it can be seen that a small current (1-2 A) is used to turn on the solenoid which in turn sends 200 A to the starter motor. This allows the pilot to operate a small light-duty switch that in turn controls the high-current starter motor.

Brakes and Clutches

Many motor-driven devices used in aircraft must be designed so that the operated mechanism will stop at a precise point. For example, when landing gear is being retracted or extended, it must stop instantly when the operation is complete. If the driving motor is connected directly to the operated mechanism, a great amount of strain will be imposed upon the motor

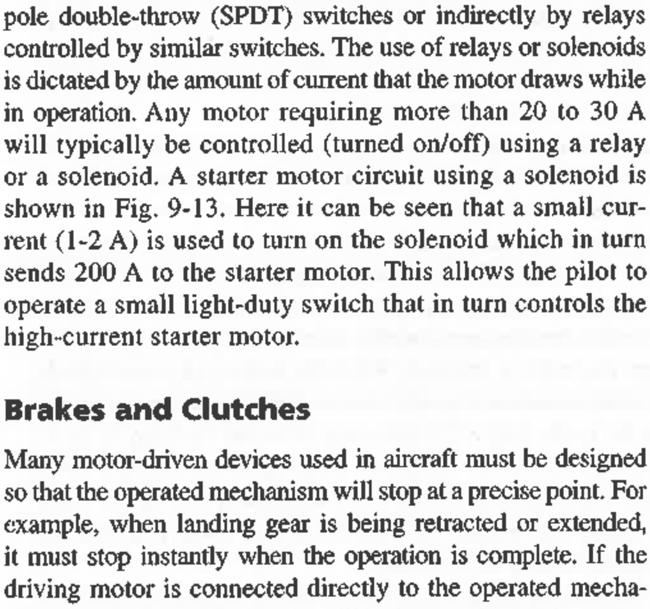


FIGURE 9-13 Solenoid used to control a motor.

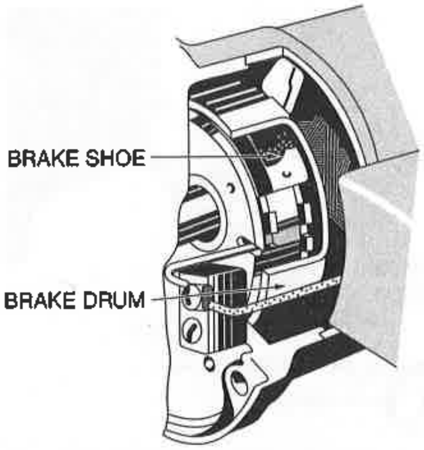


FIGURE 9-14 Drum-type brake.

when the mechanism is forced to stop. This strain is due to the momentum of the armature and other moving parts. In installations requiring an instantaneous stop, a brake and clutch mechanism is employed to prevent damage when the operating mechanism is stopped.

One type of brake mechanism for actuator motors is illustrated in Fig. 9-14. This brake consists of a drum mounted on the armature shaft and internal brake shoes controlled by a magnetizing coil. The coil is placed inside the brake shoes, and when the motor current is turned off, the coil is de-energized and the brake shoes are forced against the drum by spring pressure. Conversely, when the power is turned on, the coil pulls the brake shoes away from the drum.

A disk-type brake, commonly used in actuator motors, consists of a rotating disk mounted on the armature shaft and a cork-lined braking surface on the stationary structure of the motor. A magnetizing coil is used to release the brake when the motor is energized, and a spring engages the brake when the current to the motor is turned off. A small amount of end play is allowed in the armature assembly mounting to provide clearance when the brake is released. When the brake coil is energized, the entire armature assembly moves slightly in a direction such that the brake disk will move away from the braking surface. When the current is turned off, a spring moves the assembly in the opposite direction, and the friction produced between the brake disk and the cork-lined braking surface causes the armature to stop very quickly.

Clutches of several types have been designed for the purpose of disengaging the motor from the load when the power is cut off. All such clutches are engaged by magnetic attraction when the power is turned on and disengaged by spring action. A typical magnetic clutch is shown in Fig. 9-15. Two clutch faces are located within the clutch coil. One of the faces is mounted solidly on the armature shaft, and the other is connected through a diaphragm spring to the drive mechanism. When the clutch coil is energized, the two faces are magnetized with opposite polarities; hence, they are drawn together firmly. The friction thus produced causes the driven mechanism to turn with the motor. When the power is cut off, the diaphragm spring separates the faces, thus disengaging the motor.

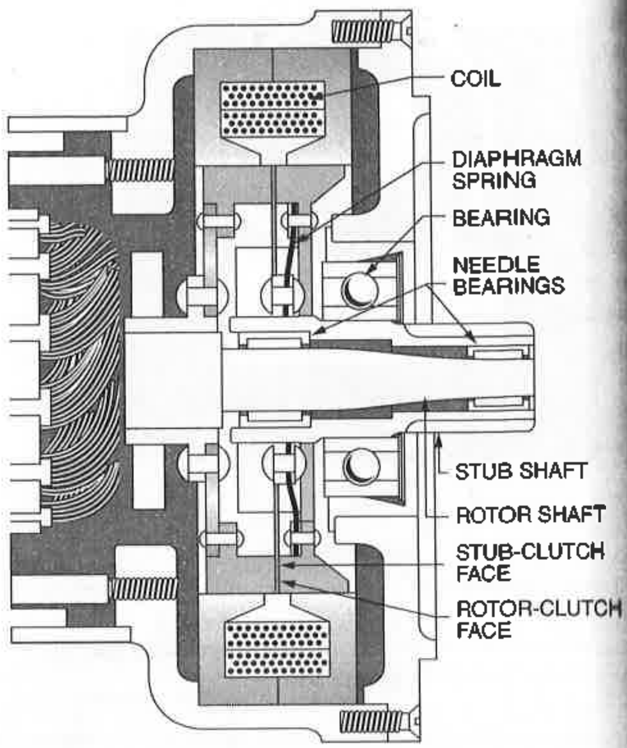


FIGURE 9-15 A magnetic clutch.

Some actuator motors are provided with a combination brake and clutch. A magnetizing coil is located in the end of the motor housing, as shown in Fig. 9-16. This coil, when energized, magnetizes a driving disk attached to the armature shaft. A driven disk is keyed to the output shaft, and when power is turned on, this disk moves against spring pressure until it engages with the driving disk. When the current is cut off, the driven disk is pulled away from the driving disk by the spring and is pressed against the brake plate at the opposite face, thus causing the driven mechanism to stop immediately.

Motors subject to sudden heavy loads are usually equipped with an overload release clutch. A clutch of this type is called a **slip clutch**, and its function is to disconnect the motor from

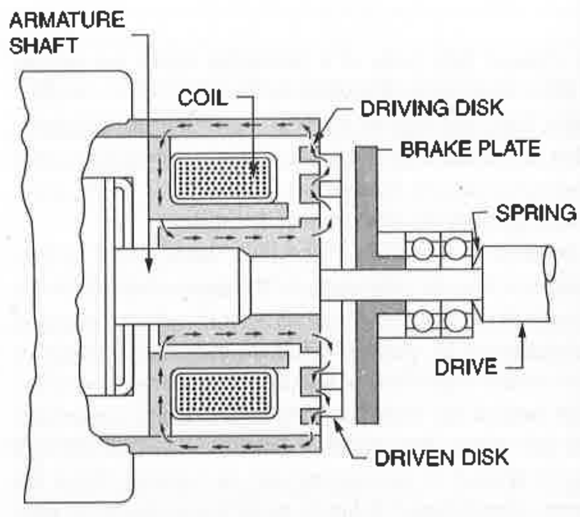


FIGURE 9-16 Brake and clutch assembly.

the driven mechanism when the load is great enough to cause damage. This clutch consists of two groups of disks, alternately arranged, with one group splined to the motor drive and the other group splined to the motor-driven mechanism. These disks are pressed together by one or more springs designed to create sufficient pressure to cause the disks to rotate as one unit when the load is normal. When the load is excessive, the disks slip, thus preventing damage due to excessive torque.

Limit Switches and Protective Devices

Because of the limited distance of travel permitted in the driven mechanism, reversible actuator motors are usually limited in their amount of rotation in each direction. It is essential, therefore, that the motor circuits be provided with switches that will cut off the power when the driven mechanism has reached the limit of its travel. Switches of this type are called **limit switches** and are actuated by cams or levers linked or geared to the driven mechanism. The adjustment of these switches is critical because severe damage may result if the motor continues to run after the limit of operation is reached. Stripped gears and broken shafts are often the result of improperly adjusted limit switches. If the driven mechanism is strong enough to withstand the torque imposed by the motor, the fuse or circuit breaker in the motor circuit will usually cut off the current to the motor.

Adjustment of each of the limit switches is accomplished by running the motor to the limit of travel and then adjusting the switch-actuating mechanism so that it has just opened the switch. The switches should be adjusted to open slightly before the extreme limit is reached.

Some actuator motors are provided with a thermal circuit breaker, or **thermal protector**, which is designed to protect a motor from overload and excessive heat. This device is mounted on the motor frame, and when heat reaches a predetermined limit, the circuit breaker will open and cut off the current to the motor. After the motor has cooled sufficiently, the circuit breaker will automatically close, thus permitting normal operation.

Figure 9-17 is a schematic diagram of a reversible-motor circuit with a thermal protector and a coil for operating the clutch and brake. Both of the limit switches shown in Fig. 9-17 are normally closed. Since they open only when the motor has reached the limit of travel in one direction or the other, it is readily apparent that there will never be a time when both switches are open. Notice that the thermal circuit breaker and the clutch coil are both in the ground (negative) side of the circuit and will therefore be in operation for either direction of travel.

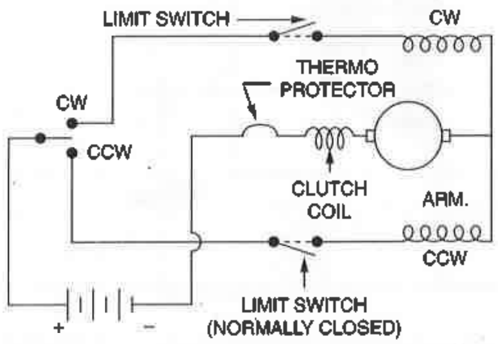


FIGURE 9-17 Schematic diagram of a reversible-motor circuit.

Proximity Sensors and Differential Transducers

Many motors on modern aircraft are controlled by LRUs which analyze a variety of input data, process the information, and send motor activation signals accordingly. This type of motor control system is found extensively on complex high-tech aircraft such as the Gulfstream GV, The Boeing 787, and the Airbus A-380. In an effort to make these aircraft more reliable, designers and engineers have strived to illuminate moving parts that could wear or become misadjusted. On many computerized aircraft, a proximity sensor has replaced the limit switches that have traditionally been used to turn on/off a motor. A **proximity sensor** is a solid-state component, able to detect the presence of nearby objects without any physical contact. Proximity sensors, with the aid of sensitive electronic circuitry, can simply detect when an object comes close enough to active the sensor. The object does not have to make physical contact as with a traditional limit switch. This arrangement creates a more reliable means of detecting position of moving components. The disadvantage of a proximity sensor is that they can only switch very low voltage and current levels; therefore, they must use some type of electronic circuitry for motor control.

A proximity sensor often emits an electromagnetic field or a beam of electromagnetic radiation. The sensor is designed to detect any changes in the magnetic field or return signal. The return signal changes when another object comes in close proximity to the sensor. The object being sensed is often referred to as the proximity sensor's **target**. Different proximity sensor targets demand different sensors. For example, a capacitive photoelectric sensor might be suitable for a plastic target; an inductive proximity sensor always requires a metal target. A common proximity sensor is shown in Fig. 9-18.

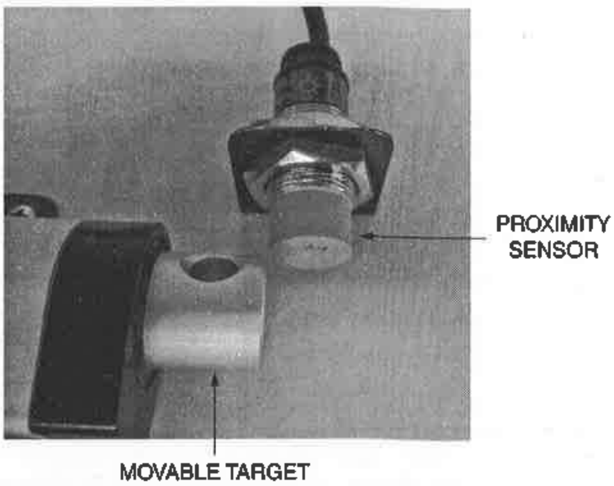


FIGURE 9-18 Proximity sensor and target.

The maximum distance this sensor can detect is defined as the "nominal range." Using the proximity sensor electronic circuit, some sensors can adjust the nominal range. Proximity sensors can have a high reliability and long functional life because of the absence of mechanical parts and lack of physical contact between sensor and the sensed object; for this reason they have become very popular on modern aircraft and aerospace vehicles. Common uses for proximity sensors include position sensing for moving components, such as landing gear, flight controls, air control valves, and cargo door locks.

Another modern sensor used to determine the position of a moving component is called a **differential transducer.** The two common transducers used to measure position are called the **linear variable differential transducer (LVDT)** and the **rotary variable differential transducer (RVDT).** These sensors can detect position of an object as a variable condition; a proximity sensor can only detect one position of an object. The LVDT and RVDT utilize the concepts of electromagnetic induction as found in a common transformer. In a simple form these sensors can be thought of as a transformer with a movable core material.

The linear variable differential transducer has three coils placed end-to-end around a tube as seen in Fig. 9-19. The center coil is the primary winding, and the two outer coils are the top and bottom secondary windings. A cylindrical ferromagnetic core, attached to the object whose position is to be measured, slides along the axis of the tube. An alternating current drives the primary and causes a voltage to be induced into both secondary coils. The ac frequency is usually relatively high, in the range 1 to 10 kHz, to help facilitate the electromagnetic induction and make the transducer more efficient. As the core moves, the primary magnetic linkage to the two secondary coils changes and causes the induced voltages to change. The coils are connected so that the output voltage is the difference (hence differential) between the top secondary voltage and the bottom secondary voltage. When the core is in the exact center position, equal voltages are induced in the two secondary coils, but the two signals are 180° out of phase and therefore cancel each other. The output voltage is theoretically zero whenever the core is centered; this is known as the **null position.** The transducer has the most sensitivity at this point. If the LVDT core is moved toward the top, the induced voltage in the top coil increases and the voltage in the bottom coil decreases. If the core moves in the opposite direction crossing the center null position, a phase shift occurs between the primary and secondary voltages. As the core moves farther from the center position the voltage change increases.

The secondary coil output signals are typically sent to an LRU containing the control circuitry needed to monitor position. The LRU can be programmed to control the motor that is used to move the component and LVDT core. The use of LVDTs and electronic controls has allowed engineers to design a motor circuit that will slow the motor as it approaches the stopping point; or more than one stopping point can be designed into the circuit.

The LVDT is carefully designed with long and slender coils to make the output voltage essentially linear over a wide displacement that can be several inches long. The sliding core of

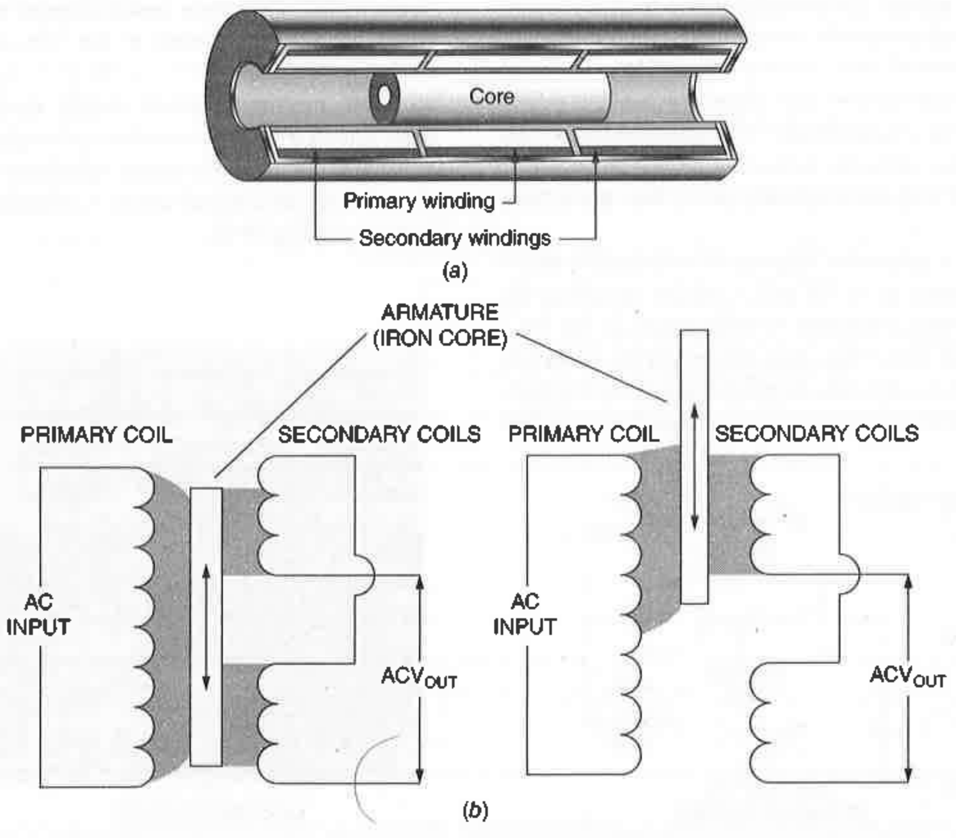


FIGURE 9-19 Linear variable differential transducer (LVDT): (*a*) construction, (*b*) electrical.

An LVDT often rides in a high-density plastic sleeve with very little friction; this makes the LVDT a highly reliable device. The LVDT is typically designed to be completely sealed against the environment and can be placed almost anywhere on the aircraft. LVDTs are commonly used for position feedback sensors in flight control servo mechanisms.

A rotary variable differential transducer (RVDT) is another type of electrical transformer used for measuring angular displacement. As the name implies, the RVDT is used to measure the movement of objects that rotate. Similar to the LVDT, the RVDTs utilize brushless, noncontacting technology to ensure long life and the reliability required by aircraft. As seen in Fig. 9-20, most RVDTs are constructed with a two-pole rotor that is connected to the moving component. Located around the rotor is the primary winding and the two secondary windings. The theory of operation is similar to that just described for the LVDT, except the input motion is rotational, not linear.

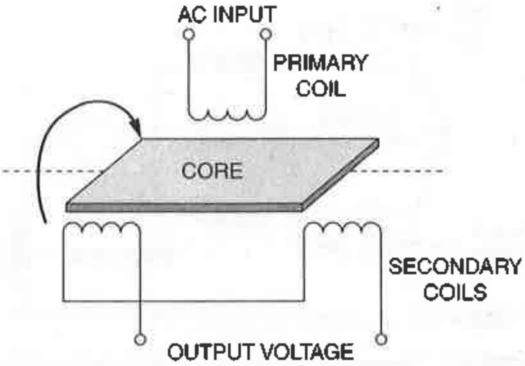


FIGURE 9-20 Rotary variable differential transducer (RVDT).

DC Motor Construction

An exploded view of a typical dc actuator motor is shown in Fig. 9-21. The principal sections of the motor assembly are the armature, the field coils and field frame, the brake assembly, and the thermal-protector assembly. The armature is a standard drum type wound on a laminated soft-iron core. Also mounted on the armature shaft are the commutator at one end and the brake-lining disk at the other.

The field for the motor is provided by two poles formed to fit around the armature with a clearance of about 0.01 in. [0.025 cm]. The field coils are double-wound to provide for

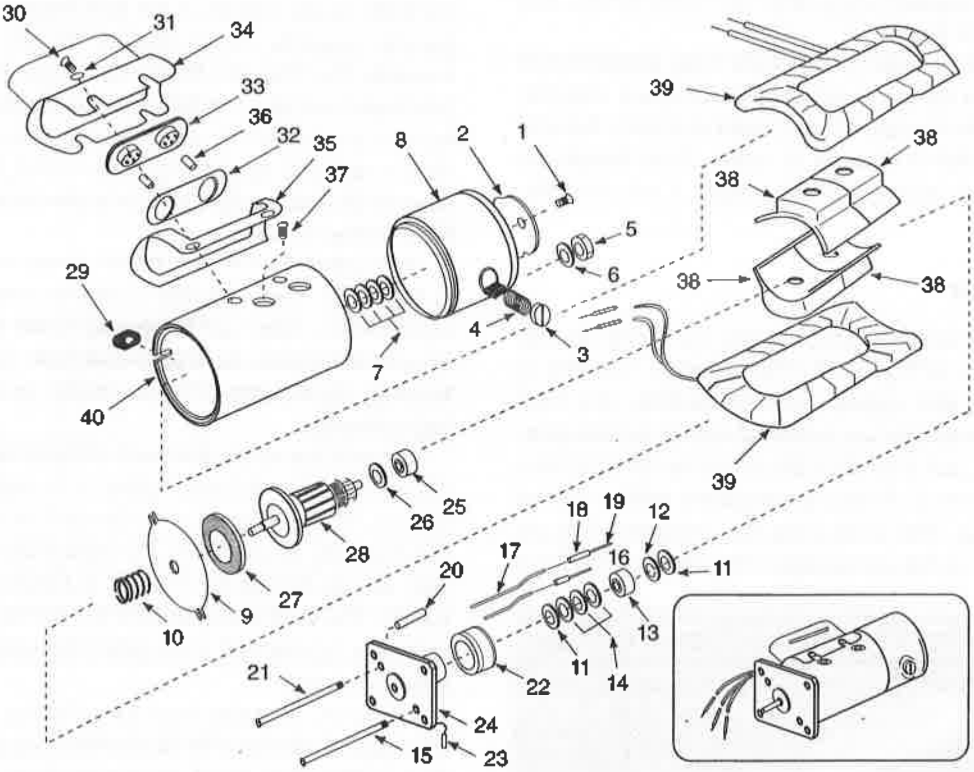


FIGURE 9-21 Exploded view of a dc actuator motor: (1) screw, (2) name plate, (3) brush retainer, (4) brush assembly, (5) nut, (6) washer, (7) shim washers, (8) motor cap, (9) brake armature, (10) brake armature spring, (11) spacer washer, (12) shim washer, (13) ball bearing, (14) shim washers, (15) motor assembly stud, (16) insulating sleeve, (17) wire, (18) insulating sleeving, (19) brush connector, (20) insulating sleeving, (21) motor assembly stud, (22) brake-coil assembly, (23) base-registering pin, (24) motor-base assembly, (25) ball bearing, (26) shim washer, (27) brake lining, (28) armature assembly, (29) motor lead grommet, (30) thermal-protector-case screw, (31) washer, (32) thermal-protector retainer, (33) thermal protector, (34) thermal-protector case, (35) thermal-protector gasket, (36) insulating sleeving, (37) field-pole screw, (38) field pole, (39) field winding, (40) motor housing.

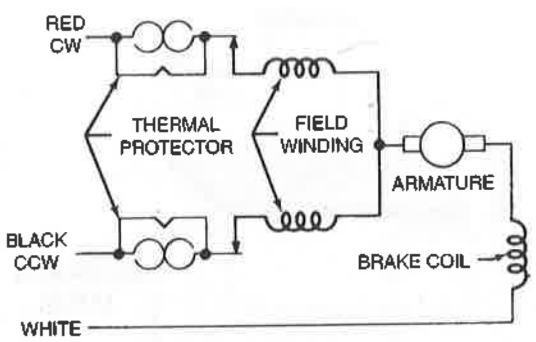


FIGURE 9-22 Thermal protectors wired in a motor circuit.

the reversal of field polarity necessary to reverse the motor rotation. Thermal protectors are connected in the circuit for each field (see Fig. 9-22).

The brake assembly consists of a coil, a brake armature, and a brake lining mounted on the lining disk on the motor armature. The brake armature is a disk held in place by the motor studs, which pass through slots on the outer periphery of the armature. When the motor is not energized, the brake armature is held against the brake lining of the motor armature by a coil spring. This prevents the motor from turning. When the motor is energized, the magnetic brake coil draws the brake armature away from the brake lining, and the motor is free to turn.

Both ac and dc actuator motors have been manufactured in very small sizes for use in aircraft and aerospace vehicles. Figure 9-23 is a photograph of an actuator assembly that can be operated by either a dc or an ac motor. Even though the actuator and motor assembly is very small, it can exert tremendous force.

Starter Motor

A typical direct-cranking starter motor for small aircraft engines is shown in Fig. 9-24. The armature winding is of heavy copper wire capable of withstanding very high amperage. The windings are insulated with a special heat-resistant enamel, and after they are placed in the armature, the entire assembly is double-impregnated with a special insulating varnish. The leads from the armature coils are crimped in place in the commutator bars and then soldered

FIGURE 9-23 Linear actuator.

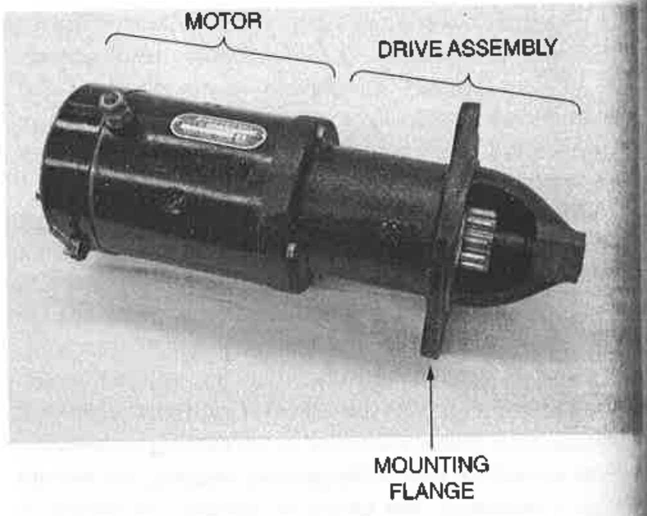


FIGURE 9-24 Starter motor for light aircraft.

with high-melting-point solder. An armature constructed in this manner will withstand the severe loads imposed for brief intervals while the engine is being started.

The field-frame assembly is of cast-steel construction, with the four field poles held in place by countersunk screws threaded into the pole pieces. The pole pieces are closely fitted to the inside contour of the field frame to provide the best possible magnetic circuit, because the field frame carries the magnetic flux from one field to the others. In other words, the field frame acts as a conductor for the magnetic lines of force; hence it is a part of the magnetic circuit from the field poles. Since a motor of this type is series-wound, the field windings must be of heavy copper wire of a size sufficient to carry the high starting current.

An exploded view of a starter motor and drive is shown in Fig. 9-25. This complete assembly consists of six major components. These are the **commutator end head assembly**, the **armature**, the **frame-and-field assembly**, the **gear housing**, the **Bendix-drive assembly**, and the **pinion housing assembly**.

The gear cut on the drive end of the armature shaft extends through the gear housing, where it is supported by a roller bearing. The gear mates with the teeth of the reduction gear that drives the Bendix shaft. The shaft is keyed to the reduction gear, and the Bendix drive is held in position on the shaft by a roll pin. The shaft is supported in the gear housing by a closed-end roller bearing and in the pinion housing by a graphitized bronze bearing.

When the armature turns the reduction gear, the Bendix-drive pinion meshes with the flywheel ring gear on the engine. This is done because of the inertia of the Bendix reduction gear; that is, when the armature begins to turn, the reduction gear is still at rest. This creates a relative motion between the reduction gear and the armature. Since the gear is mounted on a "threaded" shaft, the gear moves along the threads as the armature rotates and the starter engages into the engine flywheel gear.

A detent pin engages in a notch in the screw threads, which prevents demeshing if the engine fails to start and the starting circuit is de-energized. When the engine starts and reaches a

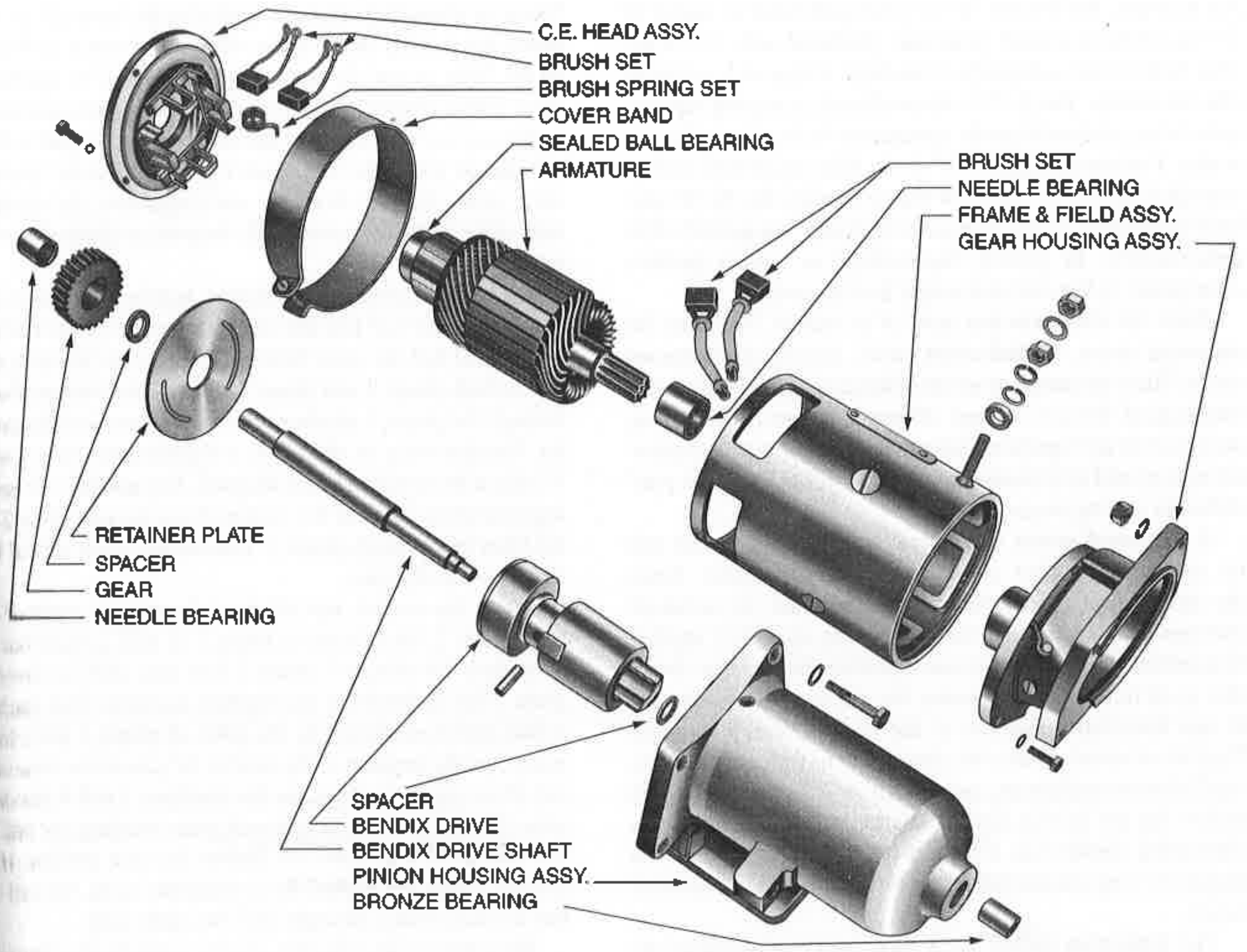


FIGURE 9-25 Exploded view of starter motor and drive. (*Prestolite.*)

predetermined speed, centrifugal force moves the detent pin out of the notch in the screw shaft and allows the pinion to demesh from the flywheel gear.

In the last decade or so, advancements to motor technologies have allowed for the production of smaller and lighter aircraft starter motors. These new motors incorporate more powerful electromagnets, better cooling, and improved heat resistance of the components. The motors are designed to spin at a higher rpm than older motors which helps to improve engine starting. A faster motor requires a different gear reduction assembly and produces greater torque. Many modern starter motors are designed to be interchangeable with older style motors by using a mounting adaptor. A modern motor with the mounting adaptor removed is shown in Fig. 9-26.

AC MOTORS

Theory of Operation

The basic principles of magnetism and electromagnetic induction are the same for ac and dc motors, but the application of the principles is different because of the rapid reversals of direction and changes in magnitude characteristic of alternating current. Certain characteristics of ac motors make most types more efficient than dc motors; hence such motors are used commercially whenever possible. During recent years ac power systems have been developed for large aircraft with higher voltage and higher amperage capacity than ever before.

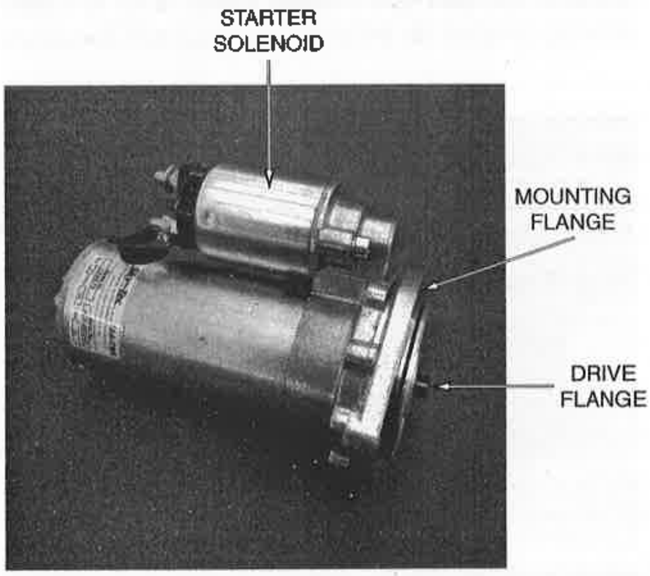


FIGURE 9-26 Modern starter motor for a piston engine aircraft.

For example, the Boeing 787 ac generators have an output of 235 V; previous aircraft generators produced only 115 V ac. This aircraft takes advantage of this high voltage in a variety of electric motors. The B-787 utilizes electric power for replacement of systems traditionally operated by hydraulics and pneumatics. For example, the B-787 is the first commercial airliner to employ an electric motor for engine starting. The B-787 also uses high-power electric motors for hydraulic pumps and cabin pressurization. In general, high-voltage ac motors produce more power in less size and weight than dc motors.

There are three principal types of ac motors. These are the **universal** motor, the **induction** motor, and the **synchronous** motor. There are many variations of these types, including combinations of features to meet different requirements. Among such motors are repulsion motors, split-phase motors, capacitor motors, and synchronous motors that utilize induction principles for starting torque.

A **universal motor** is identical with a dc motor and can be operated on either alternating or direct current. Since the direction of current flow in the field and the armature changes simultaneously when alternating current is applied to a universal motor, the torque continues in the same direction at all times. For this reason the motor will turn steadily in one direction regardless of the type of current applied. Typical universal motors are those used in vacuum cleaners, small electric appliances, and electric drill motors. Universal motors are not used in aircraft electric systems, because the alternating current has a frequeney of 400 Hz, and at this frequency very substantial energy losses occur in a universal motor.

The **induction motor** has a wide variety of applications because of its operating characteristics. It does not require special starting devices or excitation from an auxiliary source and will handle a wide range of loads. It is adaptable to almost all loads when an exact and constant speed is not required. The two major components of an induction motor are the stator and the rotor as shown in Fig. 9-27.

If a source of direct current is connected to two terminals of a stator winding, it will be found that sections of the interior surface of the stator have a definite polarity. If the dc connections are reversed, the polarity of the stator will also reverse.

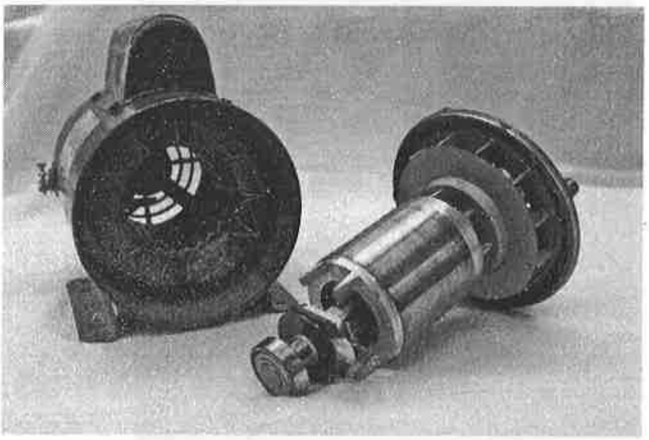


FIGURE 9-27 AC induction motor.

When an alternating current is applied to the connections of the stator, the polarity of the stator will reverse twice each cycle. Many high power ac motors are designed to operate on three-phase alternating current. When multiphase currents are applied to the windings of a stator, a rotating magnetic field is established within the stator (see Fig. 9-28). As the current in each phase changes direction and magnitude, the combined field of the stator will rotate at the frequency of the alternating current.

If we study carefully the diagrams and the graph for position in Fig. 9-28, we will find that phase 1 is positive with maximum current and that the stator field is vertical. The current is negative in both phase 2 and phase 3, with all the current flowing through the phase-1 winding in both the stator and the generator. The generator, or alternator, is represented by the inverted Y coils at the bottom of each diagram. In position 1 we see that approximately one-half the current flows through phase 2 and the other half through phase 3. This results in the vertical field shown in the diagram.

When the current has changed through an angle of 30° to position 2, the current in phase 1 is still positive but has decreased, the current in phase 2 is at zero, and the current in phase 3 has increased in the negative direction. This results in a field produced entirely by the poles of phases 1 and 3 in the stator, and the position of the field is 30° clockwise from vertical. If we study the diagrams for positions 3 and 4 and determine the current flow through each phase winding, we will find that the stator field turns 30° farther for each position. If the current values are plotted for a complete cycle, we will find that the field rotates through 360° for each cycle.

The rotor in an induction motor consists of a laminated iron core in which are placed longitudinal conductors. In a **squirrel-cage** rotor these conductors are usually copper bars connected together at the ends by rings. When this assembly is placed in the rotating field produced by the stator, a current is induced in the conductors. Since the conductors are short-circuited, there is a flow of current from those on one side of the rotor, through the rings at the ends of the rotor, to the conductors on the other side. This current produces a magnetic field that is at an angle to the field of the stator. If the rotor field came into line with the stator field, there would be no torque; hence, the rotor field must always be a few degrees behind the stator field. The percentage of difference in the speeds of the stator and rotor fields is called the **slip**. It must be emphasized that this slip is absolutely necessary. The only field provided initially by the input of current to the motor is the field produced by the stator. The rotor has no electrical connection with the external power, and the only way it can produce a field is by having current induced within itself as the flux of the rotating stator field cuts across it. The interaction of the rotor field with the stator field then produces the torque that causes the rotor to turn.

When the motor is mechanically connected to a load, the load tends to slow the rotation of the rotor. This causes the slip to increase, and the rotor conductors cut a greater number of lines of force per time interval, thus increasing the rotor current and the rotor field. This stronger field produces an increased torque, which enables the motor to carry the increased load.

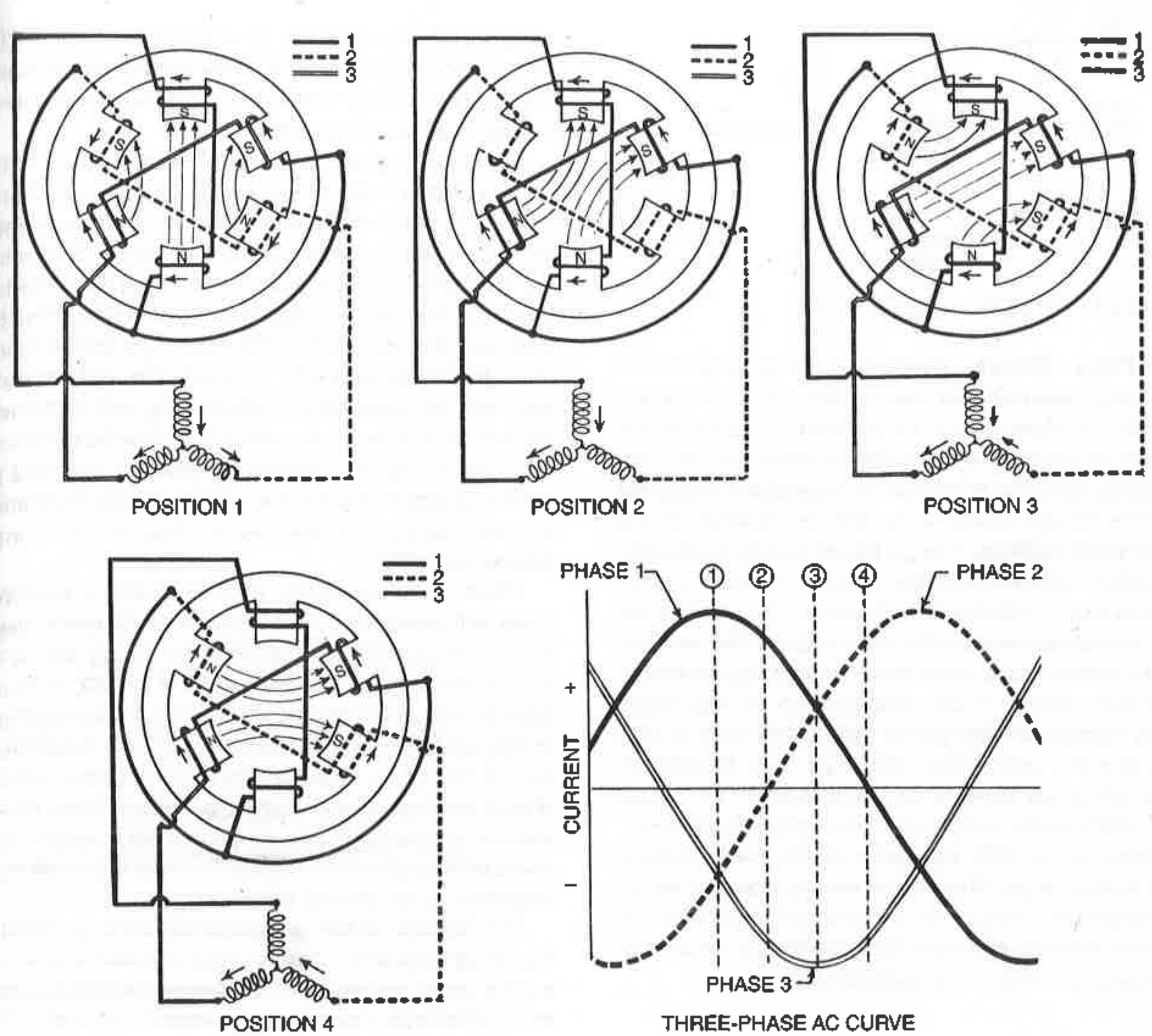


FIGURE 9-28 Rotating field of an ac motor.

There is another effect that must be considered when a load is applied to an induction motor. This is a lowering of the power factor caused by the inductive reactance of the rotor. When the rotor is turning at almost synchronous speed, that is, the speed of the stator field, the frequency of the rotor current and the inductive reactance of the rotor are low. As the load is applied to the motor, the slip increases, and there is a corresponding increase in the frequency of the rotor current. This increases the inductive reactance of the rotor, and the power factor of the motor consequently decreases. It will be remembered that the power factor is equal to the cosine of the phase angle between the voltage and the current and that inductive reactance increases this phase angle. In order to maintain system efficiency, motors must be designed to keep the phase angle to a minimum.

When the load on an induction motor becomes so great that the torque of the rotor cannot carry it, the motor will stop. This is called the **pull-out point**.

Improvement of Starting Qualities

An induction motor will start satisfactorily under no load without any special starting devices. However, when such a motor is connected directly to a substantial load that must be moved when the motor starts, it is usually necessary to add resistance in the rotor circuits. There are several methods for accomplishing this, but the explanation of one method is sufficient for this text.

From the study of alternating current, it will be remembered that the power factor for alternating current flowing in a purely resistive circuit is 100 percent. On the other hand, alternating current flowing in a purely inductive circuit would have a power factor of 0 percent if such a circuit were possible. Therefore, the addition of resistance to an inductive circuit will have the effect of improving the power factor. To add the necessary resistance to a rotor circuit for starting purposes, two squirrel-cage windings are used. One of these windings is of copper and has low resistance, and the other is of copper-silver compound and has high resistance. When the starting current is applied to the motor, the high-resistance winding produces the starting torque because of its high power factor. As the rotor gains speed, the effect of the high-resistance winding decreases, and the effect of the low-resistance winding increases. When the motor is operating at normal speed, it has the advantage of a low-resistance rotor winding.

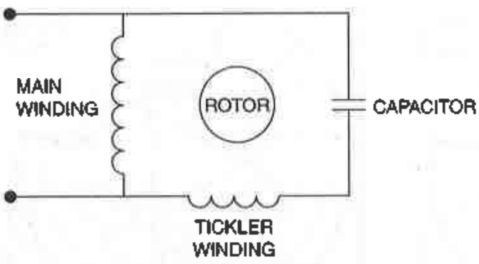


FIGURE 9-29 Circuit for a capacitor motor.

Split-Phase Motors. Single-phase induction motors have no torque when the rotor is at rest; hence, it is necessary to incorporate into them devices for providing a starting torque. This can be accomplished by providing the motor with two separate windings and using an inductor or a capacitor to change the phase of the voltages applied to the different windings. This is known as **phase splitting**. A motor having devices for this purpose is called a **split-phase motor.** Figure 9-29 shows a motor circuit in which a capacitor is used to cause the current in one winding to lead the current in the other winding. This, in effect, causes the motor to act as a two-phase motor during starting.

Split-phase motors of the capacitor type are used extensively in industry for low-power applications such as drill presses, grinders, small lathes, and small saws. In large aircraft the split-phase motor is used as an actuator for various types of comparatively small loads, such as small blower fans.

As shown in Fig. 9-29, a capacitor is often used in order to provide starting torque. When the motor has attained a certain rpm, a centrifugal switch opens and cuts out the capacitor circuit. Motors that employ a capacitor for starting or for continuous operation are often called **capacitor motors.**

Repulsion Motors

A repulsion motor utilizes the repulsion of like poles to produce the torque for operation. The rotor is wound like an armature and employs a commutator and brushes. The brushes are short-circuited across the commutator at an angle that causes the induced current in the windings to produce a polarity in the rotor that will be in opposition to the polarity of the stator. That is, a north pole produced in the rotor will be near a north pole in the stator. The rotor is therefore caused to rotate because of the repulsion between the like poles. As the rotor turns, the brushes on the commutator remain in the same position, and so the polarity of the rotor remains in the same position, even though the rotor turns. The repulsion principle is used in some motors to provide starting torque, after which the motor operates as an induction motor.

Synchronous Motors

Synchronous motors, as the name implies, rotate at a speed that is synchronized with the applied alternating current. These motors have some features in common with induction motors and a construction similar to that of alternators. The stator consists of a laminated soft-iron shell with coils wound through slots on the inner surface. A three-phase synchronous motor has three separate windings in the stator and produces a rotating field like the stator of an induction motor. The rotor may be a permanent magnet in a very small synchronous motor, but in larger motors the rotor is an electromagnet excited by an external source of direct current.

The theory of operation of a synchronous motor is very simple. If a magnet is free to turn and is placed in a rotating field, it will align itself with the field and rotate at the same speed. If no load is placed on such a motor, the center of the rotor poles will be exactly in line with the center of the stator field poles. In practice this does not occur because of friction. Friction and load cause the center of the rotor poles to lag behind the center of the field poles formed by the stator. The angle between the rotor field and stator field is called the **lag**, and it increases as the load on the motor is increased. If the load becomes so great that it overcomes the magnetic reaction, the pull-out point is reached and the motor will stop. At this time the incoming current will increase to a short-circuit value, and the torque will become negligible.

When operating within its load limits, a synchronous motor will rotate at the same speed as the alternator supplying the current, provided that the alternator has the same number of poles as the motor. Since the speed of a synchronous motor depends entirely on the frequency of the current supply, such motors are useful when constant speeds and frequencies are desired. One of the common uses of synchronous motors is to change the frequency of alternating current. Since the motor will turn at a precisely constant speed, it can be used to drive an alternator through a differential gear system to provide an exact frequency of any desired value.

Synchronous motors are commonly used on airplanes in the electric tachometer. A three-phase alternator is connected to a drive on the engine, and the alternator output is connected to a synchronous motor in the tachometer indicator. (Alternators will be discussed in Chap. 11.) The frequency of the current is directly proportional to the engine speed; hence, the synchronous motor in the indicator will rotate at a speed proportional to engine speed. The indicating needle is coupled to the synchronous motor through a permanent magnet and drag cup. The distance that the needle moves along the rpm scale is proportional to the speed of the motor.

A synchronous motor differs from an alternator in that it has a high-resistance squirrel-cage winding placed in the rotor to give a good starting torque. This winding causes the motor to start as an induction motor and run as a synchronous motor. When the motor has reached synchronous speed, it is turning with the magnetic field, and the conductors of the squirrel-cage winding are not cutting lines of force. If the rotor tends to hunt or oscillate, however, the squirrel-cage winding will have an induced current, which tends to dampen the oscillations and prevent hunting.

Motor Losses

The efficiency of electric motors of any type is largely determined by the losses of power resulting from friction, resistance, eddy currents, and hysteresis. The power used to overcome the friction of bearings is called the **friction loss.** This loss may also include the loss due to wind friction, which is sometimes

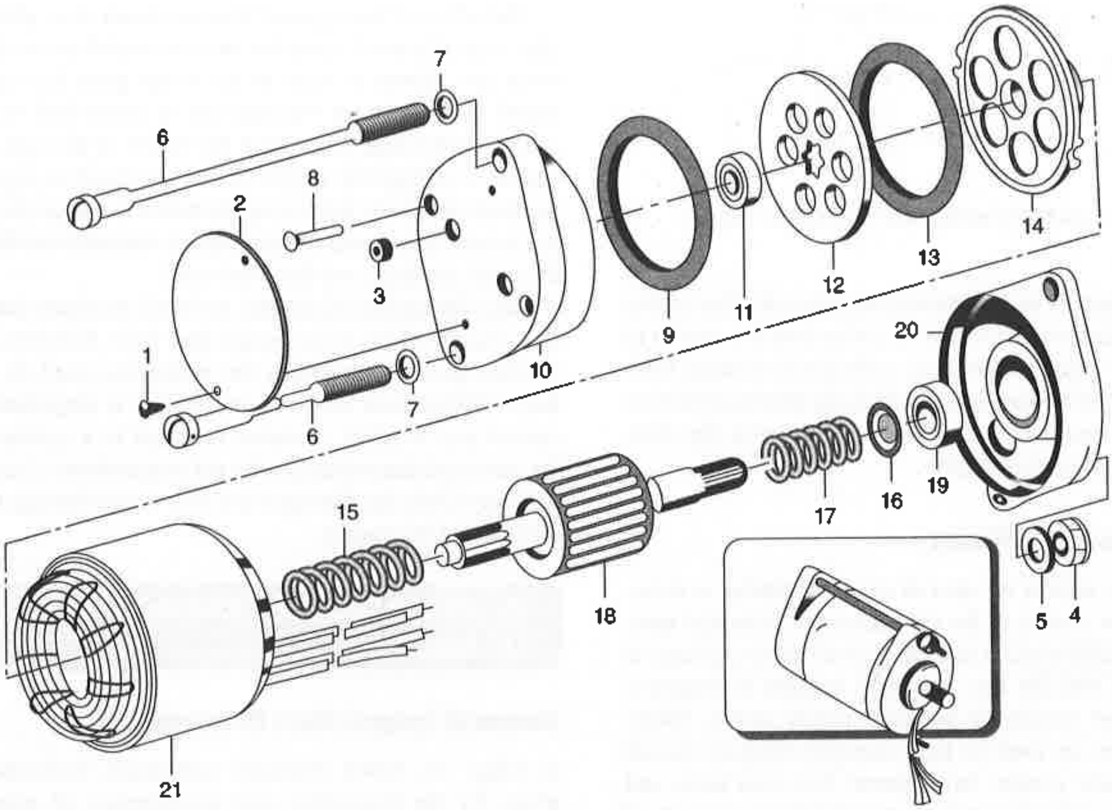


FIGURE 9-30 Exploded view of a single-phase reversible ac motor: (1) identification-plate screw, (2) identification plate, (3) adjusting screw, (4) main assembly nut, (5) washer, (6) main assembly screw, (7) washer, (8) aligning pin, (9) brake lining, (10) end bell, (11) ball bearing, (12) break disk, (13) brake lining, (14) brake armature, (15) brake spring, (16) spring retainer washer, (17) compression spring, (18) rotor assembly, (19) ball bearinq, (20) motor base, (21) stator assembly.

called **windage loss** and is comparatively high when a motor is equipped with a fan to provide cooling by forced ventilation. The power used to overcome the resistance of the windings is called **resistance loss**, or **copper loss**. Copper losses are dissipated in the form of heat.

The currents induced in the armature core and the field poles are called **eddy currents** and are responsible for considerable loss in the form of heat. These losses are reduced by constructing the armature and field cores of laminated soft iron, with the laminations insulated from one another.

Hysteresis losses occur when a material is magnetized first in one direction and then in the other in rapid succession. The effect of hysteresis is to cause the change in strength of the magnetic flux to lag behind the magnetizing force and is presumably due to the friction between the molecules of the material as they are shifted in direction by the magnetizing force. Hysteresis losses are noticeable because of their heating effect. Any condition that produces heat in a motor causes a loss of power, or energy, because heat is one of the principal forms of energy and requires power to produce it.

The construction of electric motors with laminated armatures and field-pole cores helps to solve cooling problems because much of the heat encountered during operation is the result of the losses described above. This type of construction is particularly important for high-speed actuator motors. Actuator motors must have a high power-to-weight ratio, and to attain this it is necessary to operate them at relatively high speeds. For this reason all losses must be reduced to a minimum.

Single-Phase Reversible AC Motors

Single-phase reversible ac motors are found on transport-category aircraft and are used to drive valve assemblies and other relatively small actuators. If large amounts of mechanical energy are needed, three-phase motors are used. Single-phase reversible ac motors typically contain two stator windings. The motor's direction is determined by the current flow through the clockwise or counterclockwise winding. This can be regulated with a double-pole double-throw (DPDT) switch in the external circuit. The construction of a single-phase reversible ac motor consists principally of a squirrel-cage rotor, a double-wound stator, and a brake assembly (see Fig. 9-30). The core of the rotor is constructed of laminated soft iron. Slots are provided in the surface of the core for the copper bars that form the squirrel cage. At each end the copper bars are soldered or welded to copper rings.

The double-wound stator provides the split field that is necessary to establish torque for starting under load. The stator leads are brought to the outside of the motor, where they are connected to a capacitor, as shown in Fig. 9-31. Note that when the control switch is placed in the clockwise position, current flow will be through the clockwise coil directly and

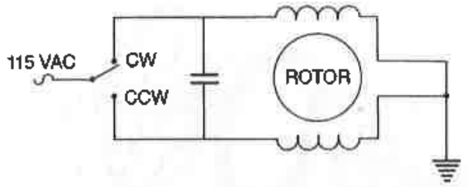


FIGURE 9-31 Circuit for a split-phase reversible ac motor.

through the capacitor to the counterclockwise coil. This causes the current in the counterclockwise coil to lead the current in the clockwise coil, thus creating a clockwise-rotating field. Conversely, when the switch is placed in the counterclockwise position, the rotating field is in a counterclockwise direction, and the motor turns accordingly.

Three-Phase AC Motors

Three-phase ac motors for aircraft are quite similar to three-phase induction motors of the commercial or industrial type. The principal difference is that the aircraft motor operates at a frequency of 400 Hz, thus making it possible to employ a motor of lighter weight for the same power output. Three-phase ac motors are used on large transport-category aircraft to drive hydraulic pumps, large blower fans, fuel boost and transfer pumps, and other systems requiring large amounts of mechanical energy.

The **three-phase induction motor** consists essentially of a three-phase Y-wound stator and a conventional squirrel-cage rotor. The three-phase stator produces a rotating field as explained previously, and this field induces a current in the rotor. The rotor current creates a field that opposes the stator field, with the result that the rotor attempts to turn at a speed that will keep it ahead of the stator field.

One type of three-phase actuator motor for aircraft is internally wired as shown in Fig. 9-32. It will be noted that the motor has a Y-wound stator; however, the neutral connections from each phase winding are individually connected to three separate legs of a full-wave rectifier. The rectifier output is directed through a clutch coil that is split to accommodate the alternating current in the neutral line.

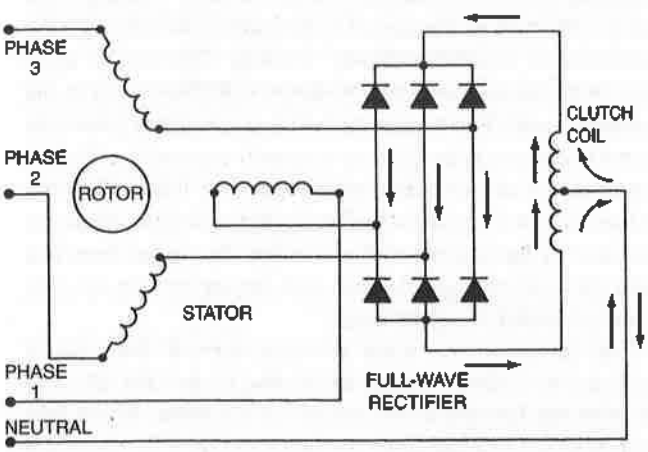


FIGURE 9-32 Circuit for a three-phase ac motor with a full-wave rectifier to provide direct current for the clutch coil.

The effect of this type of internal circuit is to allow for a high surge of current when the motor is started and a comparatively low current as soon as the motor gains full operating speed. Since the rotor windings are in series with the clutch coil, the clutch coil will receive the benefit of the high starting current to engage the clutch. When the clutch is engaged, it requires a relatively low current to hold it in that position. This low current is the result of the inductive reactance developed by the stator windings and the clutch coil.

Since the variety of electric motors is extensive and many look exactly alike, even though they have different characteristics and specifications, the technician must be certain that a replacement motor in any system is identified by the correct part number. A motor installed in a system where the electrical characteristics do not match those of the motor will very likely be damaged and may cause damage to other elements of the circuit.

INSPECTION AND MAINTENANCE OF MOTORS

General Inspection Procedures

In Chap. 10, which discusses generators, instructions are given for the inspection and maintenance of generators. Many of the instructions apply to motors as well because of the similarities between the two.

Preflight inspections of motors are usually a simple operational check. The switches for the various motor-driven units are turned on, and if operation is satisfactory, no further inspection is made. It is obvious that landing-gear actuators cannot be tested in this manner, but if the latest pilot's report is satisfactory, only a visual inspection need be made.

Depending on the amount of operation to which a motor has been subjected, inspections should be carried out on the motor at intervals set forth in the manufacturer's operation manual. This type of inspection will probably include a check of the mounting, electrical connections, wiring, brushes, brush springs, and commutator. For ac motors, it is not usually necessary to consider brushes and the commutator since only universal ac motors have brushes/commutators and universal motors are not common to aircraft.

The construction of many small dc actuator motors makes it difficult to inspect the commutator without removal and disassembly. But because these motors are usually of the intermittent type, the wear on the commutator is negligible. A periodic inspection of the brushes and replacement, if necessary, will assure satisfactory operation until the time for overhaul. New brushes should be seated as outlined in Chap. 10, covering generator maintenance. Usually, brushes for small motors can be ordered specifically for a particular model; the brush face will be already ground to the correct curvature. The seating of the brushes can be checked by removing the brushes from the motor after a few minutes of operation and examining the area that has been polished by the commutator.

Removal of the cap or cover band will give access to the brushes and holders. If a brush is held on a pivoted arm, it can be removed by lifting the arm and removing the brush screw.

For a brush in a box-type holder, merely lift the brush spring and slide the brush out of the holder.

Removal and Installation

Because of the many different types of electric motors, specific instructions cannot be given here for their removal and installation. For any particular motor on an aircraft, the technician should consult the maintenance or overhaul manual supplied by the manufacturer.

When the removal of a motor is necessary, the technician must give due consideration to the driven mechanism. In many cases a gear-train assembly must be removed with the motor. In any event, a brief visual inspection will usually enable the technician to determine the procedure to be followed.

Care must be taken to make sure that electric wiring and connector plugs are not damaged when a motor is disconnected. It is best to tape or otherwise insulate disconnected terminals, which might accidentally become short-circuited if the battery switch were to be inadvertently turned on.

If the removal of a motor leaves an opening through which dirt or other foreign matter can gain access to vital parts of a mechanism, the opening should be covered with a cloth or a plate. This is particularly important when removing a starter motor from an engine. If a nut, a bolt, or some other object should fall inside the engine, great damage may be caused, and the engine may require a complete overhaul.

The important points to be considered in the installation of a motor are as follows:

1. See that the mounting area is clean and properly prepared. Install the correct type of gasket if a gasket is required.
2. Be very careful not to cause damage when moving the motor into place. A nick or scratch in the mounting could develop into a crack and eventually cause failure.
3. Tighten screws or hold-down bolts evenly and with the correct torque. Make sure that nuts, bolts, or studs are properly safetied.
4. See that electrical connections are clean; then tighten and safety them as required.

Disassembly and Testing

The disassembly, inspection, overhaul, and assembly of an aircraft electric motor should be performed in accordance with the manufacturer's instructions. When performing maintenance, the following general rules apply:

1. Use the proper tools for each operation.
2. Mark and lay out parts in an order that will aid in assembly.
3. Do not use excessive force in any operation; if parts are stuck, determine the cause. If necessary, use a soft mallet to disengage parts. Sometimes parts are joined by means of metal pins or keys, which may be overlooked by the technician; be sure that such devices are removed before attempting to separate parts that have been joined in this manner.
4. When bearings are pressed on a shaft, or when they are stuck because of corrosion, use a bearing puller for removal.
5. Use an arbor press for the removal and installation of bearings and bushings that are press-fit. The use of this device is recommended, but if an arbor press is not available, a fiber tube that fits the inner or outer race of the bearing may be used.
6. Keep all parts of an assembly clean. the workbench should be free from dirt and grease. When greasy parts are removed, they should be cleaned. Use approved cleaning solvents for any motor part. The incorrect solvent may damage certain insulators or plastic assemblies inside the motor.

The testing of the parts of an electric motor is carried out in the same manner as tests for generator parts, as discussed in Chap. 10. A growler is used to test armatures for shorted or open coils. An ohmmeter or continuity tester is used to test for a ground between the armature windings and the core. Field coils can be tested with an ohmmeter or a continuity tester for open circuits, short circuits, and grounds.

After a motor has been assembled, it should be given an operational test before it is installed in an airplane. First, the armature should be turned by hand to see that it rotates freely; there must be no roughness or unusual noise when this is done. The motor should then be operated with a low load for about 10 min to seat the brushes. The value of the voltage applied should be according to overhaul specifications. During the time that the motor is being tested, it should be observed closely for excessive heating and vibration. Directions for testing specific motors are usually included with the manufacturer's maintenance and overhaul instructions. Motors should be disassembled only when these instructions are available.

REVIEW QUESTIONS

1. Define *electric motor*.
2. Describe the operation of a permanent magnet motor.
3. Describe the operation of an electromagnetic electric motor.
4. Describe series-wound, shunt-wound, and compound-wound motors.
5. What is the principal characteristic of a series-wound motor?
6. For what type of load would a series-wound motor be most suitable?
7. What is the principal characteristic of a shunt-wound motor?
8. Explain why a typical dc motor rotates when connected to a proper power source.
9. What determines the direction of rotation of a dc motor?
10. Why does the current being drawn by a shunt-wound motor decrease as the motor rpm increases?
11. What may happen to a series motor if it is connected to power without having a load?
12. How are dc motors reversed?
13. Describe the operational principles of a brushless dc motor.

14. Explain how proximity switches and differential transducers are used to control motors.

15. Explain the operational theory of a linear variable differential transducer.

16. What are the three principal types of ac motors?

17. Where are three-phase ac motors typically used on the aircraft?

18. How does the rotor of an induction motor react with the field of the stator?

19. Explain how the starting torque of an induction motor may be improved.

20. Name some of the internal motor losses that occur in the operation of an ac motor.

21. How is reduced weight attained in the design of motors for use in aircraft?

22. Why are heavy windings used in the armature of a dc starter motor?

23. Explain the operation of a magnetic brake assembly.

24. Why is it necessary to disengage an actuator motor from its drive when it is turned off?

25. Explain the adjustment of the limit switches in an actuator circuit.

26. List some of the typical precautions that must be observed in the installation of electric motors.

27. List general rules for the disassembly of an electric motor.

Generators and Related Control Circuits 10

INTRODUCTION

The first aircraft was designed without electrical systems; through the years, however, all aircraft became more complex and the need for electric power increased. Today, modern aircraft and aerospace vehicles are equipped with scores of different electrical and electronic systems, each requiring a substantial amount of energy.

Generators were the first means of supplying electric power for aircraft. Currently, generators or generator derivatives called alternators are found in a wide variety of sizes and output capacities. A typical generator used on a large commercial aircraft can produce 90 000 watts of electric power. The latest aircraft designed by Boeing, the B-787, uses so much electrical power that each main generator can produce 250 000 W. On multiengine aircraft, one or more generators are driven by each engine to allow for redundancy in the event of a generator failure.

An electric generator can be defined as a machine that changes mechanical energy into electric energy. On aircraft, the mechanical energy is usually provided by the aircraft's engines. Light aircraft use 14- or 28-V dc generators. Large aircraft typically employ generators that produce an alternating current of 208 or 115 V at 400 Hz. Some of the newest aircraft employ generators with an output voltage as high as 270 V. Compared with a 28-V dc system, a higher-voltage ac system will develop several times as much power for the same weight; hence, it is a great advantage to use on high voltage systems where heavy electrical loads are imposed.

GENERATOR THEORY

Electricity is produced in a generator by electromagnetic induction. As explained in Chap. 1, it is a fundamental principle that when there is a relative movement between a magnetic field and a conductor held perpendicular to the line of flux, an emf (voltage) is produced in the conductor. If the ends of the conductor are connected through a circuit, the voltage will cause a current to flow, as shown in Fig. 10-1. The direction of current flow is determined by the direction of the magnetic flux and the direction in which the conductor is moved through the flux.

A simple way to determine the direction of current flow is to use the **left-hand rule for generators.** *Extend the thumb, index finger, and middle finger so they are at right angles to one another, as illustrated in Fig. 10-2. Turn the hand so the thumb points in the direction of movement of the conductor and the index finger points in the direction of the magnetic flux. Then the middle finger will be pointing in the direction of the current flow.* Remember, current flow is from negative to positive. Flux direction is considered to be from north to south.

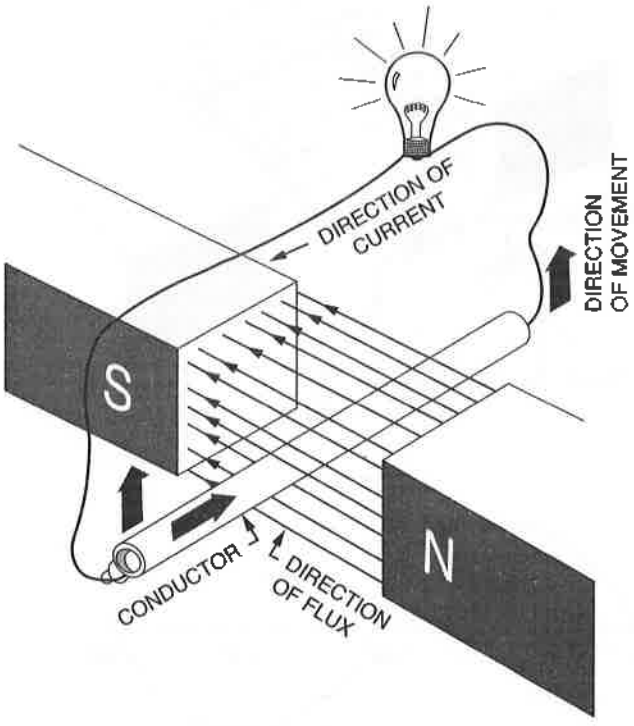


FIGURE 10-1 Generator action.

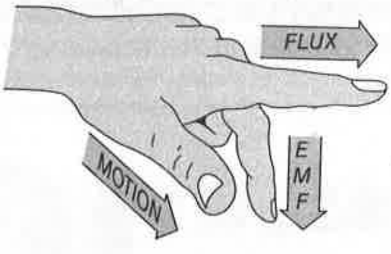


FIGURE 10-2 Left-hand rule for generators.

Simple AC Generator

A simple ac generator can be constructed by placing a single loop of wire between the poles of a permanent magnet and arranging it so that it can be rotated as shown in Fig. 10-3. The current is taken from the wire loop by means of brushes, which make continuous contact with the collector rings (slip rings). One collector ring is connected to each end of the wire loop. In Fig. 10-3, the sides of the loop are designated *AB* and *CD*. As the loop rotates in the direction indicated by the arrow, side *AB* will be moving up through the magnetic field. If we apply the left-hand rule for generators, we find that a voltage is induced that will cause current to flow from *A* to *B* in one side of the loop and from *C* to *D* in the other side of the loop. This is because *AB* is moving **up** through the field and CD is moving **down** through the field.

The voltage induced in the two sides of the loop add together and cause the current to flow in the direction *ABCD*, through the external circuit, and then back to the loop. As the loop continues to rotate toward a vertical position, the sides will be cutting fewer lines of flux, and when it reaches the vertical position, the sides of the loop will not be cutting any lines of flux but will be moving parallel to them. At this position, no voltage is induced in the loop because a conductor must cut across flux lines in order to induce a voltage. By rotating the loop through the vertical position and back to the horizontal, a voltage will be induced again, but it will be in the opposite direction in the loop because side *AB* will now be moving **down** through the field and side *CD* will be moving **up** through the magnetic field. Soon the loop is once again in the vertical position, and no flux lines are being cut. When the loop is exactly perpendicular to the magnetic flux lines, no voltage is being produced. The current flow then repeats its cycle as long as the loop is rotated inside the magnetic field. The voltage waveform produced by this type of generator is called the sine wave.

By examining the sine wave of Fig. 10-4, it can be seen that the voltage is at zero when the loop is in a vertical position, and then it climbs to a maximum value when the loop is in the horizontal position. This is indicated on the sine curve from 0 to 90°. As the loop continues to turn, we find that the voltage is maximum at 90°, zero at 180°, maximum at 270°, and zero again at 360°.

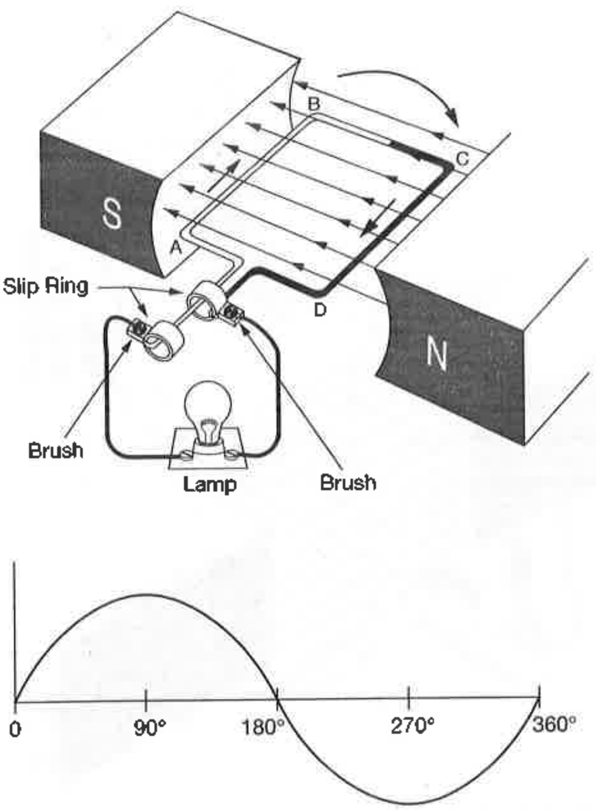


FIGURE 10-3 A simple ac generator and associated voltage wave.

Essential Parts of a Sample AC Generator

The essential parts of a simple ac generator are shown in Fig. 10-5. These are a **magnetic field**, which may be produced by a permanent magnet or by electromagnet field coils; a rotating loop or coil called the **armature** or **rotor**; **slip rings**; and **brushes** by which the current is taken from the armature. The poles of the magnet are called **field poles**. In most generators, these poles are wound with coils of wire called **field coils**. Generators containing permanent magnet fields only produce limited amounts of electrical power. Large high-power generators use an electromagnetic field winding.

Value of Induced Voltage

The voltage induced in a conductor moving across a magnetic field depends on two principal factors: the strength of the field (the flux density) and the speed with which the conductor moves across the flux lines. In other words, the voltage depends on the number of flux lines cut per second. So, the stronger the magnetic field and the faster a generator spins, the more electrical output produced.

Simple DC Generator

DC generators are used on most aircraft for battery charging, and supplying power to various electric loads. For this reason an ac generator will not meet all power requirements unless a means of rectifying the alternating current is provided. Figure 10-6*a* shows a simple generator that rectifies the output voltage/current using a commutator and brush assembly. This dc generator uses a commutator assembly to create the electrical contacts between the rotating armature coil and the stationary brushes. (An ac generator uses slip rings as shown in Fig. 10-5.)

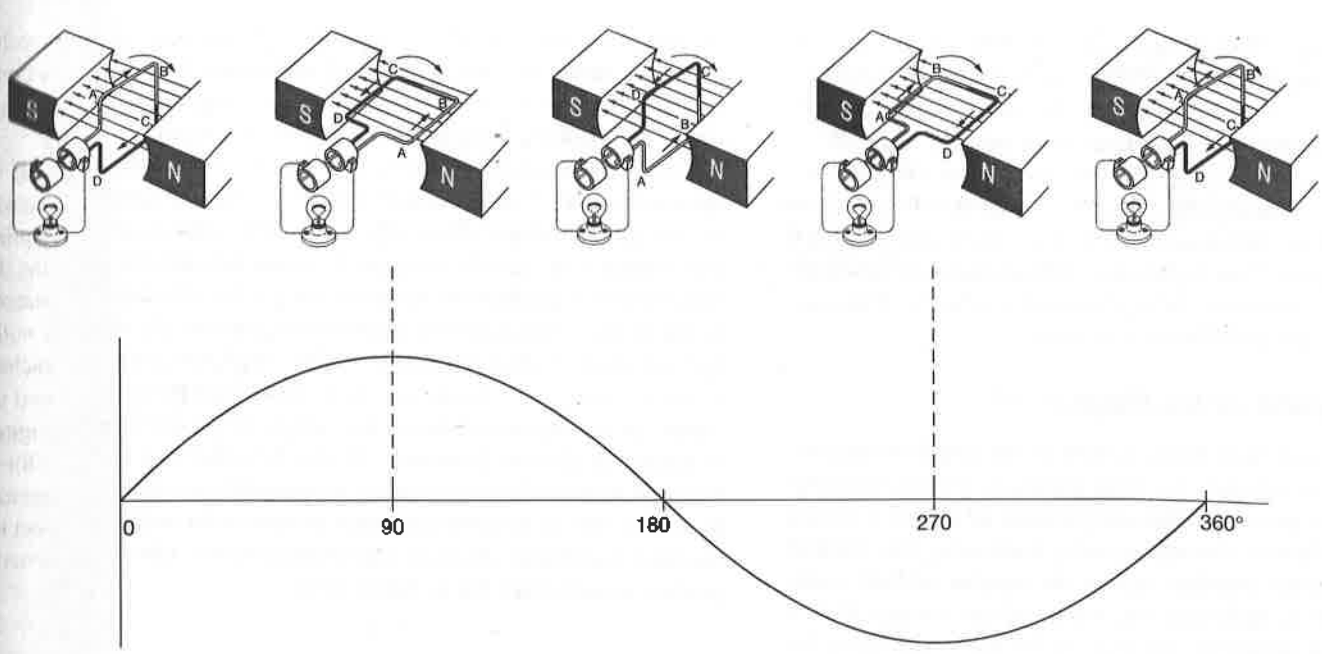


FIGURE 10-4 AC produced during generator operation.

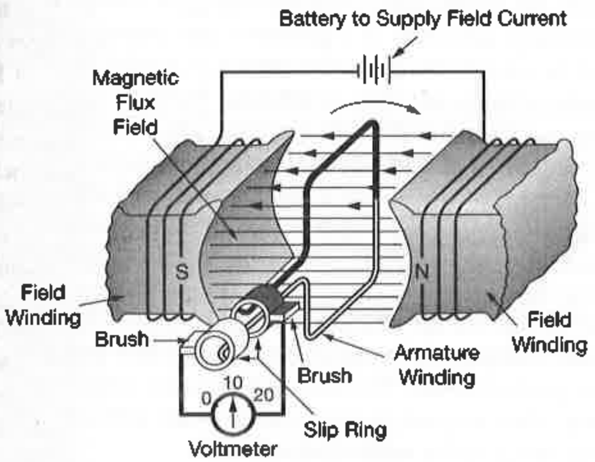


FIGURE 10-5 Essential parts of an ac generator.

The use of a commutator assembly will allow the dc generator to produce a pulsating direct current output as shown in Fig. 10-6*b*.

A **commutator** is a switching device that reverses the external connections to the armature at the same time that the current reverses in the armature. The commutator in Fig. 10-6*a* is a split ring that turns with the armature. One end of the rotating loop is connected to one half of the ring, and the other end of the loop is connected to the opposite half of the ring. The two sections of the commutator are insulated from each other. Two brushes are placed in a position relative to the commutator so that as the commutator turns, the brushes pass from one segment of the commutator to the other. This reversal occurs at the same time as the current produced in the armature reverses; there is practically no voltage produced between the two segments at this time.

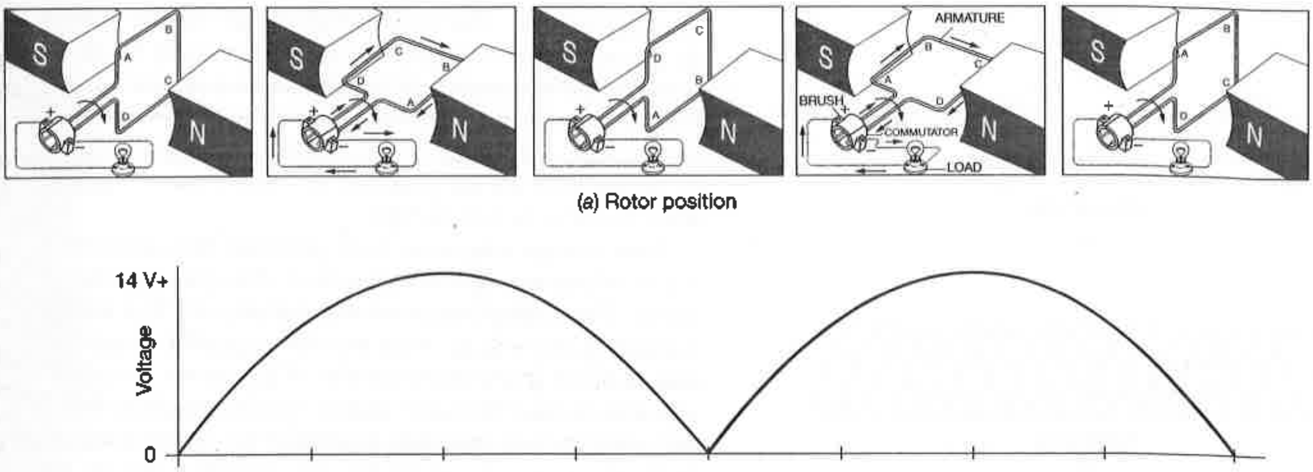


FIGURE 10-6 A simple dc generator and associated voltage wave.

Referring to Fig. 10-6*a*, observe that the side of the loop moving up through the field will always be connected to the positive brush and that the side of the loop moving down through the field will always be connected to the negative brush.

As illustrated in Fig. 10-6*b*, the current from the generator will then be traveling in one direction in the external circuit, but it will pulsate. The output current will vary in intensity from zero to maximum and back to zero through each half turn of the armature. A current of this type is called a pulsating direct current and is too unstable for most uses.

Elimination of DC Ripple

Since the pulsating direct current of the simple dc generator is not satisfactory for most purposes, it is necessary to construct a generator that will produce an almost constant voltage. This is accomplished by increasing the number of coils in the armature and/or the number of field coils. Figure 10-7*a* illustrates the nature of the voltage from a single-coil generator, and Fig. 10-7*b* shows the curve for a generator with four armature coils. Notice the great difference in the nature of the voltage.

Armature coils are wound on a laminated soft-iron core. The iron core concentrates the field flux and greatly increases the voltage generated. The laminations reduce the effects of eddy currents induced in the core.

A simplified version of a dc generator containing a four-coil armature is shown in Fig. 10-8. Here it can be seen that the four separate coils are equally spaced around the armature. As the rotor spins inside the magnetic field, four separate pulses of current are produced by the armature; each electrical pulse is shown in Fig. 10-8*b*. It is important to note that during operation, the generator produces several electrical voltage pulses (represented by the dotted lines in Fig. 10-8b); yet the commutator assembly ensures that only the very top portions of the voltage curves are connected to the generator output (represented by the solid lines in Fig. 10-8b). The positive and negative brushes connect to each commutator segment for only a short period during the rotation of the armature. The generator is designed to ensure that the brushes connect to the armature winding at the exact time the winding is producing the maximum voltage. As the armature rotates, each loop will sequentially connect to the set of brushes to ensure that the output current sent to the aircraft electrical system stays within limits.

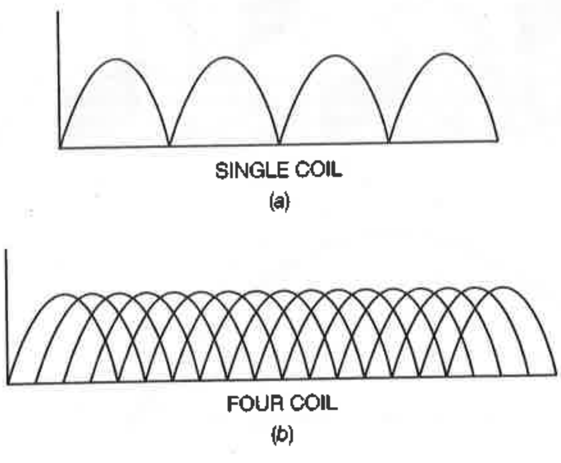


FIGURE 10-7 Comparing voltages from a single-coil armature and a multiple-coil armature.

This form of generator produces a voltage output that is suitable for most electrical components; however, some sensitive circuits like computerized LRUs and many radios require a dc voltage with virtually no ripple. For these circuits, the dc ripple output as produced by the generator must be eliminated. A simple capacitor connected in parallel with the supply voltage can greatly reduce the amount of DC ripple that reaches a sensitive load. The capacitor creates a **filter circuit** used to "filter out" the inconsistencies in the current before the signal is applied to the load. Inductors can also be added as a filter for ripple direct current. In this case, the capacitor is connected in parallel and the inductor connected in series with respect to the load. A correctly designed capacitive/inductive filter will produce an extremely flat dc power curve.

Residual Magnetism

An electromagnet will produce a much greater field strength per given size and weight than a permanent magnet. The use of electromagnetic field coils in a generator also creates an easy means to control the generator output as needed for various electrical loads and flight conditions. For these reasons, all generators used as the main electrical power source on aircraft employ an electromagnet to create the magnetic flux field. The generator field coil is typically designed with several turns of copper wire wrapped around a metal core material as shown in Fig. 10-9. As shown in this simplified diagram, the core is constructed with laminated pieces of soft iron to improve the efficiency of the generator. The soft-iron core material helps to direct the magnetic flux lines close to the generator rotor. The iron core will also retain a small portion of the magnetism when current to the field coil is turned off; this is called **residual magnetism.**

It is this residual magnetism that makes it possible to start a generator without exciting the field from an outside source of magnetism or electric current The residual magnetism in the field poles causes a weak voltage to be created when a generator begins to rotate. This small voltage is then used to power the generator's electromagnetic field, thus increasing the field strength. The increase in field strength causes a corresponding increase in generator output voltage, and a mutual increase in field strength and voltage continues until the voltage reaches the proper value for the generator. In other words, the generator is said to be self-exciting.

If the residual magnetism in the generator field should be lost or become too weak, the generator will no longer produce current. The residual magnetism can degrade over time when exposed to excess heat, when exposed to another magnetic field, or due to severe shock/vibration. If this occurs, the residual can be restored by simply sending current through the field coil windings. It is important to observe the correct polarity during this process to ensure that the magnetism polarity is also correct. This process is called **flashing the field** and will be discussed in greater detail later in this chapter.

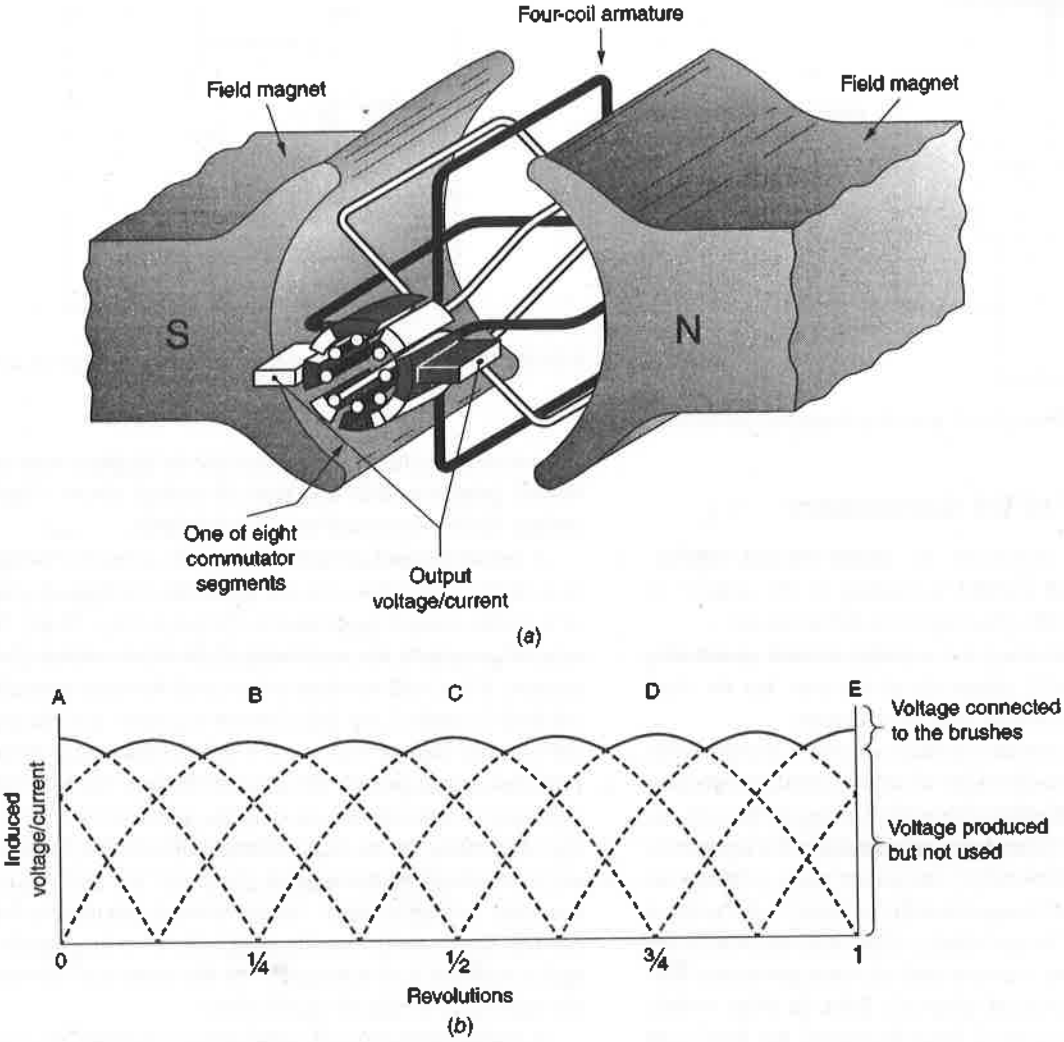


FIGURE 10-8 The output of a dc generator containing a four-coil armature.

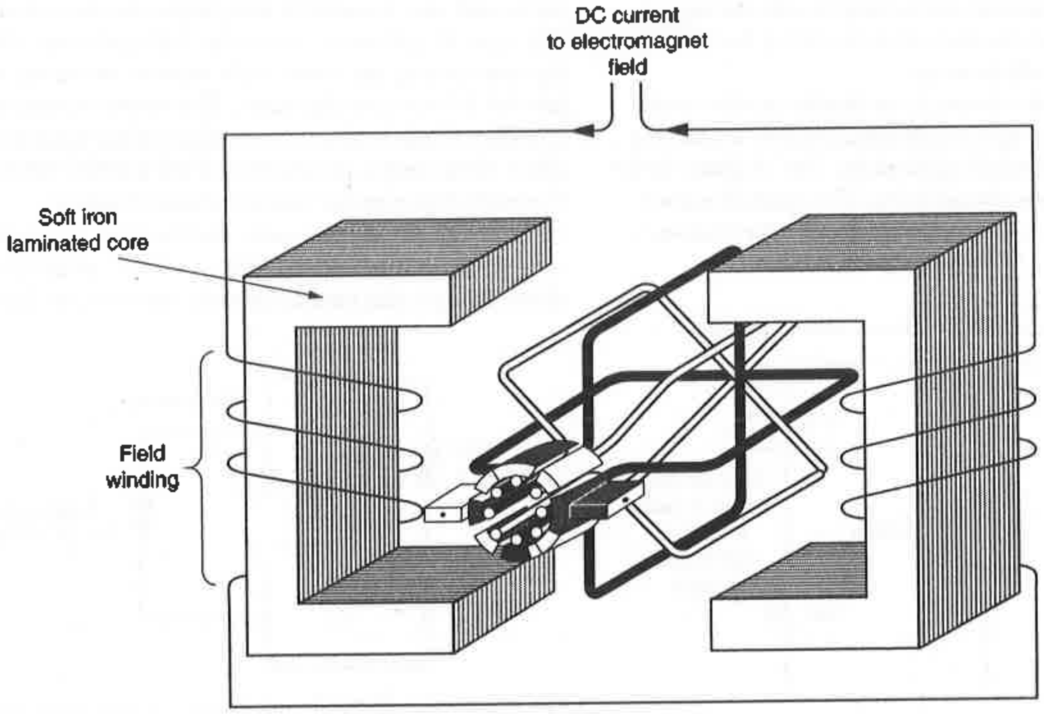


FIGURE 10-9 Generator field coil design.

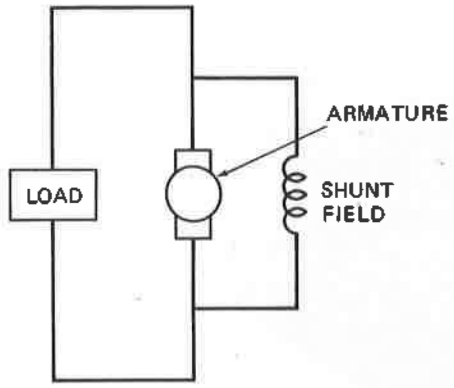


FIGURE 10-10 Diagram of a simple shunt-wound generator.

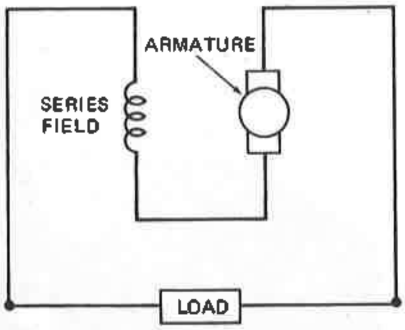


FIGURE 10-12 Diagram of a simple series-wound generator.

Characteristics of DC Generators

DC generators are classified as **shunt-wound**, **series-wound**, or **compound-wound**, according to the manner of connecting the field coils with respect to the armature.

The internal connections for a **shunt-wound generator** are shown in Fig. 10-10, where it can be seen that the field coils are connected in parallel with the armature.

The shunt-wound generator is often referred to as a **parallel-wound** generator. With this type of arrangement, the generator output can travel through the field winding or through the aircraft loads. (Remember the generator is producing power and the load and field winding are power users.) Of course the output current will proportionally "choose" the path of least resistance; so if the resistance of the load increases, the field will receive more current and increase generator output because of an increased magnetic field. In other words, as the total aircraft electrical load decreases, the total load resistance increases; therefore, field current increases and generator output will go up. Another factor to consider is that the generator rotational speed changes with engine rpm. For example, if the pilot reduces throttle setting for landing, the generator output will decrease.

From this description it is easy to see that the parallel-wound generator without some type of additional controls would only be suitable for very limited applications. The diagram of a parallel-wound generator shown in Fig. 10-11 includes a voltage/current control device. Virtually all aircraft which employ a dc generator for the main electrical power supply use a parallel-wound generator with this type of control circuit. Generator control will be discussed later in this chapter.

A **series-wound generator** contains a field winding that is in series with respect to the armature winding. A diagram of a series-wound generator is shown in Fig. 10-12. In this type of generator, the resistance of the load controls the field current. If the load resistance decreases because more electrical load is applied, the field current increases and the generator's output voltage increases. If the electrical load decreases (increasing resistance), the current through the load and the generator's field decreases and the generator's output voltage decreases. From these relationships it can be seen that an unregulated series-wound generator will not maintain a constant voltage output. Series-wound generators that are not regulated can be used in situations where a constant rpm and a constant load are applied to the generator, but they are not suitable for aircraft applications.

A **compound-wound generator** combines the features of the series- and shunt-wound generators. As illustrated in Fig. 10-13, this generator contains a field winding in series and one in parallel with respect to the armature. In this type of generator, when the load increases (decreasing resistance), the series field current increases and the parallel field current decreases. The output voltage remains constant. If the load decreases (increasing resistance), the series field current decreases and the parallel field current increases. Once again, output remains constant.

In theory, the series-wound, shunt-wound, and compound-wound generators each have certain advantages and disadvantages. On modern aircraft, however, all generators

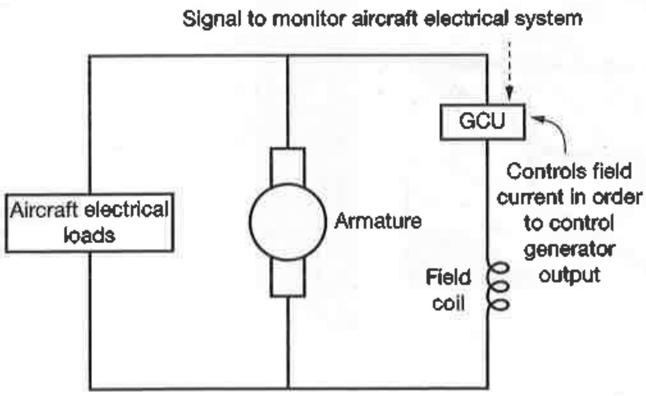


FIGURE 10-11 Voltage regulation in field circuit.

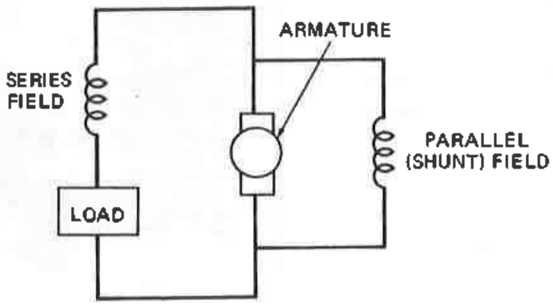


FIGURE 10-13 Diagram of a simple compound-wound generator.

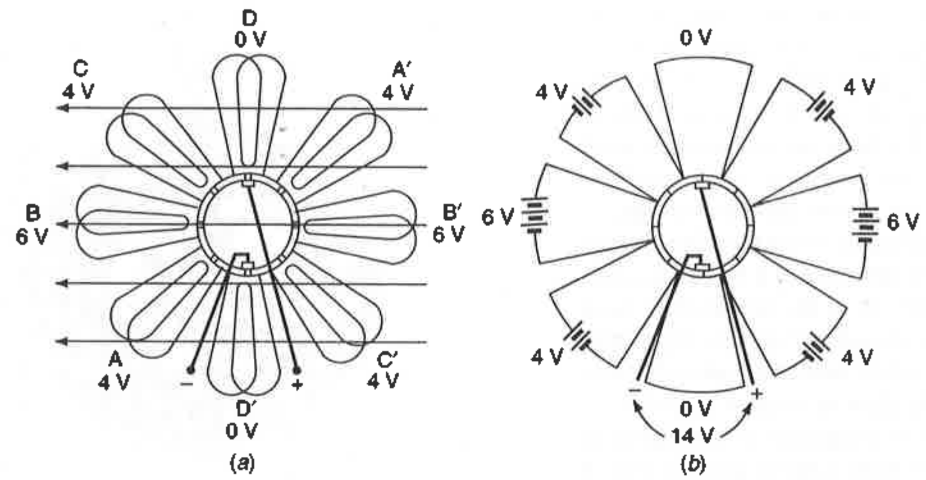


FIGURE 10-14 Armature circuit with battery analong.

contain some means of controlling the output voltage and current. The shunt-wound generator used in conjunction with a voltage regulator is the most common type of dc generator system for aircraft. The voltage regulator adjusts the current to the shunt field in order to maintain the necessary output under a variety of rpm and load conditions.

Analysis of an Armature Circuit

In a previous paragraph it was explained that a practical generator has many coils of wire in the armature. These coils are connected to the commutator segments in such a manner that they are in series with one another. Figure 10-14*a* shows the connections for a typical commutator in a two-pole generator. Assume that the armature has eight coils of two turns each wound around the armature through oppositely positioned slots. If the magnetic flux is horizontal, no voltage will be induced in the vertical coils because the coil sides will be moving parallel to the lines of force and will not be cutting any of them. The coils in positions *B* and *B*' will be cutting across a maximum number of flux lines and will therefore have a maximum emf induced in them.

For the purpose of illustration, we shall assume that this emf is 6 V. The coils at positions *A*, *A*', *C*, and *C*' will then have an induced emf of approximately 4 V each. The result is that three voltage-producing coils are connected in series in each half of the armature.

Figure 10-14*b* shows a battery analogy of the armature circuit. In each of the two series circuits in the armature, there are two 4-V coils and one 6-V coil. The total emf from each series is 14 V, and since the two circuits are connected in parallel, the amperage will be twice that of one series circuit.

The armature-winding arrangement illustrated in Fig. 10-14 is known as **progressive lap winding**. There are several different types of windings used for generators and motors, but the one shown here is adequate for the purpose of this discussion.

Armature Reaction

Since an armature is wound with coils of wire, a magnetic field is set up in the armature whenever a current flows in the coils, as in Fig. 10-15*a*. This field is at right angles to the generator field shown in Fig. 10-15*b* and is called **cross magnetization** of the armature. The effect of the armature field is to distort the generator field and shift the neutral plane, as illustrated in Fig. 10-15*c*. Remember, the neutral plane is the position where the armature windings are moving parallel to the magnetic flux lines. This effect is known as **armature reaction** and is proportional to the current flowing in the armature coils.

The brushes of a generator must be set in the neutral plane, that is, they must contact segments of the commutator that are connected to armature coils having no induced emf. If the brushes were contacting commutator segments outside the

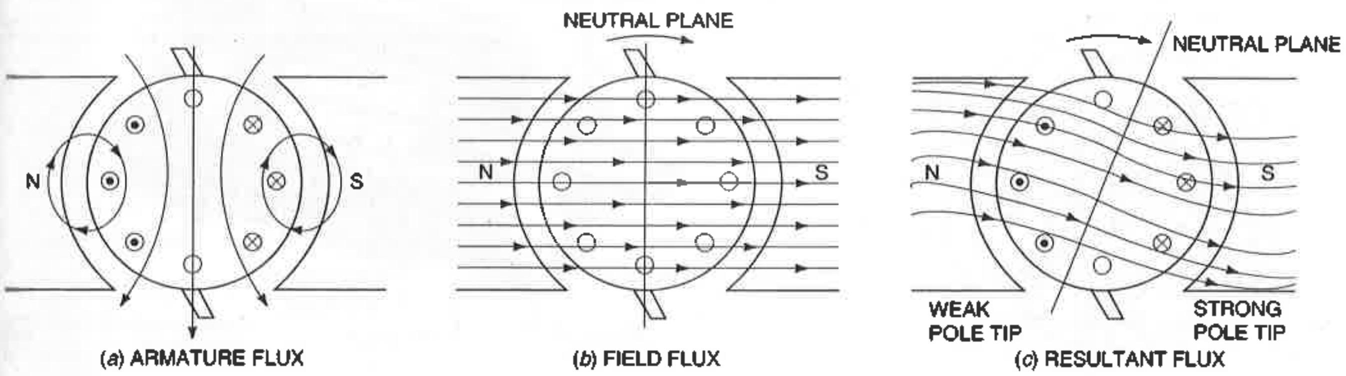


FIGURE 10-15 Armature reaction.

neutral plane, they would short-circuit "live" coils and cause arcing and loss of power. Armature reaction causes the neutral plane to shift in the direction of rotation, and if the brushes are in the neutral plane at no load, that is, when no armature current is flowing, they will not be in the neutral plane when armature current is flowing. For this reason, it is desirable to incorporate a corrective system into the generator design.

There are two principal methods by which the effect of armature reaction is overcome. The first method is to shift the position of the brushes so that they are in the neutral plane when the generator is producing its normal load current. In the other method, special field poles, called **interpoles**, are installed in the generator to counteract the effect of armature reaction.

The brush-setting method is satisfactory in installations in which the generator operates under a fairly constant load. If the load varies to a marked degree, the neutral plane will shift proportionately, and the brushes will not be in the correct position at all times. The brush-setting method is the most common means of correcting for armature reaction in small generators (those producing approximately 1000 W or less). Larger generators require the use of interpoles.

Interpoles

The use of interpoles is the most satisfactory method for maintaining a constant neutral plane in a generator. The windings of the interpoles are in series with the load; hence, the interpole effect is proportional to the load. The polarity of the interpoles is such that their effect is opposite to that of the armature field, that is, each interpole is of the same polarity as the next field pole in the direction of rotation. With this polarity, the interpole may be said to pull the generator field into the correct position. A typical interpole system is shown in Fig. 10-16.

In many generators a **compensating winding** is used to help overcome armature reaction. This winding consists of conductors embedded in the field-pole faces with one coil surrounding sections of two field poles of opposite polarity (see Fig. 10-17). The compensating winding is in series with the interpole windings; hence it works with the interpoles and increases their effectiveness. The sparkless commutation obtained by the use of interpoles and a compensating winding increases the life of the brushes and commutator, reduces radio interference, and greatly improves the efficiency of the generator.

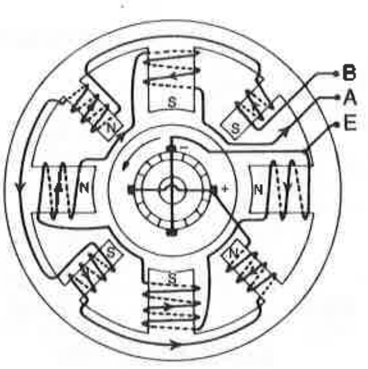
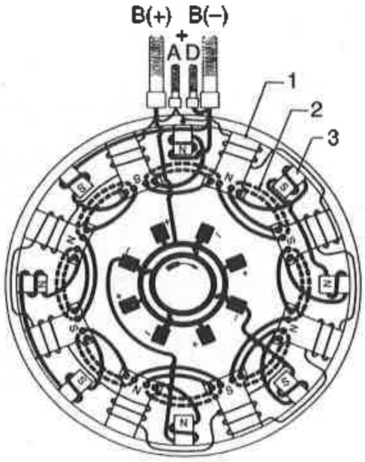


FIGURE 10-16 Generator circuit with interpoles.



1 MAIN FIELD POLE
2 COMPENSATING WINDING
3 INTERPOLE

FIGURE 10-17 Generator with interpoles and compensating winding.

DC GENERATOR CONSTRUCTION

All dc generators have several common characteristics. The armature windings connected to the commutator assembly are contained in the rotor. The field windings, which produce the electromagnetic field, are stationary or part of the stator assembly. The brushes of a dc generator are also stationary and used along with the commutator to rectify the current produced in the armature. In general, there are two main elements of all generators: the **rotor**, the assembly that rotates, and the **stator**, the assembly that is stationary. The rotor is connected to the engine through a drive belt or gear assembly and the stator is mounted to the engine. Although most dc generators are found only on older aircraft, there are still many flying and the underlying principles are important to understand. A typical generator cut-away diagram is shown in Fig. 10-18.

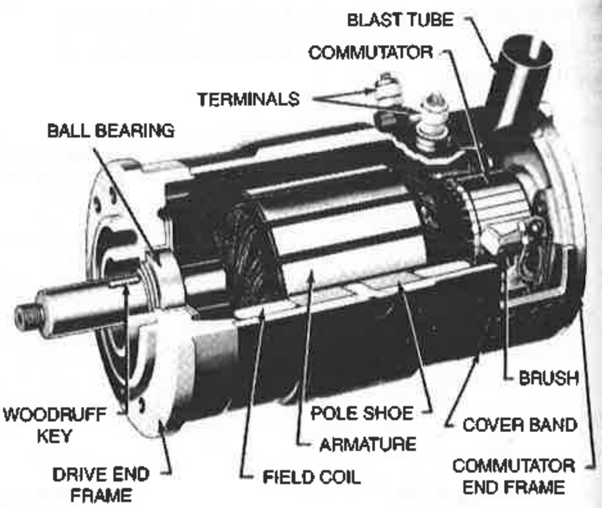


FIGURE 10-18 Typical low-output dc generators.

The following discussion will focus on a simple generator found on light aircraft. These basic design characteristics can be applied to all generators.

Armature/Rotor Assembly

The armature assembly (Fig. 10-19) consists of a laminated soft-iron core mounted on a steel shaft, the commutator at one end of the assembly, and armature coils wound through the slots of the armature core. The core is made of many soft-iron laminations coated with an insulating varnish and then stacked together. The purpose of the laminations is to eliminate or reduce the eddy currents that would be induced in a solid core. The effect of these currents was explained in Chap. 9. The laminations for the armature core are stacked together in such a manner that the slots are lined up so that the armature coils can be placed in them. Before the coil windings are installed, insulating paper or fabric is placed in the slots to protect the windings from wear and abrasion.

Insulated copper wire of a size large enough to carry the maximum armature currents is wound in coils through the slots of the armature.

Each end of the copper wire is then connected to a segment of the commutator. If the generator contains two brushes, the armature wire ends connect 180° apart; if four brushes are used, the winding ends connect to the commutator segments 90° apart.

After an armature is wound, the coils are held in place by means of nonmetallic wedges placed in the slots. On some models, bands of steel are placed around the armature to prevent the windings from being thrown out by centrifugal force when the armature is driven at high speeds.

The commutator consists of a number of copper segments insulated from the armature structure, and from each other. The insulation used must be a high-strength, high-temperature material that can be machined into thin complex shapes. A mineral substance, called mica, was used on older generators; today modern specialty plastics are often used. The segments are constructed to be held in place by wedges located between the shaft and the segments. A cross section of a typical commutator is shown in Fig. 10-20. Each commutator segment has a riser to which is soldered a lead from an armature coil. The surface of the commutator is cut and ground to a very smooth cylindrical surface. The insulation between the segments is undercut approximately 0.020 in. [0.051 cm] to make certain that it does not interfere with the contact of the brushes with the commutator.

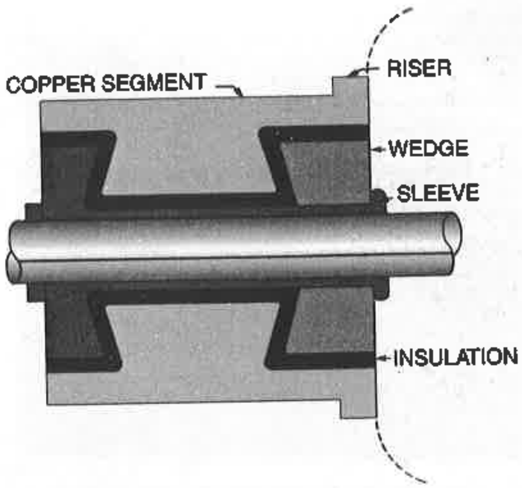


FIGURE 10-20 Cross section of a commutator.

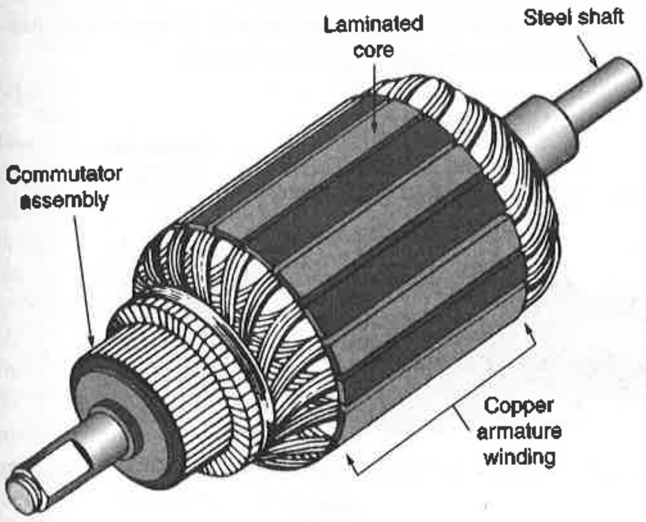


FIGURE 10-19 A typical armature assembly.

Field/Stator Assembly

The heavy iron or steel housing that supports the field poles is called the **field frame**, or **field housing**. It not only supports the field poles but also forms a part of the magnetic circuit of the field. The pole shoes are held in place by large countersunk screws that pass through the housing.

Small generators usually have two to four poles mounted in the field-frame assembly, and large generators can have as many as eight main poles and eight interpoles. The pole piecesare rectangular and in most cases are made of laminated steel. The main field windings consist of many turns of insulated copper wire. A typical field-frame assembly is shown in Fig. 10-21.

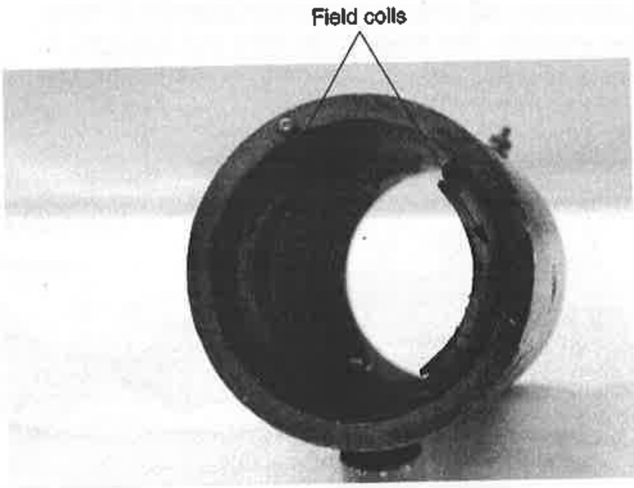


FIGURE 10-21 Generator field assembly; mounted inside generator housing.

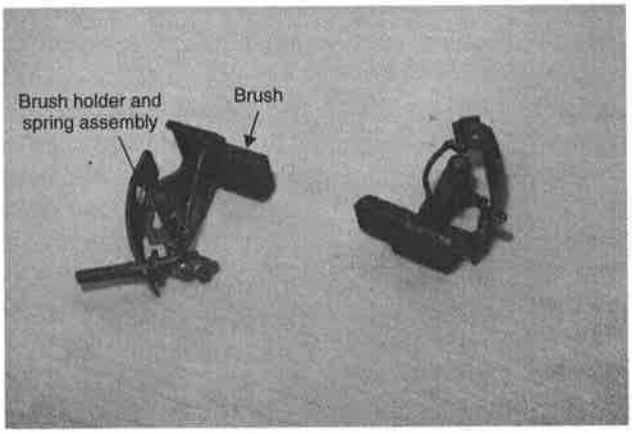


FIGURE 10-22 Generator brush assembly; removed from generator.

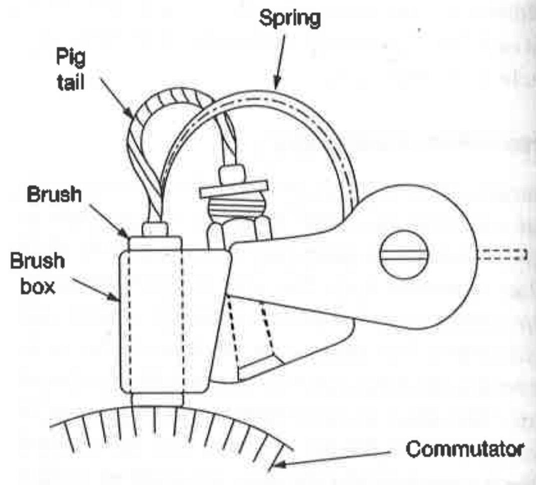


FIGURE 10-23 Diagram of a typical generator brush holder.

Brush Assembly

The brush assembly (Fig. 10-22) is located at the commutator end of the generator. The brushes are small blocks of a carbon and graphite compound soft enough to give minimum commutator wear but sufficiently hard to provide long service. Special brushes have been designed for generators operated at extremely high altitudes. These are needed because arcing increases at high altitudes and will cause the rapid deterioration of ordinary brushes.

As brushes wear, they slide in their metal holders and are held firmly against the commutator by means of springs. The tension of these springs should be sufficient to provide a brush pressure of approximately 6 psi [41 kPa] of contact surface. A flexible lead is connected from the brush to the brush frame to ensure a good electrical connection. A drawing of a typical brush holder is shown in Fig. 10-23.

End Frames

The generator **end frames** support the armature bearings and are mounted at each end of the field frame. The frame at the commutator end of the generator also supports the brush rigging assembly. The frame at the drive end is flanged to provide a mounting structure. On some generators, the end frames are attached to the field-frame assembly by means of long bolts extending entirely through the field frame. On others, the end frames are attached by machine screws into the ends of the field frame.

Generator bearings are usually of the ball type, prelubricated and sealed by the manufacturer. Prelubricated bearings do not require any service except at overhaul or in case of damage. The bearings fit snugly into the recesses in the end frames and are held in place by retainers attached to the end frames with screws. An expanded view of a typical generator is shown in Fig. 10-24.

Cooling Features

Since a generator operating at full capacity develops a large amount of heat, it is necessary to provide cooling. This is accomplished by means of passages leading through the generator housing between the field coils. In high-output generators there are also cooling air passages through the armature, and in some cases the generator will even be oil cooled. Cooling air is forced through the passages either by a fan mounted on the generator shaft, or by pressure from a ram air duct leading into an air scoop mounted on the end of the generator. Openings are provided in the end frame opposite the fan or air fittings to allow the heated air to pass through the generator housing.

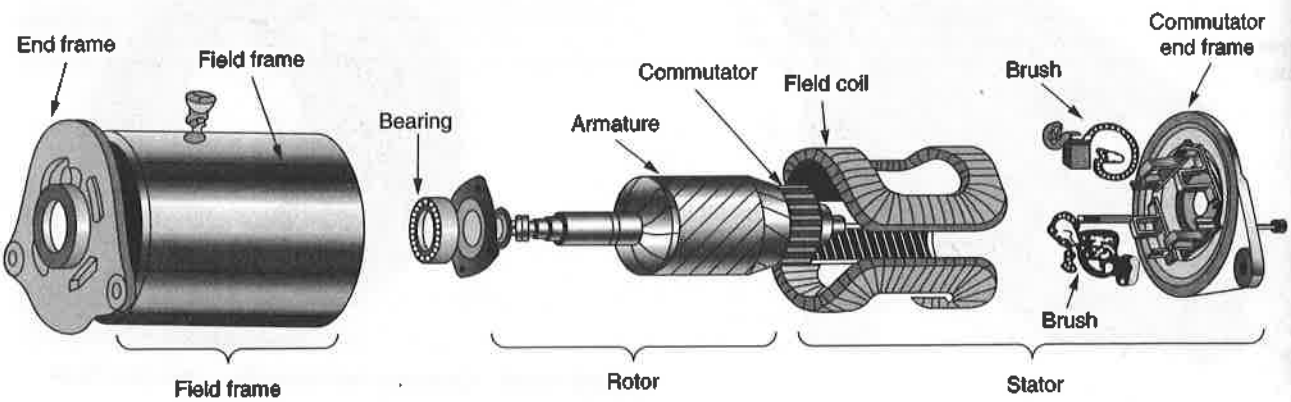


FIGURE 10-24 Expanded view of generator components.

STARTER-GENERATORS

A **starter-generator** is a combination of a generator and a starter in one housing as shown in Fig. 10-25. Starter-generators are typically employed on small turboprop and turbine-powered aircraft such as the Beechcraft King Air or Cessna Citation. Most starter-generators contain at least two sets of field windings and only one armature winding. While in the start mode, current is sent to the low-resistance field winding, which is connected in series with the armature. At this time, a high current flows through both the field and armature windings, producing the high torque required for engine starting.

While in the generator mode, the starter-generator is capable of supplying current to the aircraft's electrical system. A typical starter-generator can supply a direct current of up to 300 A at 28.5 V while in the generator mode. To generate electric power, the shunt winding of the starter-generator is energized, and the series field is de-energized. The shunt winding is a relatively high-resistance coil that produces the magnetic field to induce voltage into the armature. In this configuration, the unit operates just like a shunt-wound generator. The voltage produced in the armature sends current to the aircraft bus, where it is distributed to the various loads of the aircraft.

It should be noted that several types of starter-generators are currently in use. Some employ two separate field windings as stated above; others use only one (shunt) field winding. If only one field winding is used, special circuitry is needed in the generator control unit (GCU) to increase starting torque to an appropriate level. The technician should become familiar with any specific starter-generator before beginning maintenance procedures.

One advantage of the starter-generator is that only one drive gear mechanism is used for both the start and the generator modes. Therefore, the starter motor drive gear need not be engaged to or disengaged from the engine drive gear. Also, the starter-generator reduces both size and weight as compared to a conventional system that employs two units: a starter and a generator. The main disadvantage of starter-generators is that they are unable to maintain full output at a low rpm. Most starter-generators therefore must be used on turbine-powered aircraft that consistently maintain a relatively high engine rpm.

Starter-Generator Components

Starter-generators are designed to provide torque for engine starting and generate dc electric power for the aircraft's electrical systems. The starter-generator shown in Fig. 10-25 contains a self-excited four-pole generator. Four interpoles and a compensating winding are used to help overcome armature reaction. An integral fan is used to draw air through the unit during rotation. The cooling air is required to maintain temperature limits during high power generation. A clutch damper may be used on some units to connect the armature to the starter-generator's drive shaft. This clutch provides friction damping of any torsional loads that may be applied to the armature during operation. Changes in torsional loads occur whenever the aircraft's electric equipment is turned on or off. If the armature is connected directly to the engine, without a clutch, the torsional loads may overstress the drive shaft and cause generator failure. Some starter-generators employ a drive shaft **shear section**, which is used to protect the engine's gearbox in the event the generator mechanically fails and cannot rotate. In this situation the shear section breaks (shears) and disconnects the generator from the drive gear.

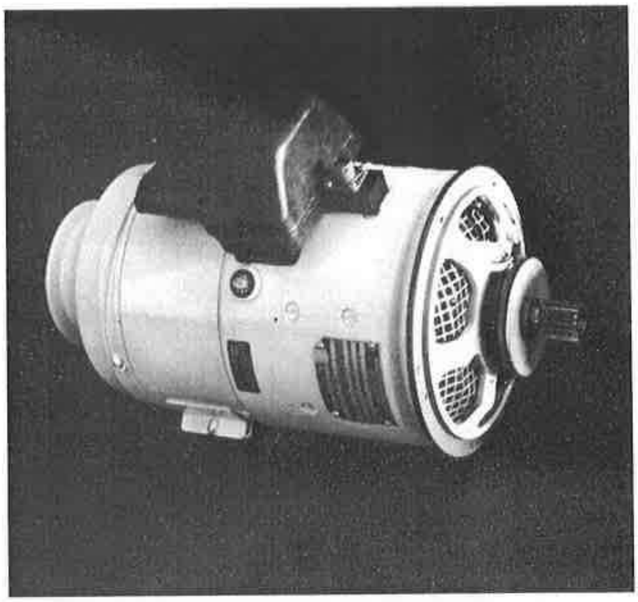


FIGURE 10-25 A typical starter-generator. (*Lear Siegler, Inc., Power Equipment Division.*)

GENERATOR CONTROL

Ways to Monitor Generator Output

There are two ways to monitor the output of a generator. The voltage produced by the generator can be indicated by a voltmeter, or the current flow from the generator can be displayed by an ammeter. One or both of these instruments are usually mounted on the aircraft's flight deck so the pilot can monitor generator operation. If only one instrument is used, the ammeter is preferred. A voltmeter should never be used without an ammeter.

The ammeter can be placed in the generator output lead, as shown in Fig. 10-26*a*, or in the battery positive lead, as shown in Fig. 10-26*b*. Ammeters located in the generator output lead measure only the current leaving the generator, therefore, they are calibrated in a positive scale only. A 30-A generator would require an ammeter scaled from 0 to 30 A. Any reading on this type of ammeter indicates that current is leaving the generator and flowing to the bus as indicated by the arrows in the diagram.

Ammeters located in the battery positive lead must be calibrated to indicate both a negative and positive value. A typical ammeter of this type reads from −60 A to 0 to +60 A. This is necessary because the current can flow through the ammeter eithere *to* or *from* the battery. If the battery is discharging, the ammeter will indicate a negative value. If the battery is

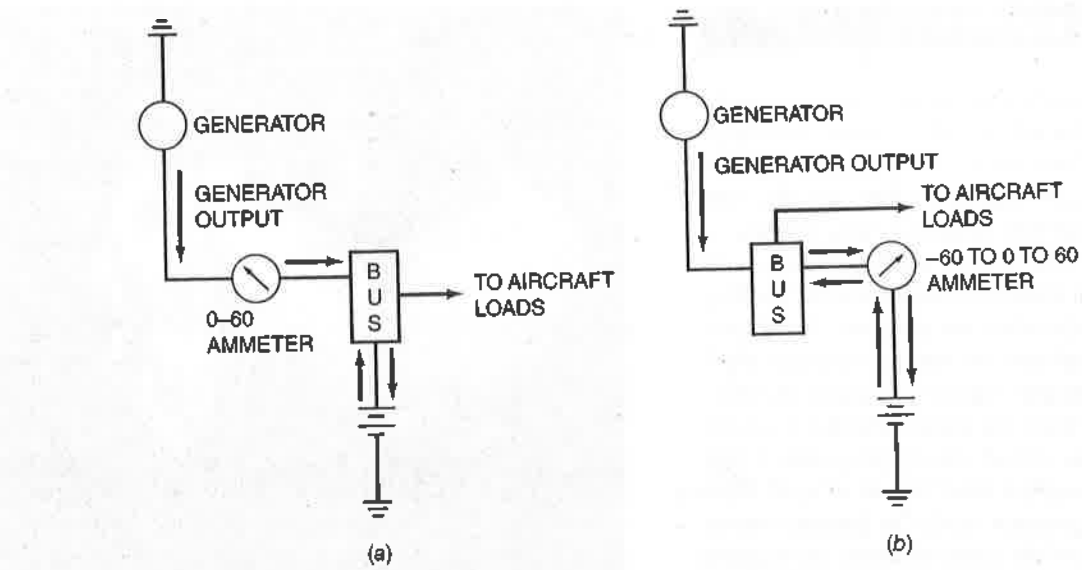


FIGURE 10-26 Ammeter placement in a generator system: (*a*) located in the generator output lead; (*b*) located in the battery lead.

charging, the ammeter will indicate a positive value. When this type of ammeter is used, the indications will be a positive value when the charging system is working properly.

Ammeters placed in the generator output lead and indicate positive values only are known as **single polarity ammeters.** Ammeters that are installed in series with the battery positive lead are called **dual polarity ammeters.** Both types of meters are commonly found on aircraft, so always know the system prior to analyzing generator output using the ships ammeter.

A voltmeter is often necessary to correctly monitor a generator's output on multiengine aircraft. The voltage of an operating generator must be slightly higher than battery voltage. This is necessary to ensure that the battery receives a charging current from the generator. Generators produce nearly 14 V for systems using 12-V batteries and 28 V for systems using 24-V batteries. With multigenerator systems it often becomes necessary to monitor the output voltage of each generator in order to determine which, if any, generator has failed. Some multiengine aircraft contain only one voltmeter, which can measure either bus voltage, right generator voltage, or left generator voltage by means of a control switch. This saves weight and space on the instrument panel.

Before making any determination as to the condition of a generator or generator system, be sure to run the aircraft and monitor all related instruments. At that time, consider the two different types of ammeters, specifically what they measure. This procedure will help to ensure a proper system diagnosis.

Some of the latest aircraft utilize digital instruments for display of generator outputs. In this case, a generator control unit would be used to monitor the generator and send a digital signal to the display management unit. This unit would analyze the generator status and send any warning or caution information to a flat panel display. The advantage of this type of display system is flexibility; during normal operation the generator information might not even be displayed, but if a fault occurs, the pilot would see a warning message and all appropriate generator output data.

Principles of Voltage Regulation

In the section of this chapter describing generator theory, it was explained that the voltage produced by electromagnetic induction depends on the number of lines of force being cut per second by a conductor. **In a generator, the voltage produced depends on three factors: (1) the speed at which the armature rotates, (2) the number of armature windings in the rotor, and (3) the strength of the magnetic field in the stator.** In order to maintain a constant output voltage from a generator under all speed and load conditions, some type of operator control is needed.

Since the generator is directly driven by the engine, it is obvious that the speed of a generator cannot be varied according to load requirements. Also, it is impossible to change the number of turns of wire in the armature during operation. Therefore, the only practical way to regulate the generator output voltage is to control the **strength of the field.** This is easily accomplished, because the strength of the field is determined by the current flowing through the field coils, and this current can be controlled by a variable resistor in the field circuit.

The simplest type of voltage regulation is accomplished as shown in Fig. 10-27. In this arrangement, a rheostat (variable resistor) is placed in series with the generator shunt field circuit. If the voltage rises above the desired value, the operator can reduce the field current with the rheostat, thus weakening the field and lowering the generator output. An increase in generator output is obtained by reducing the field circuit resistance with the rheostat. All methods of voltage regulation in aircraft electrical systems employ the principle of a variable or intermittent field resistance. Modern voltage regulators have been

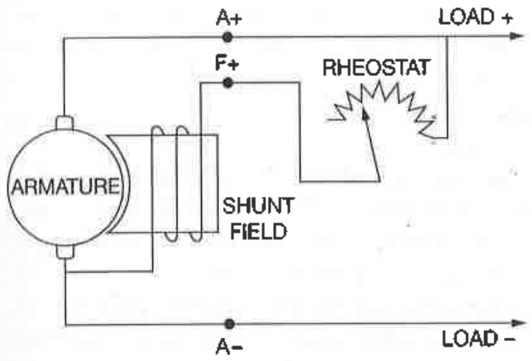


FIGURE 10-27 A simple voltage regulator (a variable resistor).

developed to such a high degree of efficiency that the emf of a generator will vary only a small fraction of a volt throughout extreme ranges of load and speed conditions.

Voltage regulators or **generator control units (GCU)** for modern aircraft are usually of the solid-state type, that is, they employ transistors and diodes as controlling elements. Because there are still many older airplanes in use that employ vibrator-type and variable-resistance voltage regulators, we shall examine these in the following sections.

Vibrator-Type Voltage Regulator

A generator system using a vibrator-type voltage regulator is shown in Fig. 10-28. A resistance that is intermittently cut in and out of the field circuit by means of vibrating contact points is placed in series with the field circuit. The contact points are controlled by a voltage coil connected in parallel with the generator output. When the generator voltage rises to the desired value, the voltage coil produces a magnetic field strong enough to open the contact points. When the points are open, the field current must pass through the resistance. This causes a substantial reduction in field current, with the result that the magnetic field in the generator is weakened. The generator voltage then drops immediately, causing the voltage coil electromagnet to lose strength so that a spring can close to the contact points. This allows the generator voltage to rise, and the cycle is then repeated. The contact points open and close many times a second, but the actual time that they are open depends on the load being carried by the generator and the generator (engine) rpm. As the generator load is increased, the time that the contact points remain closed increases, and the time that they are open decreases. Adjustment of the generator voltage is made by increasing or decreasing the tension of the spring that controls the contact points.

Often temperature greatly affects the generator output; therefore, this adjustment should be made only under specific conditions set up by the manufacturer.

Because the contact points do not burn or pit appreciably, vibrator-type voltage regulators are satisfactory for generators that require a low field current. In a system in which the generator field requires a current as high as 8 A, the vibrating contact points would soon burn and probably fuse together. For this reason high-output generators would typically employ a complex solid state control unit.

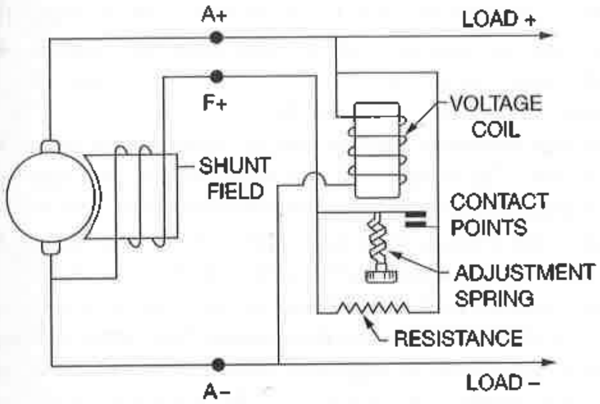


FIGURE 10-28 Vibrator-type regulator circuit.

Carbon-Pile Voltage Regulator

When carbon disks are assembled like a stack of quarters, the discs can be used as a variable resistance. This variable-resistance carbon stack is often referred to as a **carbon pile**. The resistance of the carbon varies as the discs are squeezed together; more pressure and the resistance is decreased, less pressure and the resistance increases. Carbon is often used as a low-cost reliable resistance in a variety of industrial applications. A stack of carbon discs can be found on equipment needing a variable resistance capable of high current. The greater the current requirement controlled by the carbon stack, the greater the dimensions of each disk. For the most part, carbon-pile regulators are no longer found on aircraft; however, the concepts will be presented here to help the reader understand the theory of generator control systems.

The carbon-pile voltage regulator derives its name from the fact that the regulating element (variable resistance) consists of a stack, or **pile**, of carbon disks (see Fig. 10-29). Usually, the carbon pile has alternate hard carbon and soft carbon (graphite) disks contained in a ceramic tube with a carbon or metal contact plug at each end. At one end of the pile, a number of radially arranged leaf springs exert pressure against the contact plug, thus keeping the disks pressed firmly together. For as long as the disks are compressed, the resistance of the pile is very low. If the pressure on the carbon pile is reduced, the resistance increases. By placing an electromagnet in a position where it will release the spring pressure on the disks as the voltage rises above a predetermined value, a stable and efficient voltage regulator is obtained.

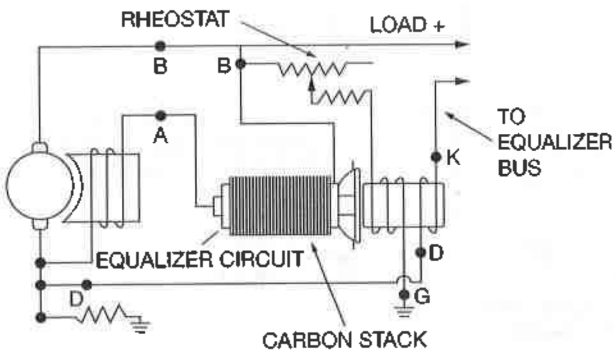


FIGURE 10-29 Carbon-pile voltage regulator circuit.

The carbon-pile voltage regulator is connected in a generator system the same way any other regulator is connected, that is, with a resistance in the field circuit and an electromagnet to control the resistance. The carbon pile is in series with the generator field, and the voltage coil is shunted across the generator output. A small manually operated rheostat is connected in series with the voltage coil to provide for a limited amount of adjustment, which is necessary when two or more generators are connected in parallel to the same electrical system.

Equalizing Circuit

When two or more generators are connected in parallel to a power system, the generators should share the load equally. The following example of an equalizing circuit is for explanation purposes only; the actual system found on aircraft would be more complex and most likely solid state. Although the components of a complex system are different, the basic operational theory will be similar. An understanding of this equalizing circuit can be applied to a variety of different aircraft which employ multiple generators. If the voltage of one generator is slightly higher than that of the other generators in parallel, that generator will assume the greater part of the load. For this reason, an equalizing circuit must be provided that will cause the load to be distributed evenly among the generators. An equalizing circuit includes an equalizing coil wound with the voltage coil in each of the voltage regulators, an equalizing bus to which all equalizing circuits are connected, and a low-resistance shunt in the ground lead of each generator (see Fig. 10-30). The equalizing coil will either strengthen or weaken the effect of the voltage coil, depending on the direction of current flow through the equalizing circuit. The low-resistance shunt in the ground lead of each generator causes a difference in potential between the negative terminals of the generators that is proportional to the difference in load current. The shunt resistor is of such a value that there will be a potential difference of 0.5 V across it at maximum generator load.

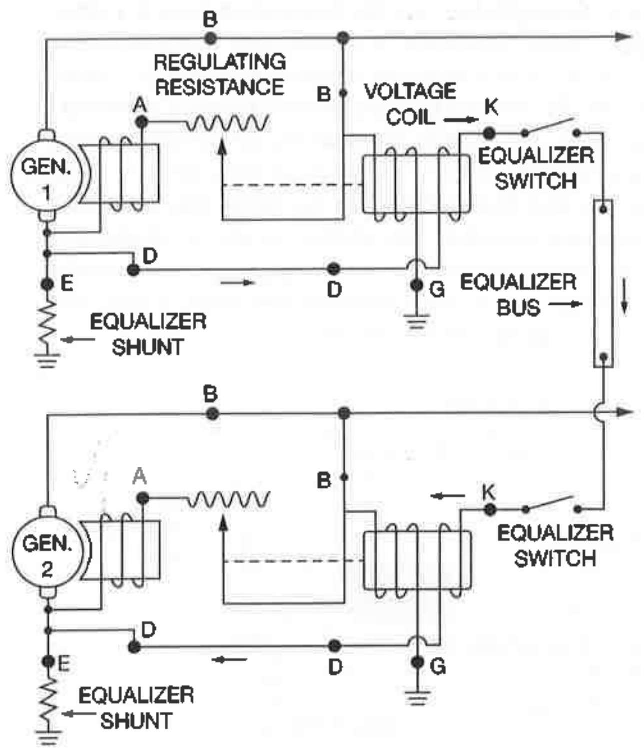


FIGURE 10-30 Equalizing circuit.

Assume that generator 1 in Fig. 10-30 is delivering 200 A (full load) and that generator 2 is delivering 100 A (half load). Under these conditions there will be a potential difference of 0.5 V across the shunt of generator 1 and 0.25 V across the shunt of generator 2. This will make a net potential difference of 0.25 V between the negative terminals of the generators. Since the equalizing circuit is connected between these points, a current will flow through the circuit. The current flowing through the equalizing coil of voltage regulator 1 will be in a direction to strengthen the effect of the voltage coil. This will cause more resistance to be placed in the field circuit of generator 1, thus weakening the field strength and causing the voltage to be reduced. The drop in voltage will result in the generator taking less load. The current flowing through the equalizing coil of voltage regulator 2 will be in a direction to oppose the effect of the voltage coil, thus causing a decrease in the resistance in the field circuit of generator 2. The generator voltage will increase because of increased current in the field windings, and the generator will take more of the load. To summarize, the effect of an equalizing circuit is to lower the voltage of a generator that is taking too much of the load and to increase the voltage of the generator that is not taking its share of the load.

Equalizing circuits can correct for only small differences in generator voltage; hence, the generators should be adjusted to be as nearly equal in voltage as possible. If the generator voltages are adjusted so that there is a difference of less than 0.5 V. between any of them, the equalizing circuit will maintain a satisfactory load balance. A periodic inspection of current flows and voltage values should be made to see that the generator loads are remaining properly balanced.

Reverse-Current Cutout Relay

In every system in which the generator is used to charge batteries as well as to supply operating power, an automatic means must be provided for disconnecting the generator from the battery when the generator voltage is lower than the battery voltage. If this is not done, the battery will discharge through the generator which could endanger the flight. Numerous devices have been manufactured for the purpose of automatically disconnecting the generator, the simplest being the **reverse-current cutout relay**. Figure 10-31 is a schematic diagram illustrating the operation of such a relay.

A **voltage coil** and a **current coil** are wound on the same soft-iron core. The voltage coil has many turns of fine wire and is connected in parallel with the generator output; that is, one end of the voltage winding is connected to the positive side of the generator output, and the other end of the winding is connected to ground, which is the negative side of the generator output. This is clearly shown in the diagram. The current coil consists of a few turns of large wire connected in series with the generator output; hence, it must carry the entire load current of the generator. A pair of heavy contact points is placed where

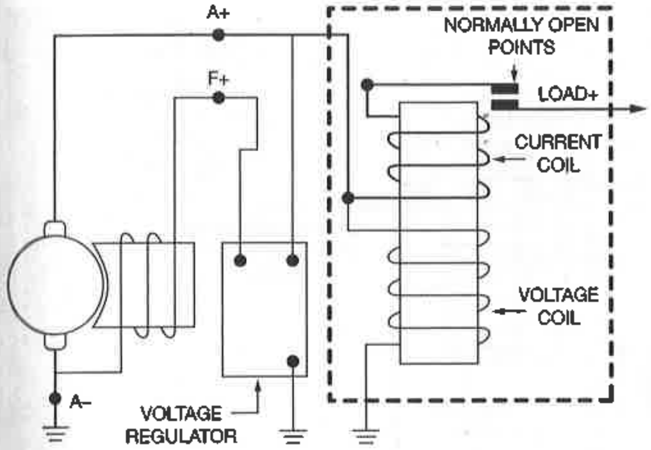


FIGURE 10-31 Reverse-current cutout relay circuit.

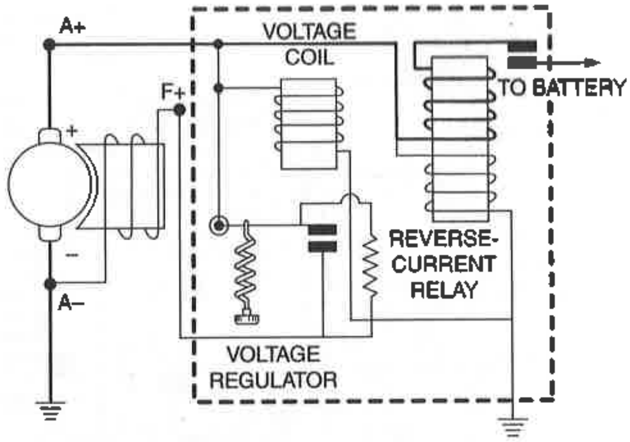


FIGURE 10-32 Two-unit generator control.

it will be controlled by the magnetic field of the soft-iron core. When the generator is not operating, these contact points are held in an open position by a spring.

When the generator voltage reaches a value slightly above that of the battery in the system, the voltage coil in the relay magnetizes the soft-iron core sufficiently to overcome the spring tension. The magnetic field closes the contact points and thus connects the generator to the electrical system of the airplane. As long as the generator voltage remains higher than the battery voltage, the current flow through the current coil will be in a direction that aids the voltage coil in keeping the points closed. This means that the field of the current coil will be in the same direction as the magnetic field of the voltage coil and that the two will strengthen each other.

If a problem with the generator circuit should occur, the generator voltage will decrease and fall below that of the battery. In this case, the battery voltage will cause current to start flowing toward the generator through the relay current coil. When this happens, the current flow will be in a direction that creates a field opposing the field of the voltage winding. This results in a weakening of the total field of the relay, and the contact points are opened by the spring, thus disconnecting the generator from the battery.

Generally speaking, the tension of the spring controlling the contact points should be adjusted so that the points will close at approximately 13.5 V in a 12-V system and at 26.6 to 27 V in a 24-V system. However always refer to the manufacturer's technical data prior to any adjustments. A two unit regulator containing a voltage regulator and reverse-current relay is shown in Fig. 10-32.

Current Limiter

In some generator systems, a device is installed that will reduce the generator voltage whenever the maximum safe load is exceeded. This device is called a **current limiter** and is designed to protect the generator from loads that will cause it to overheat and eventually create a safety hazard.

The current limiter operates on a principle similar to that of the vibrator-type voltage regulator. Instead of having a voltage coil to regulate the resistance in the field circuit of the generator, the current limiter has a current coil connected in series with the generator load circuit (see Fig. 10-33).

When the load current becomes excessive, the current coil magnetizes the iron core sufficiently to open the contact points and add a resistance to the generator field circuit. This causes the generator voltage to decrease, with a corresponding decrease in generator current. Since the magnetism produced by the current-limiter coil is proportional to the current flowing through it, the decrease in generator load current also weakens the magnetic field of the current coil and thus permits the contact points to close. This removes the resistance from the generator field circuit and allows the voltage to rise again. If an excessive load remains connected to the generator, the contacts of the current limiter will continue to vibrate, thus holding the current output at or below the minimum safe limit. The contact points are usually set to open when the current flow is 10 percent above the rated capacity of the generator.

The current limiter described above should not be confused with the fuse-type current limiter. The fuse-type limiter is merely a high-capacity fuse that permits a short period of overload in a circuit before the fuse link melts and breaks the circuit.

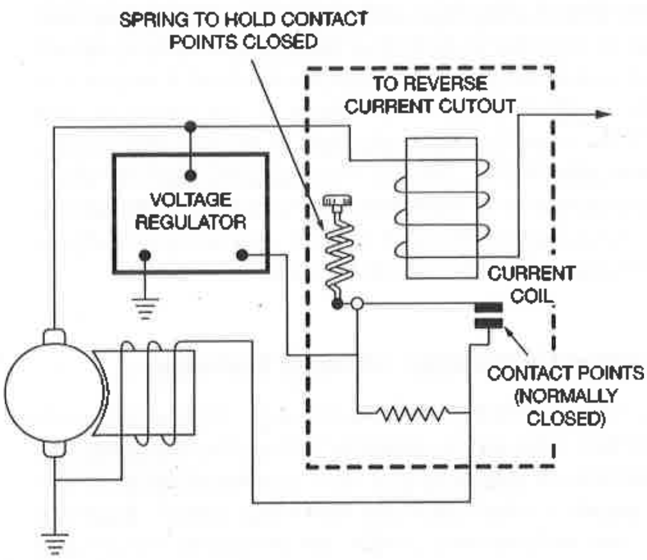


FIGURE 10-33 Current-limiter circuit.

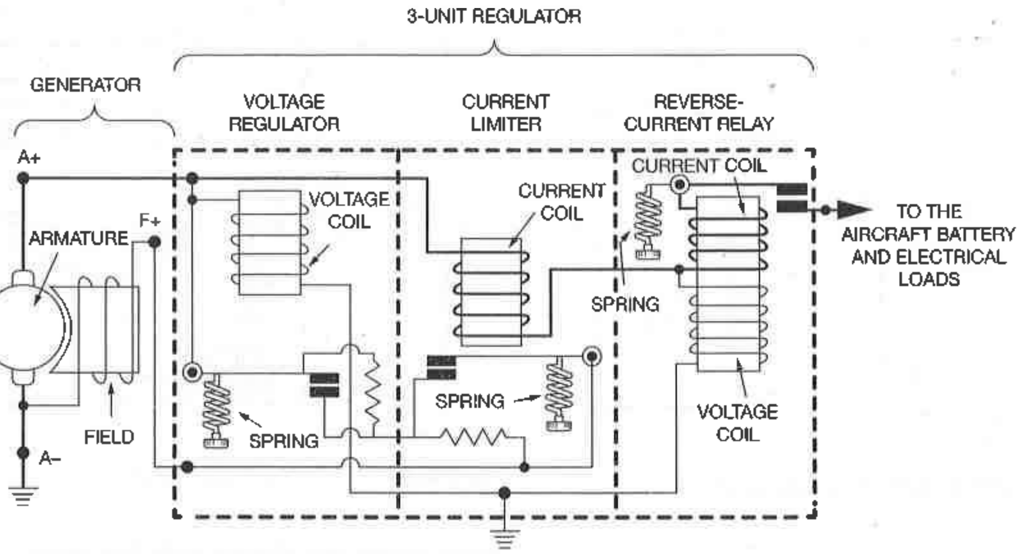


FIGURE 10-34 Three-unit generator control.

Three-Unit Regulator

When the three control circuits (voltage regulator, current limiter, and reverse-current relay) are combined into one unit, it is called a **three-unit regulator**. Various members of the industry may also call the three-unit regulator a **generator control unit (GCU)** or simply a **voltage regulator**. By any name, the generator control is a combination of the three circuits just presented all contained in one housing. As seen in the Fig. 10-34, the generator field current is controlled by both the voltage regulator and current limiter circuits. The reverse-current relay controls the main output current of the generator to prevent reverse current. Each of these circuits will open or close a set of contact points in order to ensure the generator system maintains the correct output for any flight or electrical load variable.

A three-unit regulator with the protective cover removed is shown in Fig. 10-35; in this diagram, it is easy to see the three distinct relay coils and associated contact points. This type of regulator is typical of those found on light aircraft with generators that output approximately 90 A or less. The unit is approximately 6 in. wide, 4 in. tall, and 4 in. deep with the cover on. Although many of these regulators have minor adjustments, they are often replaced when the charging system is out of calibration. On most aircraft, the generator control unit is mounted near the generator, typically on the engine side of the aircraft firewall.

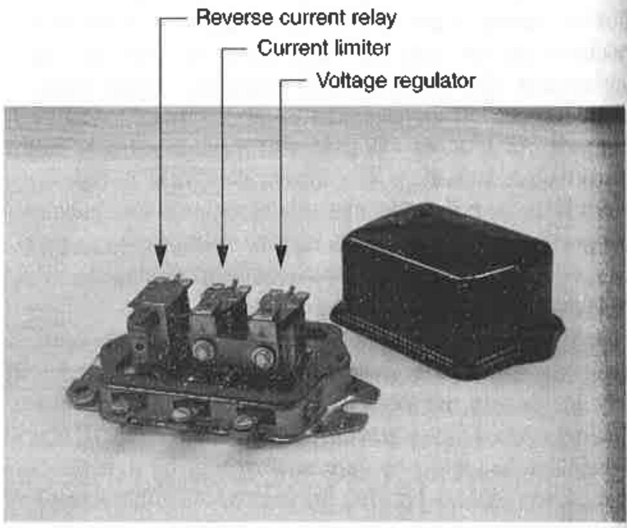


FIGURE 10-35 A three-unit generator regulator.

Starter-Generator Control Systems

The control circuits of a starter-generator are relatively complex; they must control current for both starting and generating operations. A typical shorter GCU is pictured in Fig. 10-36; it contains a voltage regulator, the various control circuits for the start and generator modes, and protection circuits used during abnormal operating conditions. The GCU electronic components are contained on three printed circuit boards. Each board is mounted on a forged aluminum base, which acts as a heat sink for those components which must dissipate heat. The entire unit is enclosed by an aluminum cover that allows for all external connections to be exposed.

GCU Functions

The start mode of a starter-generator is controlled through a circuit independent of the GCU. During starting, battery or auxiliary power unit (APU) current is sent to the starter-generator via a starter contactor. The starter contactor is energized by the engine start switch on the flight deck. While in the generator mode, the GCU controls the generator output, system protection, and self-test functions. If a fault is detected in the generator system, the GCU will illuminate

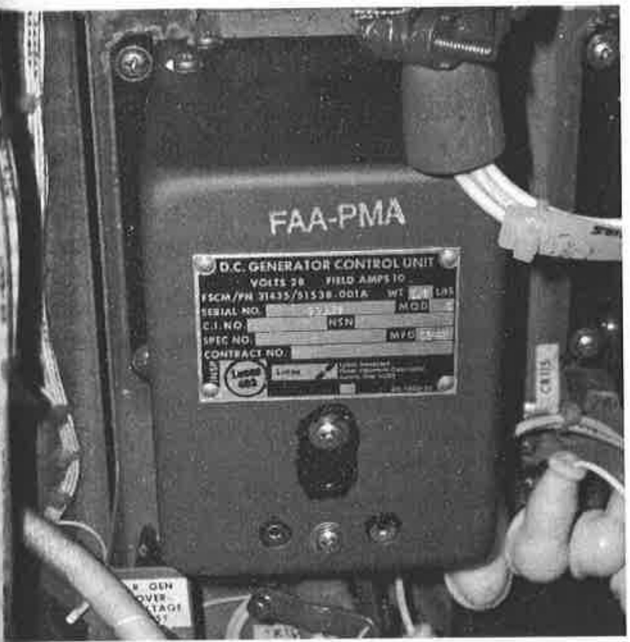


FIGURE 10-36 A typical Generator Control Unit (GCU) installed in a turboprop aircraft.

the appropriate annunciator on the flight deck and may sound a warning horn or tone. The generator control unit is capable of performing the following 10 functions:

1. *Voltage Regulation* The voltage regulator section of the GCU maintains a constant generator voltage under various loads, temperatures, and rotational speeds. The current of the generator field circuit is controlled through the field transistor. This transistor varies the field current pulse time to vary generator output. This is similar to the voltage relay in the three-unit regulator discussed earlier.

2. *Generator Line Contactor Control* The generator line contactor control provides a means of connecting the generator output to the aircraft's dc load bus. This circuit operates with a time delay to ensure that generator voltage is nearly equal to bus voltage immediately following initial engine starting. Several inhibiting signals are also employed to ensure proper contactor positioning (open or closed) when failure conditions are sensed.

3. *Overvoltage Protection* The overvoltage protection circuit prevents damage to aircraft equipment in the event an excessive generator output occurs. If the generator output voltage exceeds the preset limits, an integrator starts to function. This integrator is used as an inverse time delay, so that a slight overvoltage condition is allowed for a much longer time than a severe one before a trip occurs. In this way, unusually large but momentary voltage transients will not cause a nuisance trip of the field relay. If a severe overvoltage is sensed, the generator is de-energized and the line contactor is opened. A completely separate circuit is used to open the generator line contactor as soon as the voltage exceeds 40 V dc. This feature not only provides redundant protection for utilization equipment but also allows a faster response of the line contactor after a failure. Unlike the overvoltage with inverse time delay, this function is not latched, so that manual reset is not required after a temporary overvoltage condition.

4. *Overload and Undervoltage Protection* The overload and undervoltage protective functions cooperate to de-energize the system in the event of an overload condition. An overload condition is sensed by the GCU as either a generator overcurrent condition as indicated by an excessive generator interpole voltage or an undervoltage condition. When the GCU senses either condition, an internal time delay is initiated. If the overload condition continues for a period of approximately 10 s, the GCU trips the field relay, de-energizing the generator and opening the line contactor.

5. *Reverse-Current and Differential Voltage Protection* The reverse-current protection function senses generator interpole voltage to determine whether the generator is acting as a load on the system rather than a power source. If, because of a failure or during a normal engine shutdown, current begins to flow into the generator, this is sensed and the line contactor is opened. An inverse time delay is used to quickly open the contactor under severe conditions, while more time is allowed during normal shutdowns. This prevents needless cycling of the contactor during a transient condition. The circuit is not latched, and so no reset is required to reclose the contactor after reverse current is sensed. The contactor is held open owing to differential voltage sensing once reverse current has been detected. The differential voltage function also operates on generator buildup to keep the generator line contactor from closing until the generator output voltage is within 0.5 V dc of the bus voltage.

6. *Reverse-Polarity Protection* The reverse-polarity protection function protects the utilization equipment from reverse-polarity buildup of the generator. This protection trips the field relay to de-energize the generator.

7. *Anticycle Protection* The anticycle protection feature prevents more than one reset attempt of the generator field relay for each activation of the generator control switch. Because the generator output voltage is used for GCU control power, and this voltage disappears after a trip, the system would repetitively build up in voltage and trip again if a fault existed in the system.

8. *Latching Field Relay Control* A magnetic latching field relay is used to de-energize the generator after a fault condition has been sensed. The field relay is used to de-energize the generator by opening the generator shunt field excitation path and open the line contactor by opening its power input. The field relay is tripped by a protection function such as overvoltage, overload, undervoltage, reverse polarity, or open ground wire sensing; it may also be tripped by an external switch applying a ground signal to the GCU.

9. *Flash and Start Relay Control* The field-flashing relay and the associated circuitry ensure that the generator output can be built up from the residual voltage without help from any other power source. The residual voltage bootstraps the generator upward to a point where the field relay is reset and then to a higher voltage to energize the field-flashing relay. Once the field-flashing relay is energized, the field flash path is broken, but the normal voltage regulator circuitry is able to operate at this voltage level, and so the generator continues to build up to the normal operating voltage.

10. *Overvoltage and Overload Protection Self-Test* Provisions are made within the GCU to enable it to periodically exercise the overvoltage, overload, and undervoltage protection circuits. A passive failure of the circuitry would not otherwise be discovered until that function was required to operate. If an external-test switch applies generator output voltage to the GCU, the protection will be biased to a point where it will operate, even though normal voltage appears on the generator output. If a trip of the channel results within a few seconds after the voltage has been applied, the circuit is working correctly.

GENERATOR INSPECTION, SERVICE, AND REPAIR

Generator Load Balancing

When it is desired to balance the load among multiple generators in any system, the technician should always follow the procedure set forth by the manufacturer of the aircraft. This procedure will be found in the manufacturer's service or maintenance manual.

The test procedure is usually begun by checking all generators with a precision voltmeter. This is done after the generators and engines are warmed up to normal operating temperature. Under these conditions, all generators are adjusted to exactly the same output voltage (28 to 29 V for a 24-V system). A substantial load is then turned on, and the ammeters are examined. All generator loads should be within ± 10 percent of one another. If the generator loads are not within these limits, the generator with the greatest error should be adjusted first. A small adjustment to the voltage regulator should produce an instant change in the load current for the generator being adjusted. If the load on one generator is reduced, the other generators will add load. The ammeters for all generators should be watched while the adjustments are being made.

If the aircraft generators cannot be properly balanced, the system should be repaired before the aircraft is returned to service. The process of balancing generators is often referred to as **paralleling the generators**. If both generators are producing equal voltage, they will carry equal current loads if connected in parallel.

Generator Troubleshooting

The first step in troubleshooting a generator circuit on an aircraft is to determine what type of system is in use. If the system is on a small airplane, it is likely that the control unit is a three-element type, that is, that it contains a voltage regulator, a reverse-current cutout relay, and a current limiter. If the system contains a 24-V generator or starter-generator, it is likely that a more complex control is employed. Modern starter generator systems are found on most corporate and commuter aircraft. These aircraft contain transistorized or digital GCUs, which often contain built in self-test features to aid in system troubleshooting. Always refer to the current manufacturer's data and electrical wiring diagrams prior to any troubleshooting.

The two most likely indications of generator system failure are (1) no or low voltage and (2) battery discharge. If the aircraft's ammeter indicates a battery discharge, the generator may not be producing the proper voltage. The voltage at the generator's output terminal can then be measured, and if approximately 2 to 6 V is present with the system operating, the generator is operating from residual magnetism only. This means that there is no current through the generator field coils and some component of the field circuit is defective. Likely suspects include wiring connections, the generator master switch, the voltage regulator, and the generator's field. If zero volts is measured between the generator's output terminal and ground with the system operating, the generator has lost its residual magnetism, or the armature circuit is defective. A generator output voltage of zero may also indicate a generator brush failure.

If it becomes necessary to determine if the voltage regulator or the generator is defective, simply bypass the voltage regulator circuit. This is done by connecting a voltage directly to the generator's field circuit monitoring generator output. If current is fed into the field of a rotating generator, that generator should produce a normal or above-normal output voltage. Since there are two different methods of wiring a generator's field, one must first determine which method is being used. With one method, the field positive is connected to the voltage regulator, as illustrated in Fig. 10-37*a*; with the other method, the field negative is connected to the voltage regulator, as shown in Fig. 10-37*b*. To bypass the voltage regulator,

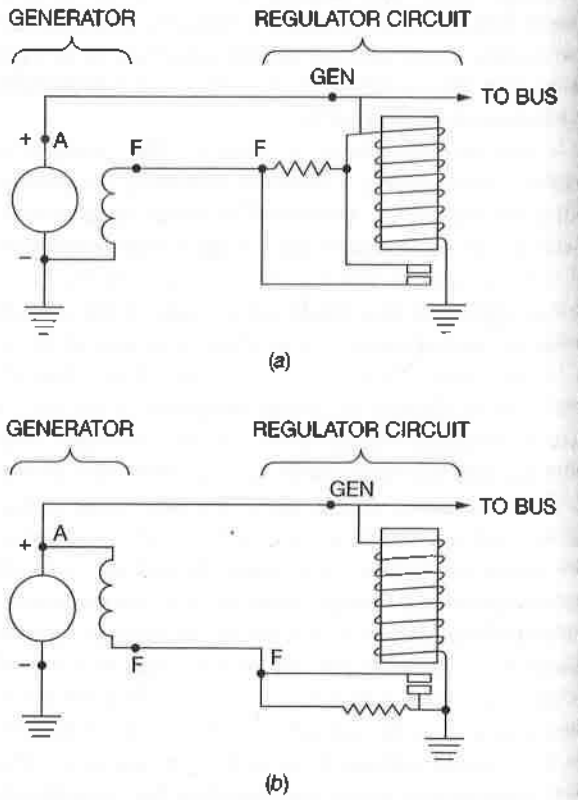


FIGURE 10-37 Different arrangements for field control circuits: (*a*) controlling field positive voltage; (*b*) controlling field negative voltage.

the correct voltage signal (positive or negative) must be connected to the generator F terminal with the regulator disconnected and the generator armature rotating. If the voltage measured at the generator output terminal to ground is less than system voltage, the generator is defective.

If the generator output voltage is at or above the normal value, the generator is good and the voltage regulator most likely is defective. There may be some defective conditions that this test will not detect; however, for the most part, bypassing the regulator is valid. Many factors must be considered when one is troubleshooting a generator system; always become familiar with the system before troubleshooting begins.

Starter-Generator Maintenance

All starter-generator maintenance and inspection procedures should be performed in accordance with current manufacturer's data. Most manufacturers require periodic inspections of starter-generators to ensure proper system operation. These inspections can be performed as often as every 200 flight hours or as part of a progressive inspection. The interval between starter-generator overhauls should not exceed 1000 h unless specified by the aircraft manufacturer. The typical brush life for starter-generators ranges from 500 to 1000 h. Both the brushes and the commutators must be inspected to ensure that they do not wear beyond operational limits.

The following information is intended as a general reference of typical troubleshooting inspection techniques. The specific details of the starter and generator circuits will vary significantly between installations. However, in general, all starter-generators require that current be sent to both the armature and the field for starting and that current be sent only to the field for generating purposes. The units that control the current to and from the starter-generator can be bypassed to determine proper system operation. This procedure should be performed only after achieving a complete understanding of the system. This will ensure that no components will be damaged by the bypass test.

If the generator is determined to be defective, one or more of the following procedures can be employed. The starter-generator can be removed from the engine by loosening the attachment bolts or the quick-attach-detach (QAD) adapter. A QAD adapter is mounted to many generators and starter-generators to allow for easy removal and installation of the unit. This eliminates long maintenance times for generator replacement. Typically, only one bolt or latching mechanism must be loosened to remove a unit that uses a QAD adapter. Always be careful to properly support the starter-generator during removal and installation. The unit's drive shaft *shear section* can be damaged if the starter-generator is allowed to hang, unsupported, by the drive shaft spline.

Cleaning the starter-generator should be accomplished by removing the brush inspection cover and using compressed air, at about 40 psi, to blow away any carbon and copper dust. This dust collects around the electrical windings and brush assembly as a result of normal brush and commutator wear.

An approved solvent should be used to clean the exterior of the unit. Once the unit is cleaned, a thorough visual inspection should be performed. Items that require special consideration are the brush assembly, the commutator, the cooling system, and the drive shaft.

The brushes should be checked for cracks, chips, frayed leads, and general integrity. Many brushes incorporate a **wear groove** in order to facilitate inspection. The amount of wear groove visible indicates the service life remaining on that particular brush. Fig. 10-38 shows a typical wear groove reference. The brush holders and springs should also be inspected for damage or excess wear. On many units, the starter-generator brushes can be replaced without brush seating if **"instant-filming"** brushes are installed. Instant-filming brushes contain a lubricating additive that improves brush conductivity and wear characteristics. These brushes can be replaced in the field without commutator resurfacing if the commutator is not excessively worn.

The commutator of the starter-generator should be inspected for burned spots, pitting, or excessive wear. The commutator insulators should be undercut to 0.020 in. [0.051 cm] on most models. The cooling fan, any related vent holes, and air ducts should be inspected and cleaned thoroughly. Any loose, cracked, or bent fans should be replaced.

The drive mechanism should be inspected for excess wear or damage. Most starter-generators incorporate a damper assembly to absorb excessive shock loads. This damping assembly is subject to extreme load changes during normal operation; therefore, it should be inspected carefully to ensure proper system operation. If any defects are found, the starter-generator should be sent to an appropriate overhaul facility. The drive shaft or spline should be inspected for excess wear or damage, and any defective mounting gasket or O-ring should be replaced prior to installation of the starter-generator. After installation of the unit, a thorough operational check should be performed to ensure that the system functions properly.

Flashing the Field

If a generator fails to show any voltage whatsoever when it is operating at the proper rpm, this condition is often due to the loss of the residual magnetism in the field. This can be corrected by **flashing the field**.

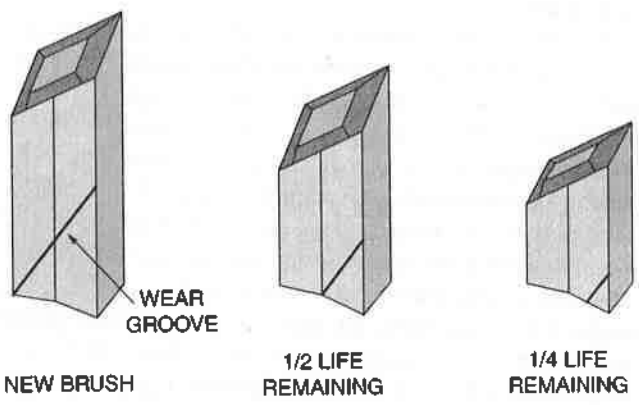


FIGURE 10-38 Typical generator brush wear groove.

To flash the field of any generator, a voltage must be momentarily applied with the correct polarity to the field coil. Prior to flashing the field, always disconnect the voltage regulator from the generator. This will prevent possible damage to the regulator circuit. It is also important to observe polarity, connecting positive voltage to the field positive lead and negative voltage to the field negative lead. The internal wiring of the generator must be known to ensure proper polarity during the flashing operation; consult the appropriate service or maintenance manuals.

Inspection

Generators in service should be given a periodic inspection of external connections, wiring, brushes, commutator, mounting, and performance. These inspections should be carried out according to the manufacturer's instructions; however, a good general rule is that generator inspection should be performed at least every 100 flight hours. Keep in mind aircraft technicians often perform inspections; however, generator maintenance is typically performed at certified repair stations. The following inspections are considered essential and a general description of related maintenance is shown below.

1. Inspect the generator terminal connections to see that they are clean and tight.
2. Inspect the flange mounting for cracks or looseness of mounting bolts. See that there are no oil leaks around the mounting.
3. Remove the cap or band that covers the brushes and cummutator. Blow out any accurmulation of carbon dust with dry compressed air. Inspect the brushes for amount of wear, and see that they slide freely in the holders. If a brush is binding in the holder, it should be removed and cleaned with a clean cloth moistened with unleaded gasoline or a good petroleum solvent. If brushes are worn in excess of the tolerances specified by the manufacturer, they must be replaced. Inspect the tension of the brush springs by lifting them with the fingers. A weak spring should be adjusted or replaced. If a spring scale of the proper range is available, it may be used to measure the brush-spring tension; the spring tension should measure within the manufacturer's specifications.
4. Inspect the commutator for cleanliness, wear, and pitting. A commutator in good condition should be smooth and of a light chocolate color. If there is a slight amount of roughness on the commutator, it can be removed with No. 000 sandpaper or a special abrasive stick manufactured for cleaning commutators and seating brushes. If an abrasive stick is used, the proper application is to hold the end of the stick against the commutator while the generator is running. This is done until the commutator is smooth, clean, and bright. After smoothing, all sand and dust particles should be blown out with compressed air. Never clean a commutator or seat brushes with a metallic abrasive paper. The metal particles may become lodged between the commutator segments and short-circuit the armature. Dirt may be removed from the commutator with a cloth moistened with a petroleum solvent. Oil on the brushes and commutator indicates a faulty oil seal in the engine. If this condition exists, the generator should be removed, disassembled, and thoroughly cleaned. If the end frame of the generator has an oil drain vent, it should be inspected to see that it is open. Before the generator is reinstalled, the engine oil seal at the generator drive must be replaced.
5. Inspect the area inside the commutator end of the generator case for lead particles. If particles of lead are visible, it is likely that the armature has been overheated. This may have been caused by overloading of the generator for a sustained period, by short-circuited coils in the armature, by short-circuited segments of the commutator, or by the sticking of the reverse-current-relay points. The generator should be removed and a new or rebuilt armature installed. Before the generator is reinstalled, the cause of armature failure should be determined and corrected.
6. Always inspect the mounting of the generator to the aircraft. The structure must be free of cracks and all bolts correctly torqued. The mounting bracket bolt holes should be carefully inspected. If any elongated holes are found, the structure must be repaired or replaced. Inspect the generator belt for wear and/or cracks. The correct belt tension is also very important. Typically, an installed belt should deflect about ½ in. when a moderate pressure is applied by hand.

Disassembly

The disassembly procedure for generators cannot be discussed in detail in this text, inasmuch as it varies among different makes and models of generators. However, if it becomes necessary to disassemble a generator, the technician should refer to the instructions furnished by the manufacturer of that particular model. If these instructions are not available, the technician can proceed as follows with reasonably good results:

1. Remove the strap or cap that covers the brushes and commutator.
2. Remove the brushes, and disconnect the flexible leads from the brush holders. Mark the brushes for their proper position in the brush rigging.
3. Disconnect the field and terminal leads, and mark the connections so that they can be reconnected correctly.
4. Remove the screws or bolts that attach the end frames to the field frame. Some generators have a nut and washer that holds the armature shaft in the bearing; in this case, the nut and washer must be removed before the end frames are taken off.
5. When both end frames are free, remove them and take out the armature. *Note:* Further disassembly can be accomplished as required, but for inspection and cleaning purposes the removal of brushes, end frames, and armature is usually sufficient.
6. After disassembly blow the brush dust from the field assembly, using dry compressed air.
7. Use a brush or cloth moistened with an approved solvent to clean the field-frame assembly, commutator, and brush rigging.

Repair of the Commutator

If the commutator is slightly rough or pitted, it can be smoothed with No. 000 sandpaper. After smoothing, blow out all sand and dust particles with dry compressed air. If the commutator is very rough or badly pitted, the armature should be placed on a metal turning lathe and a light cut taken across the surface of the commutator. This is most easily accomplished with equipment especially designed for the purpose. The cut on the commutator should be only deep enough to remove the irregularities on the surface. This cut will also correct any eccentricity that has developed as a result of uneven wear. Be sure to verify all dimensions with the appropriate technical data; it is important to maintain all tolerance limits.

After the commutator has been tuned on a lathe, it is necessary to undercut the insulation between the segments to a depth of approximately 0.020 in. [0.051 cm]. To assure a clean cut to the required depth, use a cutting tool slightly wider than the thickness of the insulation. After undercutting the insulation, smooth any burrs or sharp edges on the commutator segments with No. 000 sandpaper.

Testing

For testing armatures, a device called a **growler** is used. This device consists of many turns of wire wound around a laminated core with two heavy pole shoes extended upward to form a V into which an armature can be placed. Actually, the growler is nothing more than a large, specially designed electromagnet. Figure 10-39 shows an armature being tested on a growler. The power supply for the growler is standard 11 0-V alternating current. The current causes a noticeable hum when an armature is placed between the pole shoes; hence the name *growler.*

When placed on a growler, an armature forms the secondary of a transformer. The winding of the growler is the primary. The rapidly moving field produced by the winding of the growler induces an alternating current in the windings of the armature. By connecting a test meter between segments of the commutator and the armature on the growler (see Fig. 10-40), it can be determined whether an open circuit exists in any of the coils. The meter will indicate a given voltage when connected across segments of a good coil. To test for a short circuit in the windings, a thin strip of steel is placed on the armature segments,

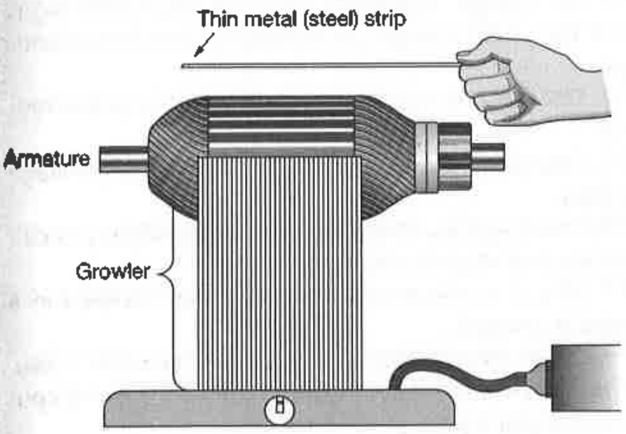


FIGURE 10-39 Armature testing using a growler.

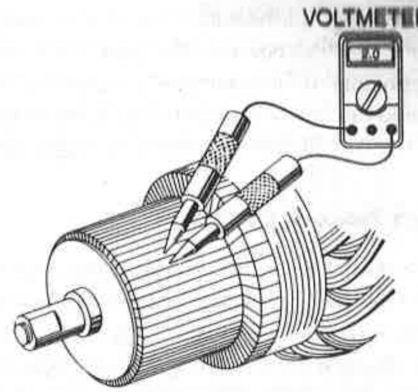


FIGURE 10-40 Testing for an open coil in an armature.

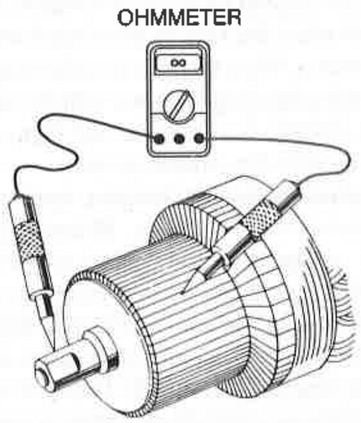


FIGURE 10-41 Testing an armature for a short to ground.

and the armature is slowly rotated between the poles of the growler. If there are no shorts, a weak magnetic attraction will be noticed. One or more shorted coils will cause a strong vibration of the metal strip at certain points on the armature surface.

To test for a ground between the windings and the core of the armature, an ohmmeter can be used. Connect one test probe of the meter to the armature shaft and one probe to the commutator segments as illustrated in Fig. 10-41. If the commutator is shorted to the armature shaft, zero resistance will be indicated. If the armature is operational, infinite resistance will be indicated on the ohmmeter.

To test a field coil for continuity, the probes of an ohmmeter are connected to the terminals of the coil. A shunt held coil should show low resistance, approximately 2 to 30 Ω, depending on the type of generator in which the coil is used. A series field coil should show practically no resistance, because it carries the entire load to the generator and the internal resistance of the generator must be as low as possible.

The field coils should also be tested for shorts to the field frame. An ohmmeter should indicate an infinite resistance between any field connection and the field frame. If zero resistance is indicated, the field is shorted to the case and should be replaced.

Service of Bearings

As stated previously, modern aircraft generators are equipped with prelubricated sealed bearings. During normal service inspections, it is not necessary to lubricate or otherwise service bearings of this type. If a bearing seizes or becomes rough, it should be replaced with a new one. Bearings can be checked by rotating the armature of the assembled generator by hand. The armature should turn freely and smoothly. If any roughness or excess noise is noted, the bearings should be replaced.

Seating of New Brushes

If new brushes are to be installed in a generator, they are typically **seated** so that the face of each brush will have maximum surface contact with the commutator. The brushes should be installed after the generator is assembled and then seated as follows: Place a strip of No. 000 sandpaper around the commutator with the sand surface against the brush face, and turn the armature in the normal direction of rotation. This causes the sandpaper to grind the face of each brush on a contour with the commutator. When the face of each brush is ground sufficiently to make maximum contact with the sandpaper of the commutator, remove the sandpaper and blow out all sand and brush particles with dry compressed air.

Another method of seating brushes recommended by some manufacturers is as follows: Mount the generator on a test stand so that it can be rotated at normal operating speeds. Install the brushes in their proper positions, and run the generator at approximately 1500 rpm. Fold a strip of No. 000 sandpaper over the end of a rigid piece of insulating material with the sand surface outside. Hold the sand surface against the commutator while the generator is rotating. Fine sand particles will be carried across the face of each brush, and the brush faces will be shaped into the contour of the commutator. After the brushes are seated, blow out all sand and dust with dry compressed air.

A third method of seating brushes, which has proved very satisfactory, is to use an abrasive stick specially designed for the purpose. This abrasive stick should be used in the same manner as the sandpaper described in the above paragraph. As the abrasive stick is held against the commutator, small particles of abrasive material are carried under the brushes, and the brush faces are ground to the contour of the commutator.

Many modern brushes are designed to be self-seating. In this case the manufacturer will provide the proper instructions for replacing the brushes. In most cases, the brushes can simply be installed and the generator rotated at a low speed for a certain "break in" period. After the break-in time, the brushes have attained the proper contour to match the commutator; the area should be properly cleaned and the system can then operate normally.

Installation

There are two basic types of driving mechanisms used on aircraft generators, direct-gear and belt-driven. To install a gear-driven generator, remove the mounting-pad cover and install the proper gasket over the studs. Fit the generator spline or gear into place, being careful not to damage the gear or drop a foreign material into the engine assembly. Tighten the nuts on the hold-down studs, applying torque as recommended. Connect the generator cables to the proper terminals, and see that all connections are clean, tight, and properly installed. If the generator employs an air duct for cooling, make sure it is connected properly

To install a belt-driven generator, mount the unit in the appropriate location and install all hardware. Then place the drive belt around the aircraft and generator drive pulleys. Once the belt is in the proper location, position the generator to tighten the drive belt, and secure all hardware and safety-equipment as necessary. The proper belt tension must be set through the generator mounting hardware. Typically, the generator can be moved slightly in order to adjust belt tension. Consult the installation instructions for proper belt adjustments.

After generator installation has been completed, the entire charging system should be tested. Both a static and a dynamic check should be performed to ensure that the generator functions properly under various load and rpm conditions. If all voltage and amperage readings are within specifications, the aircraft can be returned to service.

REVIEW QUESTIONS

1. Explain the electrical principle by which electricity is produced in a generator.
2. How may the direction of current flow in an armature be determined?
3. Name the essential parts of a dc generator.
4. What determines the voltage value in a generator?
5. How is residual magnetism utilized in a generator?
6. Give two classifications for dc generators with respect to internal circuit connections.
7. Describe the functions of a starter-generator.
8. What types of aircraft typically employ starter-generators?
9. Describe the current flow path through a starter-generator during the generator mode.
10. Describe the armature assembly for a typical aircraft generator.
11. Compare the shunt field winding in an aircraft generator with the series field winding.
12. Describe means for coolling aircraft generators.
13. For voltage regulation, which of the following is varied: rpm, field strength, or number of armature windings?
14. Describe the action of a vibrator-type voltage regulator.
15. Describe the operation of a carbon-pile voltage regulator.
16. Describe the operation of an equalizing circuit found on twin-engine aircraft.
17. Why is a reverse-current cutout relay required in a generator system?
18. Explain the operation of a reverse-current cutout relay.
19. What are common voltage values for the output of dc generators used on light aircraft?
20. What is a GCU?

21. Explain the operation of a current limiter used with a vibrator-type voltage regulator.

22. How often are inspections required for starter-generators?

23. What is meant by flashing the field?

24. If a generator produces only 2 or 3 V, what is likely to be the trouble?

25. What trouble may exist if there is no voltage from a generator?

26. List typical generator inspection procedures.

27. If you wish to overhaul a generator, what information should you have available?

28. What is the proper method for seating new generator brushes?

29. What is used to test the armature of a dc generator?

30. Describe the use of an ohmmeter to test a field for grounded windings.

31. Describe the steps for the installation of a typical aircraft generator.

Alternators, Inverters, and Related Controls 11

INTRODUCTION

There are two major types of alternators currently used on aircraft, the **dc alternator** and the **ac alternator**. DC alternators are most often found on light aircraft where the electric load is relatively small. AC alternators are found on large commercial airliners and many military aircraft. Since these aircraft require large amounts of electric power, the use of ac systems creates a valuable weight savings. Through the use of transformers, the transmission of ac electric power can be accomplished more efficiently and therefore with lighter equipment. With the transmission of electric power at relatively high voltages and low current, the power loss is kept to a minimum. As discussed in Chap. 6, transformers are used to step up or step down ac voltage.

On most conventional large aircraft, ac power is used directly to perform the majority of power functions for the operation of control systems and electric motors for a variety of purposes; however, the trend is to incorporate more high-power dc systems on large aircraft. For example, the Boeing B-787 and the Airbus A-380 have more dc electrical equipment than any previous aircraft. On light aircraft, most devices operate on 14- or 28-V dc power. If a small amount of alternating current is desirable for specific applications, an inverter is used to convert the dc voltage into an ac voltage. The ac voltage is then used to power only those particular items requiring alternating current for proper operation.

AC GENERATION

Principles of AC Generation

The principle of **electromagnetic induction** has previously been explained as it relates to both dc and ac generators. To repeat briefly, when a conductor is cut by magnetic lines of force, a voltage will be induced in the conductor, and the direction of the induced voltage will depend on the direction of the magnetic flux and the direction of movement across the flux field.

Consider the simple generator (alternator) illustrated in Fig. 11-1. A bar magnet is mounted to rotate between the faces of a soft-iron yoke on which is wound a coil of insulated wire. As the magnet rotates, a field will build first in one direction and then in the other. As this occurs, an alternating voltage will appear across the terminals of the coil. The wave shape of the ac voltage will roughly approximate a sine wave.

Aircraft DC Alternators

Almost all alternators for aircraft power systems are constructed with a **rotating field** and a **stationary armature**. AC alternators are constructed differently and will be discussed later in this chapter. Since a steady voltage must be provided for the aircraft's electrical system, the field strength of the alternator must be varied according to load requirements. For this purpose, a **regulator** or alternator control unit is employed that can furnish a variable direct current to the rotor (field) winding of the alternator. The control system is used to change this current as required to maintain a constant alternator output voltage. This variable regulator current must be supplied by a dc source.

Aircraft alternators and generators have many similarities; both units change mechanical energy into electric energy. The major differences between a dc alternator and a dc generator are the various design features. Since a generator has a rotating armature, all the output current must be supplied through the commutator and brush assembly. An alternator, having a stationary armature, can supply its output current

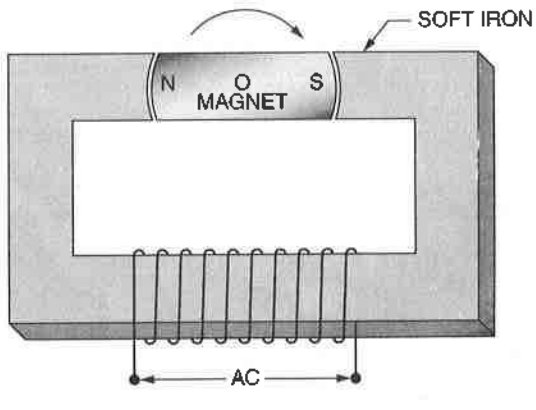


FIGURE 11-1 Simple ac generator.

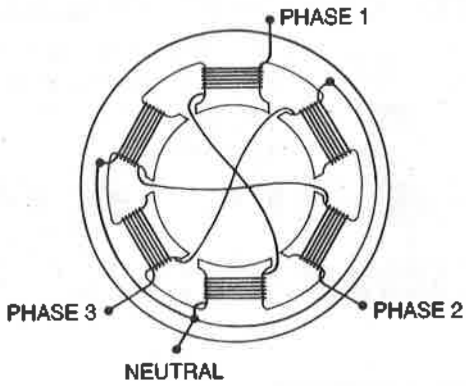


FIGURE 11-2 A Y-connected stator winding.

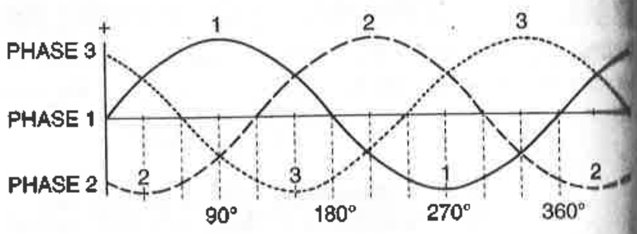


FIGURE 11-4 Output of a three-phase alternator.

through direct connections to the aircraft bus. This system of directly contacting the alternator output to the bus eliminates the problems caused by poor connections between a rotating commutator and stationary brushes. At high power levels, rotating contacts are too inefficient to be practical; therefore, alternators, as opposed to generators, are preferred on most aircraft.

Principles of Aircraft Alternators

The aircraft alternator is a **three-phase** unit rather than the single-phase type shown in Fig. 11-1. This means that the **stator** (stationary armature) has three separate windings, spaced 120° apart. The field rotates and is called the **rotor**. The schematic illustration in Fig. 11-2 will serve to indicate how the stator windings are arranged, although the windings in an actual stator will appear different. Also, it will be found that some stators will be wound in the Y configuration, and others will be wound in the delta configuration. Schematic diagrams of these arrangements are shown in Fig. 11-3.

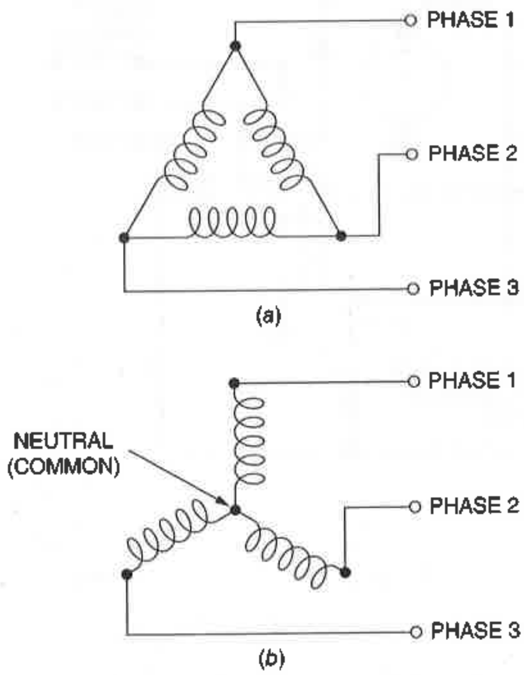


FIGURE 11-3 Diagrams of (*a*) delta- and (*b*) Y-connected stators.

The output of a three-phase alternator is shown in Fig. 11-4. Note that there are three separate voltages, 120° apart; that is, each voltage attains a maximum value in the same direction at points 120° apart. As the rotor of the alternator turns, each phase goes through a complete cycle in 360° of rotation; that is, each voltage reaches maximum in one direction, passes through zero, reaches maximum in the opposite direction, and then returns to the starting point in 360°.

Alternator System for Light Aircraft

Current produced in the armature of a dc alternator is actually a three-phase alternating current as shown in Fig. 11-4. To use this power in a light aircraft system, it is necessary to convert it into direct current. This is accomplished by means of a **three-phase, full-wave rectifier**. A rectifier for three-phase alternating current consists of six diodes. A schematic diagram of a delta-wound stator with a three-phase, full-wave rectifier is shown in Fig. 11-5. The "arrowheads" of the diode symbol point in a direction opposite the actual electron flow. Under the conventional system (current flow from positive to negative), the arrowheads would point in the direction of flow. In the diagrams in Fig. 11-6*a*, it can be seen how the current produced in each phase of the stator is rectified.

As the armature rotates the three separate voltages produced by each phase overlap, as seen in Fig. 11-6*b*. Once the current is rectified, the voltage curves remain overlapped; however, since the stator is wired in parallel, only the strongest voltage reaches the alternator output terminals. As illustrated in Fig. 11-6*b*, the effective voltage is an average of the voltage values above the intersection of the individual voltage curves. The effective voltage is equal to the rated output voltage of the alternator. This value averages near 14 V for a 12-V battery system and 28 V for a 24-V battery system.

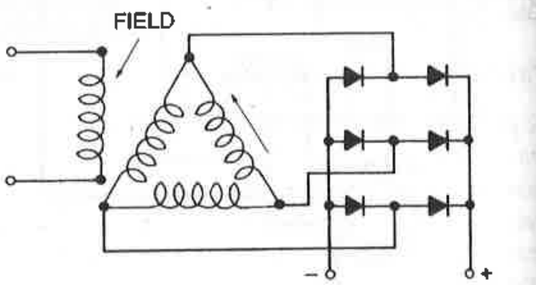


FIGURE 11-5 A schematic of a three-phase, full-wave rectifier in an alternator stator circuit.

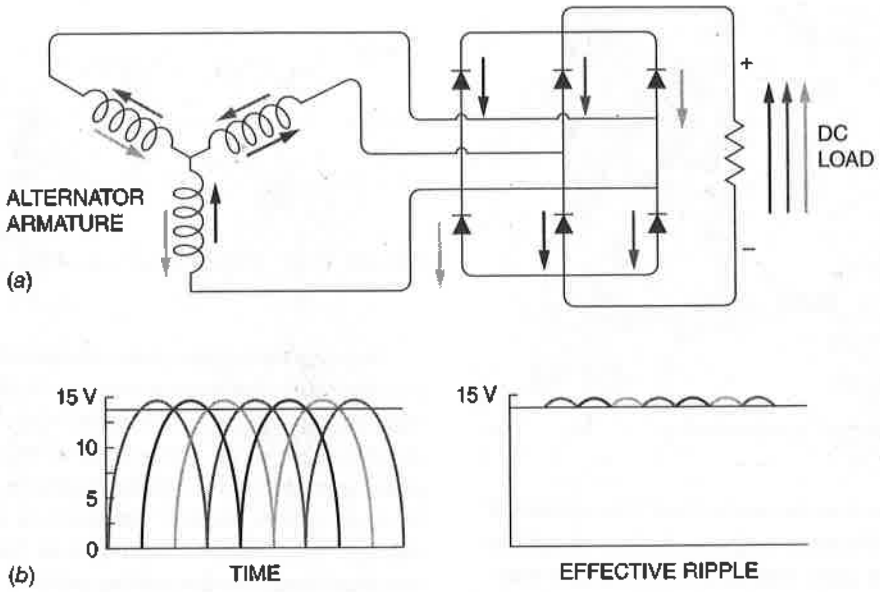


FIGURE 11-6 Rectification of a three-phase current. See also color insert.

The dc ripple voltage values actually range from approximately 13.8 to 14.2 V or 23.8 to 24.2 V. However, the dc ripple voltage changes value so quickly and so little that for all practical purposes, the voltage of the aircraft electrical system is considered to be the effective voltage of the alternator.

A typical electric power circuit is shown in Fig. 11-7. Since the rectifier is mounted in the end frame of the alternator, the alternator output terminals are marked for direct current.

A typical alternator for light aircraft is shown in Fig. 11-8. This alternator is gear driven and has a 28-V output with a maximum output of 120 A. The particular type of alternator to be used in an aircraft system can be determined from the aircraft manufacturer's parts catalog or from the catalog prepared by the manufacturer of the alternator.

Compaired to a generator, the alternator is a comparatively simple device and is designed to give many hours of trouble-free service. The principal components are the three-phase stator (armature windings), the rotor (field windings),

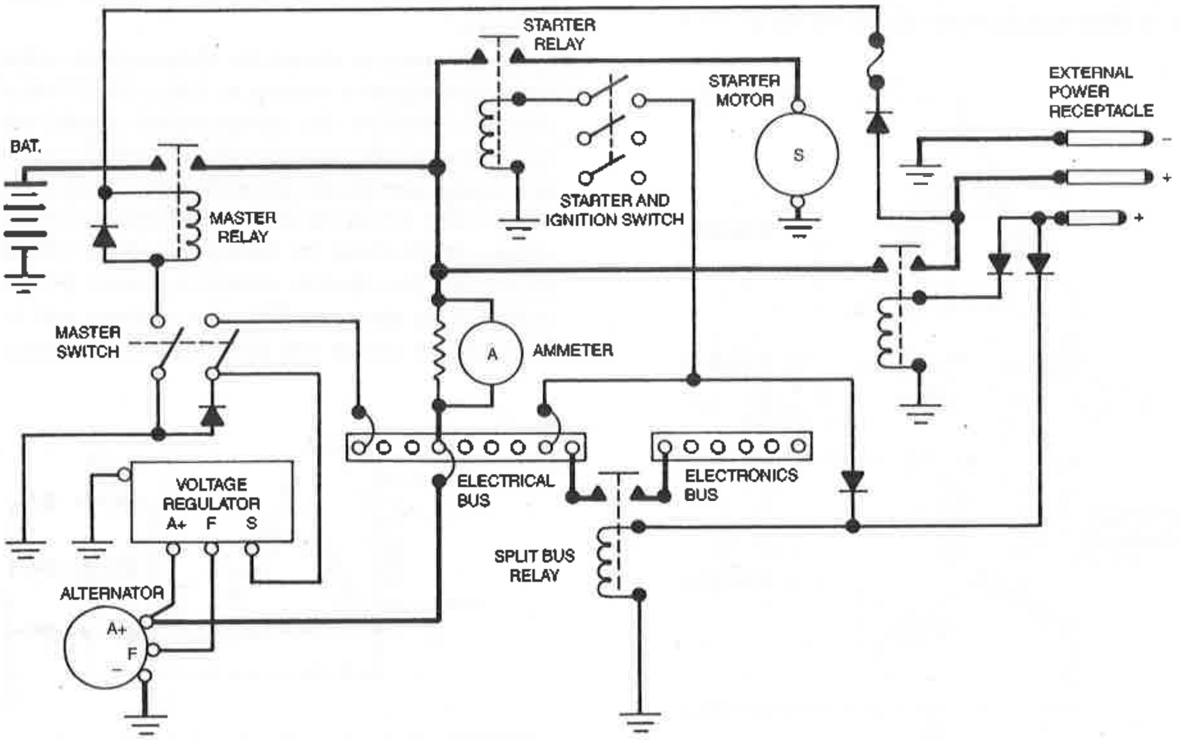


FIGURE 11-7 A typical power distribution schematic for a light aircraft containing a dc alternator.

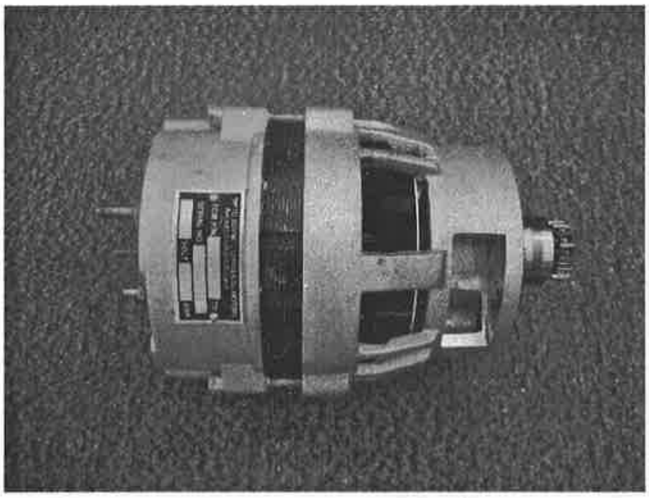


FIGURE 11-8 Gear-driven dc alternator.

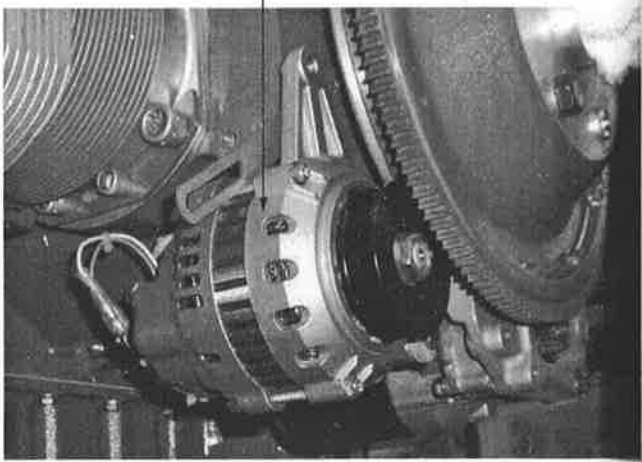


FIGURE 11-10 Belt-driven dc alternator.

and the rectifier assembly (the diodes). The rotating field winding provides the electromagnetic field, which is used to excite the stator windings. A brush set and slip-ring assembly is used to transfer current to the rotating field. Since the field coil requires a relatively low amperage (approximately 4 A maximum) to power the electromagnet, the brushes are smaller and longer-lasting than those found on dc generators. The brush assembly of a dc generator often carries well over 50 A. The stationary armature receives an induced voltage, which is connected to the rectifier assembly. The rectifier consists of six diodes connected to form the three-phase, full-wave rectifier.

A typical alternator for light aircraft has a rotor with 8 or 12 poles alternately spaced with north and south polarity see Fig. 11-9. This provides the rotating field within the stator. The strength of the rotating field is controlled by the amount of current flowing in the rotor winding. This field current is governed by the voltage regulator system. The output of the stator is applied to a full-wave rectifier consisting of six

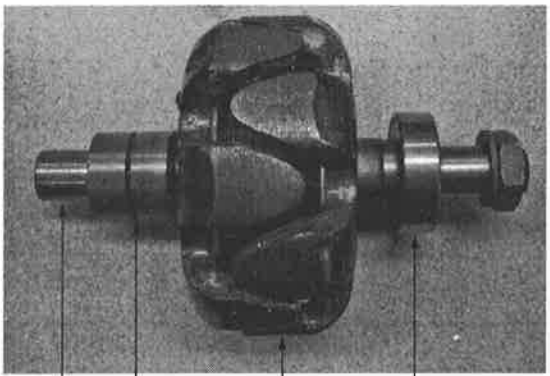


FIGURE 11-9 Alternator rotor.

diodes mounted within the alternator housing. The output of the alternator is, therefore, direct current as it is supplied to the aircraft electric power system.

Alternators for light aircraft may be driven by a belt and pulleys, or they may be gear-driven and flange-mounted on the engine. In the latter case, the engine manufacturer must provide the correct mounting and gear drive for the alternator.

Figure 11-10 shows a typical belt-driven dc alternator installed on the engine of a light aircraft. The alternator is mounted just aft of the engine flywheel on the bottom right side of the engine and the drive belt has been removed. This is a common location for belt-driven alternators; gear-driven units are installed at the rear of the engine and directly coupled to the gear box. An expanded view of the internal components of a dc alternator is shown in Fig. 11-11. Refer to this figure during the following discussions of the dc alternator components. The drive pulley and cooling fan (far right) are one assembly used to connect the alternator rotor to the engine flywheel through a drive belt. This is how the mechanical energy enters the alternator. The pulley/fan assembly is directly coupled to the alternator rotor.

The drive-end frame is designed to provide structure to the alternator and houses a bearing race, spacers, and oil seals as needed. The drive-end frame bolts to the diode-end frame (left side); once assembled the two end frames create a complete housing for the alternator. The alternator rotor consists of a field coil and pole shoe assembly mounted to the rotor shaft. The pole shoes are made of steel and direct the magnetic flux field near to the armature winding, which helps to improve the alternator efficiencies. A ball bearing is installed on the shaft and supports the rotor within the drive-end frame; the slip rings are seen on the left side of the rotor. The slip rings are the electrical contacts for the alternator field coil. The brush assembly is used to transfer field current onto the rotor through the slip rings. The brushes are designed to ride on the two slip rings; one is the positive brush, the other is the negative brush. The brush assembly is stationary and connects to the electrical circuit of the aircraft; the positive brush receives voltage/current from the

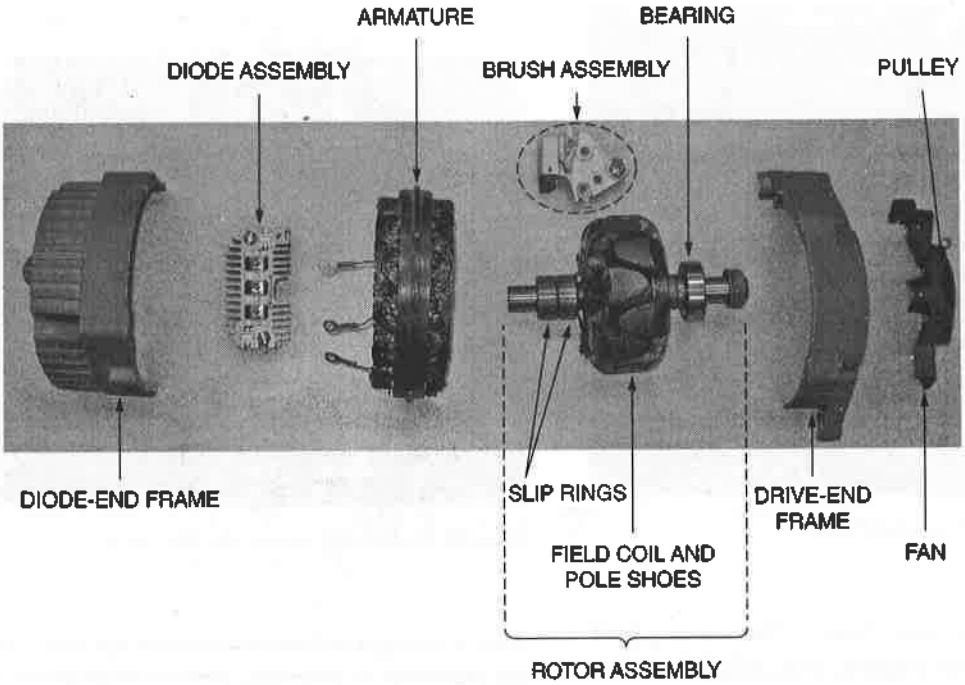


FIGURE 11-11 DC alternator main components.

alternator control unit (ACU). The negative brush is connected to ground.

The alternator armature coil and steel core assembly are designed so the rotor spins in the center of the assembly. With the field coil energized, as the rotor spins within the armature, the process of electromagnetic induction causes a voltage/current to be induced into the armature coils. The output of the armature is an alternating current and must be rectified into direct current; therefore, the armature is connected to the diode assembly. The diode assembly consists of six diodes: three positive, three negative. The positive and negative diodes must be insulated from each other. All six diodes are mounted to a heat sink which helps dissipate the heat generated by the rectification process. This heat sink contains several aluminum fins to aid the cooling process. There are four machine screws which hold the two end frames together; safety wire must be used to secure the machine screws after alternator assembly.

Maintenance of Alternators

Maintenance of alternators follows the principles of good mechanical and electrical practice and should be accomplished according to the instructions given in the maintenance manual for each particular unit requiring service. In general, the disassembly procedure is similar to that for other generators. Care must be taken to assure that the parts are marked and identified in such a manner that they can be reassembled correctly. Consider taking photographs of the disassembly process, which can be a useful reference during reassembly of the alternator.

The rotor winding can be tested with an ohmmeter or continuity tester. The reading is taken with the test probes of the instrument applied to the slip rings (see Fig. 11-12).

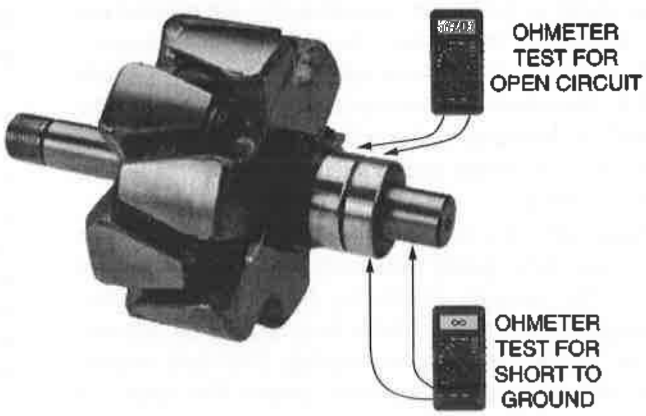


FIGURE 11-12 Use of an ohmmeter to test an alternator rotor.

The resistance of the rotor winding should be relatively low and within the limits specified by the manufacturer. Grounding of the rotor winding can be tested by connecting one test probe of an ohmmeter to the rotor shaft and the other to one of the slip rings. The reading should indicate infinite resistance. If low resistance is indicated, the rotor must be replaced.

The stator windings can be tested by checking between the stator leads with the ohmmeter (Fig. 11-13). The reading in each case should be within specifications. Normally, the reading will show low resistance. If the resistance is above or below the limits specified by the manufacturer, the stator must be replaced. To test for grounded windings in the stator, the ohmmeter is connected between one stator lead and the stator frame. The ohmmeter should show infinite resistance.

To test for open windings in the stator, one test probe of the ohmmeter is connected to the auxiliary terminal or

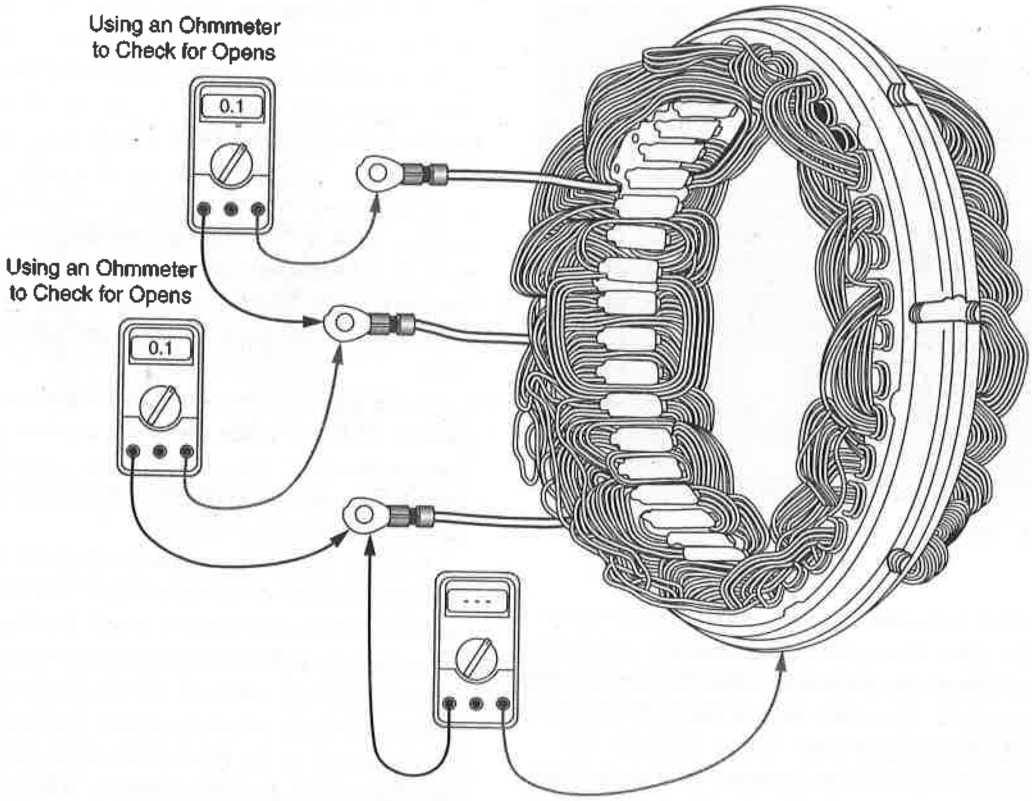


FIGURE 11-13 Using an ohmmeter to test an alternator armature winding.

to the stator winding center connection. The other probe is connected to each of the three stator leads, one at a time. The ohmmeter should show continuity in each case, and the resistance should be in the range specified by the manufacturer.

A visual inspection of an armature or field winding may also indicate defects. If the coil shows signs of overheating or contains loose windings, a shorted or faulty circuit is likely. Be especially careful when performing the ohmmeter test; the defect may be intermittent and difficult to locate. Any stator or rotor containing loose windings must be replaced. If these coils have not yet failed, they will soon. Carefully inspect all electrical connections and wiring within an alternator for security and any defects, such as cracked insulation or chaffing. Due to vibrations and the heat produced within an alternator, it is critical that all internal components are held tightly in place and without damage.

ALTERNATOR CONTROL

Unlike dc generators, dc alternators require only two means of control, a voltage regulator and a current limiter. The reverse-current cutout relay is not needed, because the rectifier assembly will not allow current flow into the armature. The current limiter for most dc alternators is a simple circuit breaker. The circuit breaker is sized to match the alternator's output current and installed on the aircraft instrument panel. The **voltage regulator** may be a vibrating type, as discussed with regard to generators, or a transistorized unit. In either case, the voltage regulator controls alternator output by varying the alternator's input. Specifically, the voltage regulator increases the field circuit's resistance to decrease the alternator's output. Conversely, a decrease of the field circuit's resistance will increase the alternator's output.

Alternator Control Unit (ACU)

Alternator control is typically accomplished by a small device mounted somewhere in the engine compartment of the aircraft. The two common terms used to describe this device are **alternator control unit** (ACU) and **voltage regulator**. Generally speaking, **ACU** is the modern term and **voltage regulator** is used to describe older systems. Both terms are used in this text and recognized by members of the industry as the device used to monitor, control, and protect alternator output. One type of ACU contains a field relay that supplies current to a transistor; the transistor controls the current to the field. A transistor contains no moving parts; therefore, there are no contact points to fail and/or change resistance. As the contact points of the older style vibrating-type regulator become pitted, the accuracy of the ACU decreases and the unit eventually fails; therefore, transistorized ACUs are generally considered more accurate and reliable.

Some ACUs contain a field relay to "turn on" the regulator and use a transistor to regulate the alternator output voltage. One example of this type of ACU consists of a field relay, a transistor, a voltage regulator winding, a diode, and resistors. An ACU of this type is shown in Fig. 11-14.

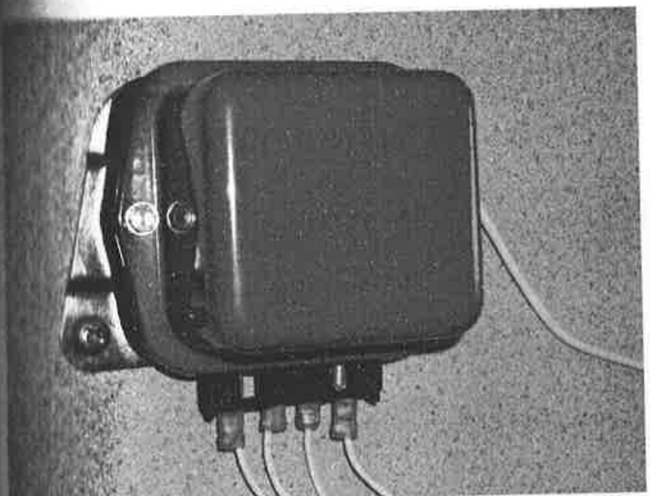


FIGURE 11-14 Alternator control unit (voltage regulator).

The field relay is similar to relays previously discussed. Essentially, the relay is an electromagnetically controlled switch used to connect the alternator output to one terminal of the alternator field. The other side of the field circuit is controlled by the transistor and the voltage regulator coil.

The field control circuit of the transistorized control unit is shown in a simplified form in Fig. 11-15. In this circuit the field relay is controlled by the alternator master switch. The alternator master switch is often one-half of a dual master switch. The other half of the switch controls a solenoid, which connects the aircraft battery to the bus. When the alternator master switch is closed, the field relay closes and connects the transistor base connection to the aircraft ground (negative connection). In a typical system this will allow about 4.5 A to flow through the field winding.

In the discussion of transistors in Chap. 6, it was explained that a *pnp* transistor becomes a good conductor through the emitter-collector section when the base circuit has negative bias. In the case of the regulator under discussion, the base circuit carries approximately 0.15 A when the voltage regulator contact points are closed.

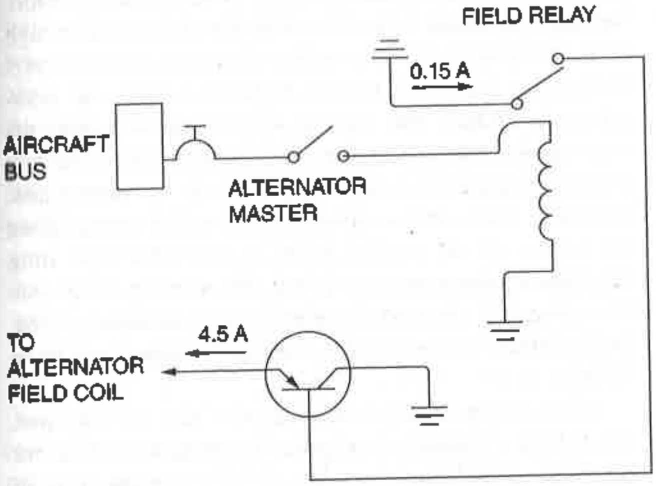


FIGURE 11-15 Simplified schematic of a transistorized voltage regulator.

When the alternator voltage attains the value for which the regulator is adjusted, the regulator contact points are opened by the magnetic force of the voltage relay, thus cutting off the base current to the transistor. The emitter-collector section then becomes nonconductive, and the field current is blocked. The alternator voltage then drops, and the regulator points close again to provide bias for the transitor-base circuit. Field current can then flow through the transistor, and the voltage rises to the regulated value. This cycle continues, with the regulator contact points vibrating rapidly (about 2000 times per second) to maintain the alternator voltage at the required value.

In this type of control unit, the transistor carries the field current (4.5 A), while the contact points control a much lower current (0.15 A). By applying a relatively low current through the contact points, the reliability of the voltage regulator is significantly increased.

A more complete schematic diagram of the ACU and alternator circuits is shown in Fig. 11-16. The diagram of the alternator shows the stator, in which the alternating current is generated; the field coil and slip rings, through which current flows to the field coil; and the six-diode rectifier. When the alternator master switch is closed, the battery and alternator are connected to the field-relay coil to produce a magnetic field that closes the relay contacts. When this happens, current flows from ground, through the emitter-collector circuit of the control transistor and the F_1 terminal of the regulator, and to the F_1 terminal of the alternator. After passing through the alternator field, the current enters the F_2 terminal of the ACU and passes through the closed field-relay contact points and out the *BAT* battery terminal of the ACU. From this point, it flows to the positive (+) terminal of the alternator, through the rectifier network, and to ground.

When the field winding of the alternator is energized, a dc voltage will be delivered to the system by the alternator, provided, of course, that the alternator is running. As alternator voltage increases, current flow through the two windings of the voltage regulator coil will increase. When the voltage reaches the value for which the regulator is adjusted, the contact points in the regulator section open. This lowers the emitter-base current in the transistor, and the transistor lowers the current to the alternator field.

With the contact points open, the alternator field winding receives less current, and the alternator voltage immediately decreases. With a lower alternator output, the spring at the end of the contact arm closes the points, and the cycle repeats as previously explained. The high rate of vibration of the contact points provides a steady voltage, for all practical purposes. Since the voltage regulator contact points are held closed by a spring, when the voltage is below the desired value, and the points are opened as a result of alternator voltage reaching this value, an increase of spring tension will cause the alternator voltage to increase. Voltage adjustments are therefore made by turning the screw that controls the spring tension.

It is important to note that the voltage regulator contact points carry only about 0.15 A when the alternator field current is over 4 A. On regulators without transistor control,

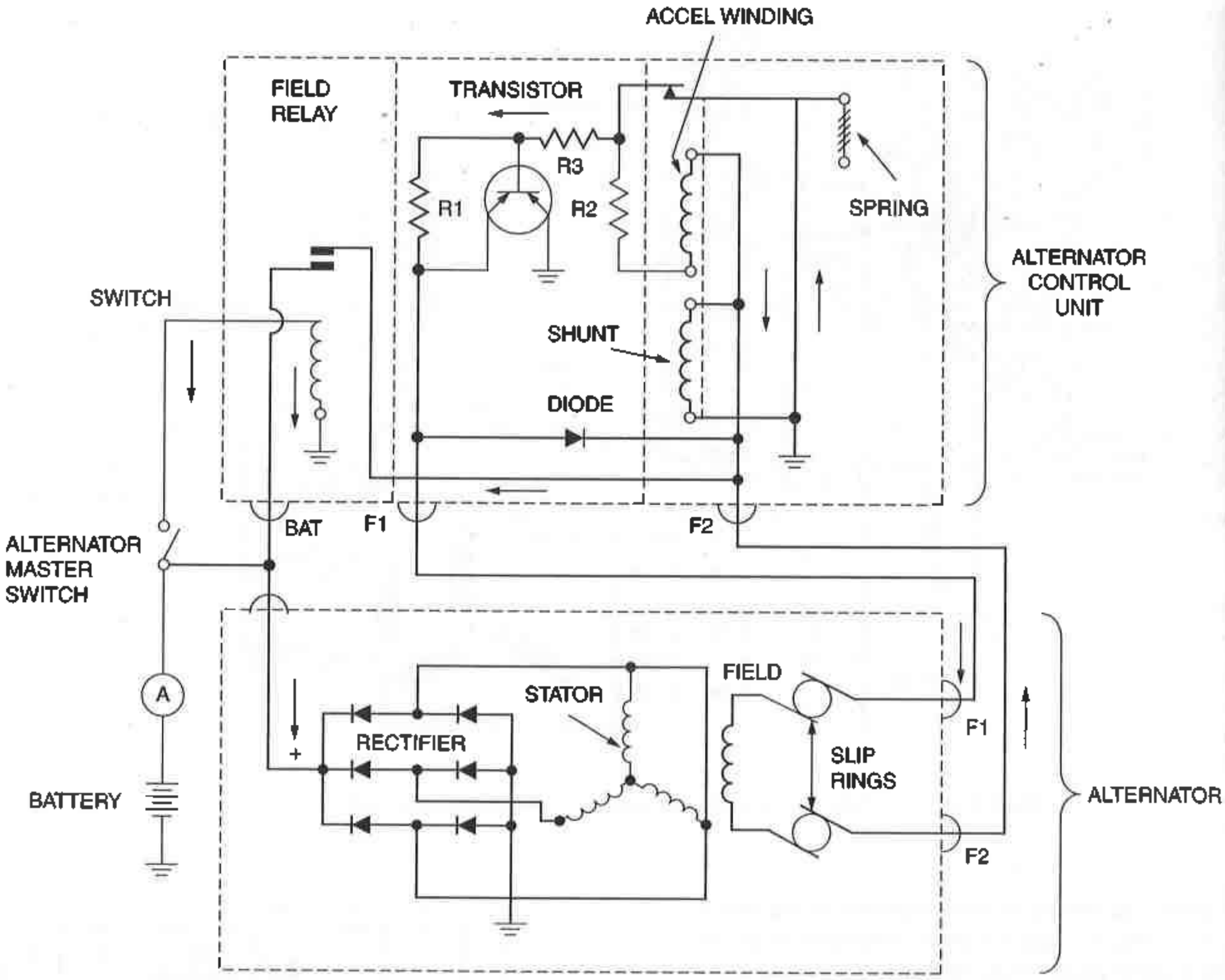


FIGURE 11-16 Transistorized voltage regulator and alternator schematic.

full generator field current must pass through the regulator contact points. Since vibrating contact points are burned by higher amperages, the use of a transistor makes it possible to increase the life of the contact points because of the lower current through the points.

In the diagram in Fig. 11-16, observe that the **accelerator winding** on the voltage regulator is connected to the regulator's F_2 terminal (a positive voltage point) and through a resistor and the contact points to ground. This winding will therefore carry less current when the contact points are open. The effect of this arrangement is to reduce the magnetic pull on the contacts as soon as the contact points open, thus making the spring more effective in closing them again. When the contact points are closed, the magnetic effect of the accelerator winding is added to the total magnetic force again, and the points reopen very quickly. The effect of the accelerator winding thus causes the contact points to vibrate (open and close) much more rapidly than they would with the shunt coil only. This is the reason for the term *accelerator winding.*

The diode in the regulator is connected directly across the field winding. If the voltage contacts opened without a diode in this circuit, the sudden interruption of field current and the resulting high voltage induced in the field winding would damage or destroy the power transistor. The diode is connected in such a manner to offer a high resistance to any applied voltage and a low resistance to any voltage of reversed polarity. The high voltage induced in the field relay, as the contact points open, is a reverse-polarity voltage; thus, the diode will short any current produced in this manner. The shorted current is therefore unable to damage the transistor.

In the use of transistors, it is important to note that high temperatures can cause improper functioning of and permanent damage to the transistors. For this reason, the transistors used with voltage regulators or in any other circuits must be kept at safe operating temperatures. The transistors used with voltage regulators usually have heavy metal bases, which act as heat sinks to carry the heat away from the active elements. In any installation, the maximum safe operating temperature for the transistor must be known, and provision must be made to assure that this temperature is not exceeded.

Some aircraft utilize an indicator light to show when the alternator is not charging the battery. One example of this type of system employs a three-terminal voltage regulator, an external field relay, and an indicator light. The circuit for such a system is shown in Fig. 11-17. An examination of this circuit shows that the alternator master switch connects the battery to the field-relay winding and causes the contact

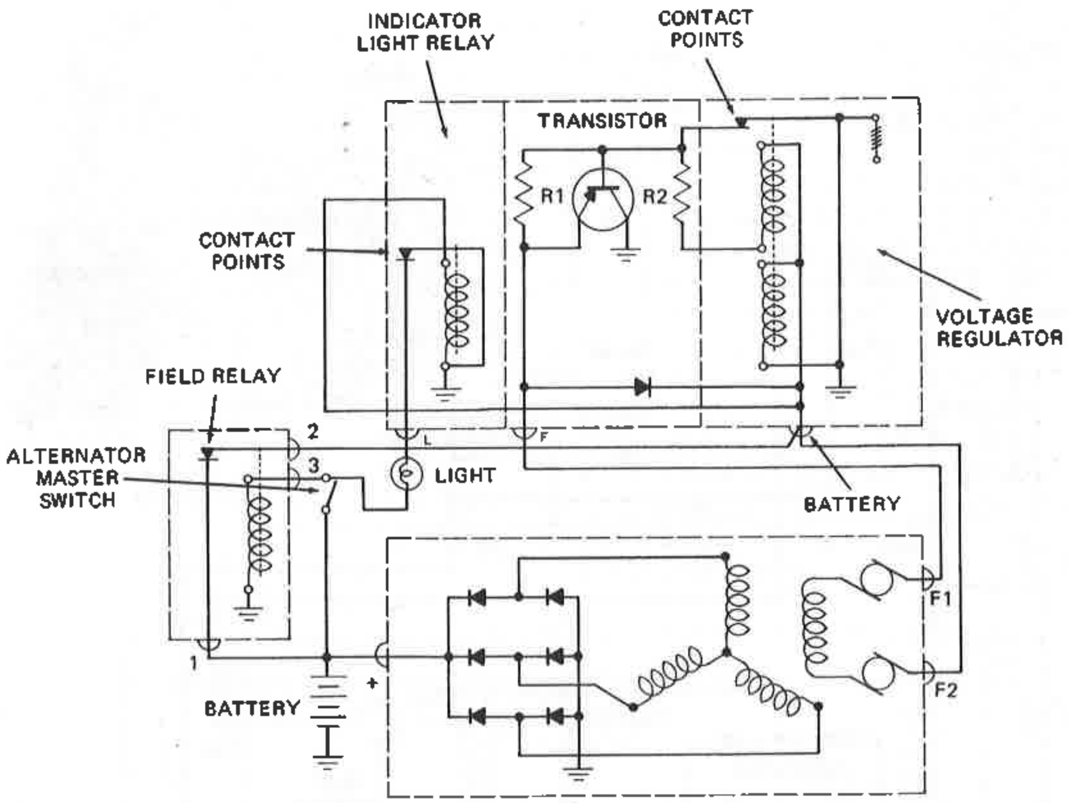


FIGURE 11-17 Transistorized voltage regulator with an indicator light circuit.

points to close. The battery is also connected to the indicator light. The indicator light circuit is completed to ground through the contact points of the indicator light relay. These points are closed when the relay is not energized; hence the light will be on. Since the field relay closes when the alternator master switch is turned on, the battery is connected to the field winding of the alternator. The alternator output voltage then opens the indicator light relay, thus turning off the indicator light.

Solid-State Voltage Regulators

A circuit diagram to illustrate the operation of a completely solid-state voltage regulator is shown in Fig. 11-18. This regulator has no moving parts and is generally considered very reliable. In the description that follows, each item will be explained in terms of actual current flow from negative to positive. For example, when the battery is furnishing current to the circuit, current flows from the negative terminal (ground) through the circuit into the positive terminal of the battery. When the battery is being charged, current is flowing into the negative terminal of the battery and out the positive terminal

In the circuit in Fig. 11-18, when the alternator master switch is closed, the battery and alternator are connected through the relay to the positive terminal (*A*) of the regulator. There is then a complete circuit from ground through the resistor R_2, the base of the **power transistor** TR_1, the diode D_1, and the resistor R_1 and back to the battery and the positive terminal of the alternator. If the output of the alternator is below the voltage for which the regulator is set, transistor TR_1 will have forward bias, and current will flow from the F_1 terminal of the alternator to the *F* terminal of the regulator and through the emitter-collector circuit of TR_1. The circuit is completed through D_1, R_1, and the relay to the alternator. This current flow excites the field of the alternator,

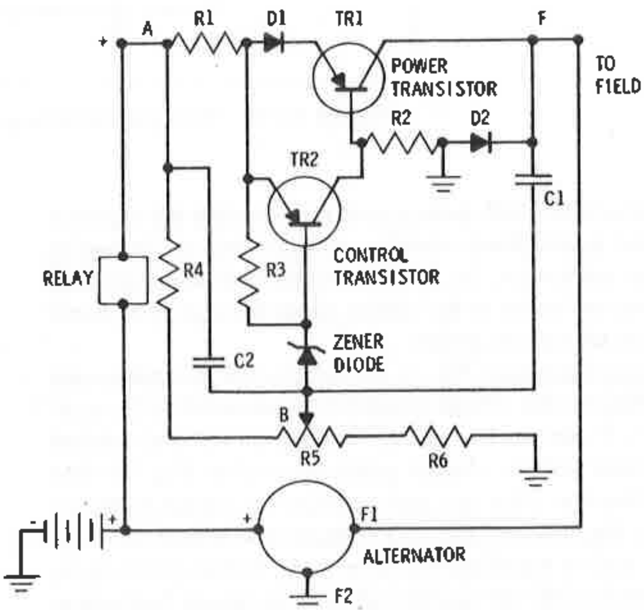


FIGURE 11-18 A schematic of a dc alternator and transistorized voltage regulator.

and the output of the alternator quickly rises to the desired level. In the circuit in Fig. 11-18, it can be seen that there is a circuit from ground through R_6, R_5, the **zener diode**, R_3, and R_1 to A. There is also a circuit from the zener diode through the emitter-base circuit of the **control transistor** TR_2 and through R_1 to terminal A of the regulator. The zener diode blocks the flow of current from R_5 until the voltage between ground and A reaches approximately 14.5 V. At this point, the zener diode begins to conduct and applies a forward bias through the emitter-base circuit of TR_2, the control transistor. TR_2 then becomes conductive, and current flows through the emitter-collector section from ground. This current flow is from ground through R_2, TR_2, and R_1 and out A. The effect of this is to short-circuit the emitter-base circuit of TR_1, and this causes TR_1 to stop conducting field current for the alternator. The alternator voltage immediately drops, and the zener diode stops conducting, thus removing the forward bias from TR_2, which also stops conducting. This returns the forward bias to TR_1, which starts conducting field current again, and the cycle repeats. This cycle repeats about 2000 times per second, thus producing a reasonably steady voltage of approximately 14.5 V from the alternator.

Transistorized Voltage Regulator Operating Theory

The two key points to understand with respect to the operation of the transistorized voltage regulator are the zener diode operation and the control of the power transistor by the control transistor. The zener diode can be compared to a relief valve that opens at a given pressure in a hydraulic system. When the zener diode conducts current, it causes the control transistor to shut off the power transistor. The reason that the control transistor can stop the flow of current through the emitter-base circuit of the power transistor is that there is a difference in the voltage drops across the emitter-base circuits of the two transistors when the control transistor's emitter-base circuit is conducting. The diode D_1 causes approximately a 1-V drop in potential across the emitter-base circuit of the power transistor when the circuit is conducting. When the emitter-collector circuit of the control transistor begins to conduct, there is no appreciable voltage drop across the control transistor; hence, a 1-V reverse bias becomes effective across the emitter-base circuit of the power transistor. This, of course, stops the emitter-base current in the power transistor.

Adjustment of alternator voltage output is accomplished through the variable resistor R_5. A change in the resistance of this resistor will change the voltage level across the zener diode, thus raising or lowering the level of alternator output voltage required to cause the zener diode to conduct.

The resistor R_1 and capacitor C_1 act to reduce the time required for the field voltage to change between maximum and minimum values. This prevents overheating of the transistors. The capacitor C_2 reduces the voltage variations that appear across the resistors R_4 and R_5, thus making the regulator more accurate. Resistor R_3 prevents leakage current from the emitter to the collector in the control transistor.

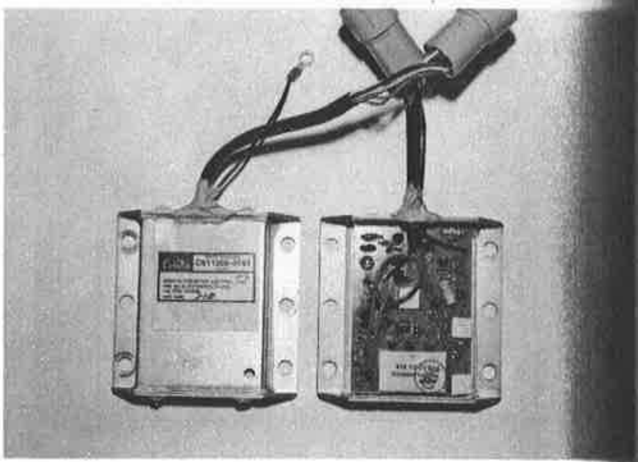


FIGURE 11-19 An alternator control unit.

Resistor R_4 is a special temperature-sensitive type that acts to increase the alternator voltage slightly at a lower temperature. This aids in maintaining adequate charge current for low-temperature operation. Diode D_2 aids in controlling field current flow as the power transistor rapidly turns the field current on and off.

Modern dc alternator charging systems have replaced the traditional "voltage regulator" with a more advanced unit often called an ***ACU***. These advanced controls often perform voltage regulation, system monitoring, and circuit protection functions all within one solid-state unit. Many Cessna light aircraft employ an ACU as shown in Fig. 11-19.

The ACU normally maintains system voltage between 28.4 and 28.9 V. This is accomplished by changing the field circuit resistance through the ACU. If system voltage rises above 28.9 V, the ACU automatically opens the alternator field circuit and shuts off the alternator. This in turn establishes a low-voltage condition (battery voltage only). If system voltage should drop below 25.2 V, the alternator warning light will illuminate indicating a system failure.

The Cirrus SR-20 is an advanced single-engine aircraft, which employs a state-of-the-art electrical system containing two completely independent charging and two 24-V battery systems. The number one battery is used for engine starts and is typical of most 24-V lead-acid batteries; the number two battery is comprised of two 12-V batteries connected in series to produce 24 V. These batteries are relatively small with only a 7.0 A-h capacity (see Fig. 11-20). This aircraft requires the redundancy of two complete systems due to the high reliance on electronic instruments. The main alternator has a capacity of 100 A at 28 V; alternator number two has a capacity of 20 A at 28 V. The outputs will be different depending on the exact model of Cirrus aircraft. During normal operation, both alternators produce power and are regulated by two independent control units called **field control modules**.

The field control modules are small solid-state ACUs installed inside the **master control unit** (MCU). With the help of digital microelectronics, the field control modules are approximately 4 × 1.5 × 1 in. in size. As seen in

FIGURE 11-20 Battery #3 Cirrus aircraft; one of two batteries connected in a series.

Fig. 11-21, the two field control modules are installed inside a weather resistant case located in the engine compartment on the firewall; this unit is the MCU. The MCU contains a variety of other electrical control circuits and components including (1) the main battery, starter, and external power contactors (solenoids), (2) a variety of ground replaceable fuses, (3) a circuit card used to control other loads, such as the landing light. The Cirrus power distribution system is discussed further in Chap. 12.

Troubleshooting a DC Alternator System

Typical procedures for troubleshooting a light-aircraft alternator system can be found within the electrical section of the aircraft maintenance manual. It must be remembered that there are variations with different systems; hence, it is important to consult the manufacturer's instructions for a particular system. A general rule to remember in all cases is that alternator voltage is controlled by varying the amount of field excitation current. The voltage regulator can therefore be bypassed by supplying field current directly to the alternator. If the engine is run while the regulator is bypassed, the alternator should produce a relatively high output voltage and current. If no voltage is produced during this test, the alternator or related circuitry is defective. All radios and sensitive electronic equipment should be turned off during this test to ensure their protection from an overvoltage condition.

Whenever troubleshooting an alternator circuit, remember that alternator output voltage must be slightly higher than battery voltage. If the alternator is turned on and the bus voltage fails to increase approximately 2 to 4 V above battery voltage, the charging system or related circuitry is defective. This voltage measurement is typically performed between the aircraft's main bus and ground.

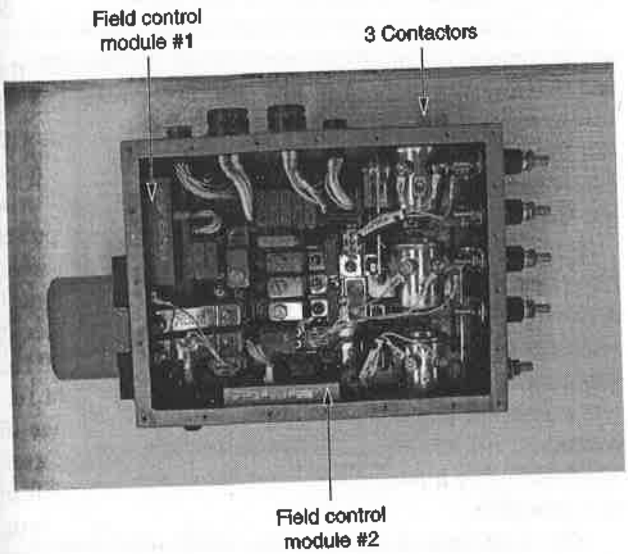


FIGURE 11-21 Cirrus aircraft master control unit (MCU). See also color insert.

Be Aware. Although there are several similarities between some aircraft dc alternators and automotive alternators, they are different. Automotive alternators and voltage regulators must not be substituted for aircraft components. A portion of the FAA Alert #63 is shown in Fig. 11-22. This illustrates several differences between an aircraft alternator and an

BE AWARE

DIFFERENCES BETWEEN AIRCRAFT AND AUTO ALTERNATORS USING A COMMON BELT-DRIVEN ALTERNATOR FOR A COMPARISON

Aircraft alternators include features not found on automotive alternators.

1. Although alternators are birotational, aircraft engines turn opposite of automotive. This means cooling fans must be canted in the opposite direction. Also, pulleys and belt sizes vary due to coming-in speed.

2. The through bolts are of a higher tensile strength utilizing an antirotational device in the form of a lock tab. The rectifier assembly has a heavy-duty diode with higher voltage and amperage capacity. Also, one excites at 90 PIV and the other at 150 PIV. Radio suppression is designed for 108 frequencies and up, which is the VHF, and 108 and down, which is FM band.

3. The brushes have a higher graphite content and they utilize a tin plate on the brush leads to prevent corrosion.

4. The stator is of the Delta wind rather than the "Y" wind, and it does not utilize the stator terminal. The aircraft unit also carries "H" insulation, which is capable of 200° Centigrade temperatures. It is also rated at 60 amperes instead of 55.

5. The rotor has a shorter shaft and a smaller thread size. Because of the opposite rotation, it is wound in the opposite direction. It also utilizes "H" insulation and Havel varnish.

6. The front and rear housings are the same as automotive. With this brief description, I hope I have enlightened you on the differences between aircraft and automotive alternators. Using automotive units in an aircraft creates a potential safety hazard, as well as a short alternator life and unreliability.

If you suspect an automotive unit on an aircraft, check with your nearest FAA-approved aircraft accessory shop or your local FAA General Aviation District Office.

NOTE: The above article was submitted by an FAA certificated Aircraft Accessory Shop.

FIGURE 11-22 Portion of FAA Alert #63. Differences between aircraft and automotive alternators.

automotive alternator. When installing replacement parts on any aircraft, always use FAA-approved units.

AC GENERATORS–AC ALTERNATORS

AC generators, often called alternators, are used as the principal source of electric power in almost all transport-category aircraft. The ac system supplies almost all the electric power required for the aircraft. Most of the electrical loads found on traditional large aircraft operate using alternating current; the battery and certain backup systems still require direct current. Where direct current is needed, power from the alternating current system is rectified and sent to one or more dc power distribution buses. It is essential that the distribution system for alternating current and direct current be kept independent of each other. The newest transport category aircraft utilizes more electrical systems than previous designs. Aircraft such as the B-787 and A-380 contain more generators, both alternating current and direct current, and elaborate distribution systems. Power distribution will be discussed in the next chapter. Virtually all aircraft contain some type of emergency power system to supply electrical energy in the event of primary system failures; in general, more complex aircraft contain a more complex emergency power system. On larger aircraft, the **auxiliary power unit (APU)** and/or a **ram air turbine (RAT)** may be used to drive an ac emergency generator. Most modern aircraft also employ one or more inverters; the inverter is a unit that changes direct current to alternating curent. The inverter can be used to produce alternating current from battery current in the event of a complete generator system failure.

It is important to remember that the terms ac generator and ac alternator are used interchangeable throughout the aerospace industry. Certain manufacturers may make a distinction between the terms; however, for the most part, they can be considered the same. Remember both generators and alternators are machines that change mechanical energy into electrical energy; they are very similar and their terms often get interchanged. This text will use both the terms; although for the most part the term ac **generator** will be used because it is most common.

AC power systems produce more power per weight of equipment than dc systems; however, most ac generators require a constant-speed drive to maintain a constant ac frequency. A **constant-speed drive** (CSD) is a type of automatic transmission that maintains a constant output rpm with a variable input rpm. Since heavy aircraft use large amounts of electric power, the employment of a constant-speed drive and an ac generator is practical. On light aircraft, where a relatively small amount of electric power is used, an ac generator requiring a constant-speed drive is simply too heavy. Modern light aircraft use dc alternators to produce electric power.

The stationary part of the alternator circuit is called the **stator**, and the rotating part is called the **rotor**. As seen in Fig. 11-23, in a basic AC alternator, the stator is actually a stationary armature, and the rotor is a rotating field, which may be produced by either a permanent magnet or an electromagnet.

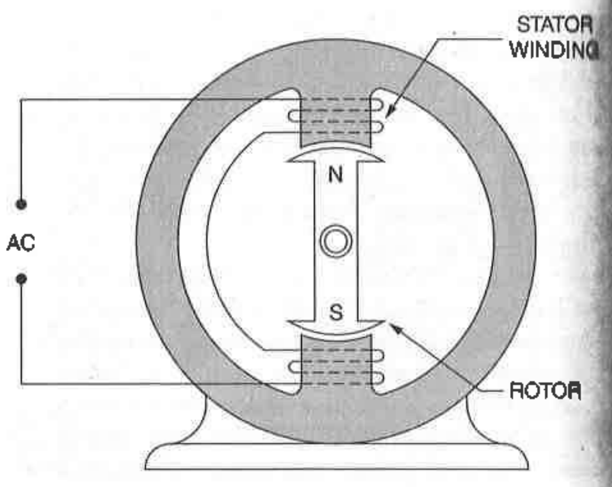


FIGURE 11-23 A simple two-pole ac alternator.

As the rotor turns, the magnetic flux cuts across the stator poles and induces a voltage in the stator winding. The induced voltage will reverse polarity every half revolution of the rotor because the flux will reverse in direction as the opposite poles of the rotor pass the stator poles. One complete revolution of the rotor in a two-pole alternator will produce 1 cycle of alternating current; that is, one complete ac sine wave will be produced for each complete revolution of the rotor.

The number of cycles of alternating current per second is called the **frequency**. Since a two-pole alternator produces 1 cycle per revolution (cpr), it is apparent that an alternator produces 1 cycle of alternating current from each pair of poles in the rotor. If we wish to determine the frequency of any given alternator, we proceed as follows: Divide the number of poles by 2, and multiply the result by the speed in rpm to obtain the number of cycles per minute. To find the cycles per second, divide the cycles per minute by 60.

Let us assume that we wish to determine the frequency of an alternator having four poles and turning at 1800 rpm. Dividing 4 by 2 gives 2 cpr, and 2 cpr multiplied by 1800 rpm equals 3600 cycles per minute. Dividing 3600 by 60 (60 s/min), we obtain 60 Hz (cycles per second).

The frequency of any alternating current produced is determined by the internal design of the generator and the speed at which it rotates. Aircraft use alternating current with a 400 Hz frequency; land-based ac generators in the United States produce current at 60 Hz for homes and industrial uses. Europe and other parts of the world produce ac power at 100 Hz. Many electrical systems are frequency sensitive; that is, they will only operate at a given frequency (or close). For example, it is likely that an ac motor designed to operate at 400 Hz on an aircraft will not operate effectively on 60 Hz. Other less complex loads, such as light bulbs, are not frequency sensitive and could operate within a wide range of frequencies. An advantage of the 400 Hz frequency used on aircraft is that it allows for smaller/lighter equipment in many cases when compared to a lower frequency ac system.

Some ac generators are not rpm controlled and create an output of variable frequency. For example, the B-787 employs four engine-driven generators, which produce an alternating current output with a frequency between 360 and 800 Hz. Of course, the electrical loads of this aircraft must be designed to accept this frequency range, or some type of control circuitry must be used to stabilize the frequency prior to use. In either case, the installation of a variable frequency generator does not require a constant-speed drive (CSD) unit, thus eliminating mechanical components and creating a more reliable system.

Alternators are classified according to voltage, amperage, phase, power output (watts or kilovolt-amperes), and power factor. The phase classification of an alternator is the number of separate voltages that it will produce. Usually, alternators are single-phase or three-phase, depending on the number of separate sets of windings in the stator. Three-phase alternators are typical for most aircraft applications. Three-phase alternators are constructed with three separate armature windings spaced so that their voltages are 120° apart.

Brushless Alternators (Generators)

The aircraft alternators and generators previously discussed all contained at least one set of brushes. The brushes are used to connect power to the rotor, as seen in Fig. 11-24. Due to their high maintenance requirements, ac alternators containing brushes are no longer found on aircraft. The **brushless alternator** is a unit of unique design that uses magnetic flux lines to transfer energy from the stator to the rotor. The use of a magnetic field to make this "moving connection" eliminates the use of brushes, slip rings, and commutators. Elimination of these components reduces the number of life-limited parts and increases the reliability and longevity of the brushless ac alternator.

Among the advantages of a brushless alternator are the following:

1. Lower maintenance cost, since there is no brush or slip-ring wear.
2. High stability and consistency of output, because variations of resistance and conductivity at the brushes and slip rings are eliminated.
3. Better performance at high altitudes, because arcing at the brushes is eliminated.

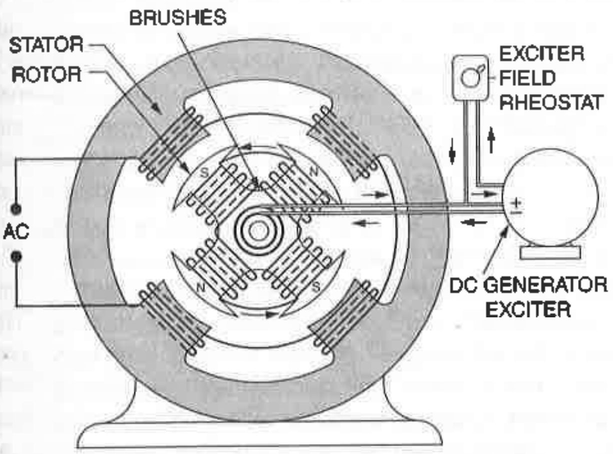


FIGURE 11-24 An ac alternator with brushes connected to a dc rotating filed.

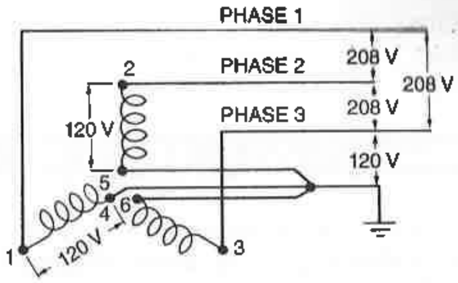


FIGURE 11-25 A Y-connected stator winding for an ac alternator.

The theory behind the brushless alternator is to use electromagnetic induction to transfer current from the stationary components of the generator to the rotating components. Typically, brushless alternators use a three-phase, Y-connected armature. The voltage across any single phase is 120 V, whereas the voltage across any two of the main output terminals is 208 V. This is illustrated in Fig. 11-25. One terminal of each separate stator winding is connected to ground, and the other terminal of the winding is the main output terminal. For aircraft circuits requiring 115/120 V, single-phase power, the circuit is connected between one main phase and ground. For three-phase power circuits such as those for high horsepower motors, all three main phases are connected to the motor.

Modern brushless alternators are called **permanent magnet generators** (PMGs). The PMG gets its name from the permanent magnet within the generator, which initiates the production of electric power. As seen in Fig. 11-26, there are actually three separate generators within one case: (1) the **permanent magnet generator**, (2) the **exciter generator**, and (3) **the main generator**. Each of these three units is an essential part of the modern brushless alternator.

A simplified diagram of a typical brushless generator is shown in Fig. 11-26; please refer to this drawing during the following discussions. The illustration shows two major elements of the generator; the rotor is represented by the shaded area located in the center left of the diagram. The rotor is surrounded by the stationary components of the generator. To understand the operation of a brushless generator, it is best to consider that the production of output current takes three distinct steps. In practical terms these three steps take place simultaneously to create the production of the alternating current. These three steps are as follows:

Step 1. As the generator begins to turn, the permanent magnet (far left side of the diagram) induces a small voltage/current into the permanent magnet armature. This current is sent to the GCU (top left of the diagram). The GCU also receives control signals and inputs from various electrical sensors to regulate the generator output. The GCU circuitry performs an analysis of all inputs and sends the appropriate current to the exciter field winding.

Step 2. The exciter field coil produces a magnetic field which induces a current into the exciter armature. The exciter field is stationary and the three-phase exciter armature is mounted on the rotor. Also, mounted to the rotor is a rectifier assembly that receives input from the exciter armature.

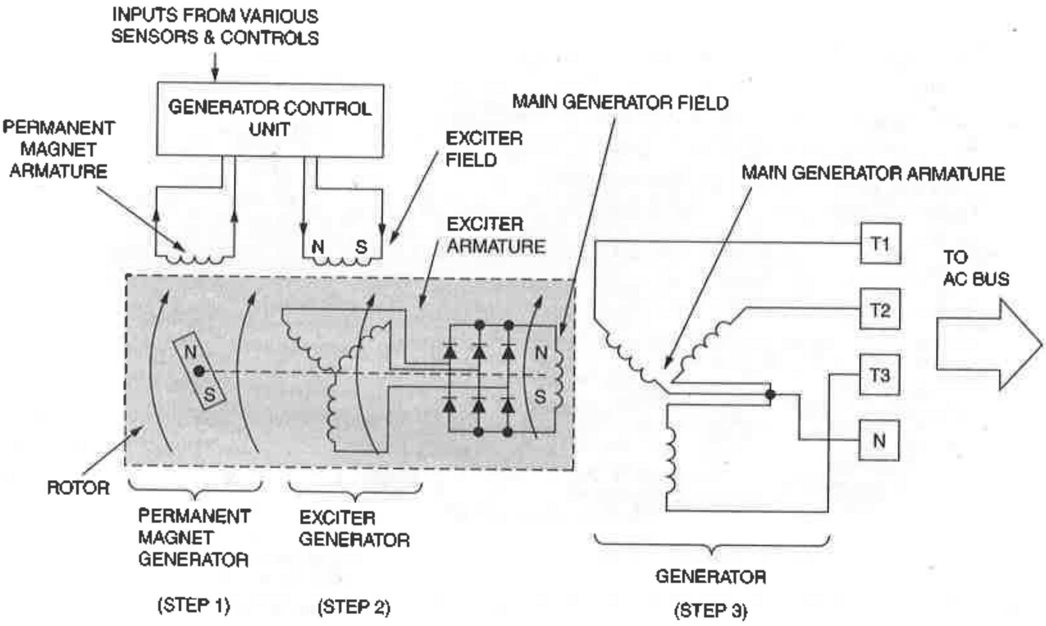


FIGURE 11-26 Diagram of a permanent magnet generator (PMG).

Step 3. The rectifier assembly outputs a direct current to the main generator field, also part of the rotor assembly. The main generator field creates a magnetism to excite the main generator armature (right side of the diagram). The main generator armature produces the power sent to the electrical loads. This is the final step in the process used by a brushless ac generator.

In short, the brushless generator contains three separate generators, each of these generators operate in sequence to produce the main output current. The name permanent magnet generator (PMG) comes from the use of a permanent magnet found in the rotor. This magnet starts the cycle that eventually produces the main generator output. The main output current of the PMG is a three-phase alternating current.

The main generator armature is a three-phase winding that produces 120 V across a single phase and 208 V across two phases. This armature is connected to the output terminals of the generator and hence supplies the electric power for the aircraft systems. As seen in Fig. 11-26, the GCU monitors the main generator output and in turn regulates the exciter field current as needed. If more generator output is required, the GCU will increase the exciter field current; this will, in turn, increase the exciter armature output and the main field current. A stronger main field will increase the main armature's output. If less generator output is needed, the GCU will weaken the exciter field current, and the generator output will decrease.

Constant-Speed Drive System

In an ac power system it is usually necessary to maintain a fairly constant speed in the ac generator. This is because the frequency of the ac generator is determined by the speed with which it is driven. It is especially important to maintain constant generator speed in installations in which the generators operate in parallel. In this case, it is absolutely essential that generator speed be kept constant within extremely close limits.

In order to provide the ac generator with a constant input rpm, a hydraulic transmission-type device is installed between the variable speed engine and the constant-speed generator. The speed device can be compared to an automatic transmission on a common automobile; at 30 mph the engine speed of a car may be 2000 rpm or, depending on the automatic transmission, the engine rpm may be 4000. Of course, there are several variables that determine the engine rpm and speed of an automobile; however, this example is similar to the operation of a constant-speed device used for aircraft ac generators. The constant-speed unit can be a separate assembly called a **constant-speed drive (CSD)**. These units are typically found on older aircraft, that is, those produced prior to about 1980. Newer transport category aircraft combine the generator and constant-speed unit into one assembly, called the **integrated drive generator (IDG)**.

CSD units are manufactured in many designs to fit a variety of applications. The principle of operation for all CSDs is essentially the same.

The complete CSD system consists of an axial gear differential (AGD), whose output speed relative to input speed is controlled by a flyweight-type governor that controls a variable-delivery hydraulic pump. The pump supplies hydraulic pressure to a hydraulic motor, which varies the ratio of input rpm to output rpm for the AGD in order to maintain a constant output rpm to drive the generator and maintain an ac frequency of 400 Hz.

A typical ac generator and constant-speed drive assembly is shown in Fig. 11-27. In this view, the CSD is on the left end of the assembly, and the generator is at the right end. The generator is cooled by an oil spray delivered by the CSD section. Most CSDs are equipped with a **quick attach/detach** (QAD) adapter. This unit allows the technician to remove and replace a generator and CSD assembly in a matter of minutes. The QAD ring is mounted to the CSD by means of several bolts through the mounting flange. To remove the

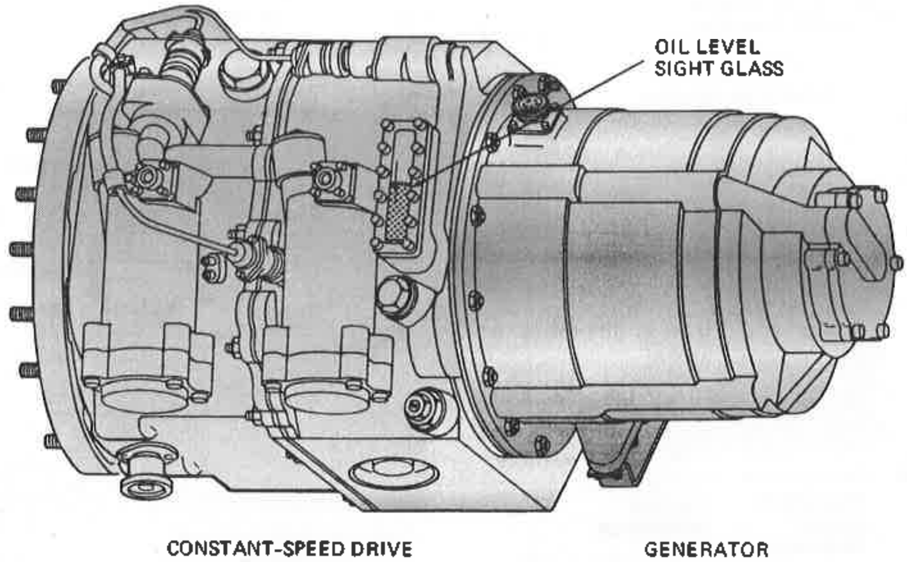


FIGURE 11-27 A typical constant-speed drive and generator assembly. (*Sundstrand Corporation.*)

generator from the aircraft, one must only release the QAD using one fastener. This mounting technique allows for quick line repair of an aircraft that has a defective generator CSD.

A normal operating temperature for the cooling oil is approximately 200°F. In order to maintain the correct cooling capacity, the oil level should be monitored periodically. A sight glass, as shown in Fig. 11-27, is employed on most constant-speed drives to allow the technician a quick check of the oil level. In the case of an in-flight oil loss or an overtemperature condition, a warning indicator will light up on the flightdeck. In this situation, the CSD should be disengaged immediately and inspected upon landing.

Most constant-speed drive units are equipped with an electrically activated generator-drive disconnect mechanism. This disconnect couples the CSD input shaft to the CSD input spline. The CSD disconnect is operated manually from the aircraft's flightdeck or automatically by a generator control unit. The disconnect is activated in the event of certain generator system failures.

Integrated Drive Generator

The IDG is a state-of-the-art means of producing ac electric power. As illustrated in Fig. 11-28, the IDG contains both the generator and the CSD in one unit. This concept helps to reduce both the weight and the size of the traditional two-unit system. The CSD, containing hydraulic trim units and a differential assembly, converts the variable engine rpm to an alternator input speed of 12 000 rpm. Older alternators typically rotate at 8000 to 9000 rpm. The 30 percent increase in alternator speed, along with improved cooling features, has allowed for a reduction in alternator size without a decrease in output power.

The IDG used on many Boeing 757 aircraft is produced by the Sundstrand Corporation. This unit is capable of producing 90 kilovolt-amperes (kVA) continuously, 112.5 kVA for a 5-min overload, and 150 kVA for a 5-s overload. The output voltage is 120 V ac at 400 Hz. This IDG is shown in Fig. 11-29.

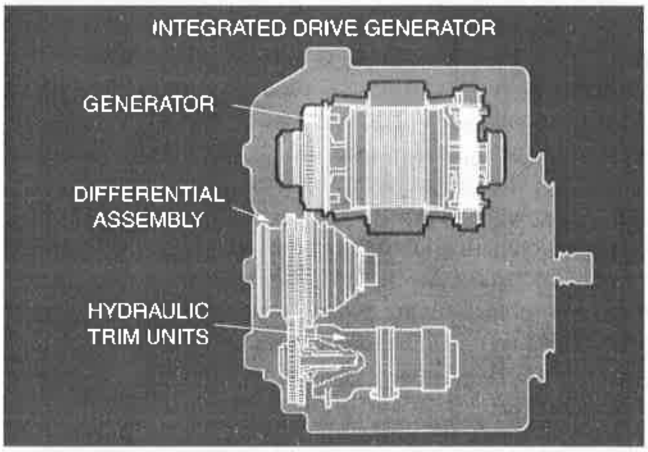


FIGURE 11-28 An integrated drive generator. (*Sundstrand Corporation.*)

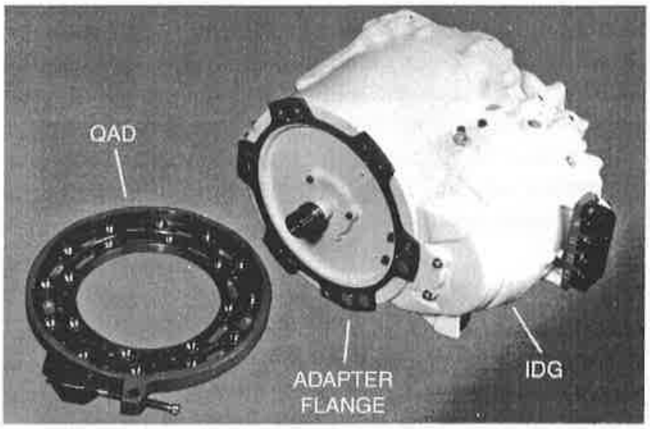


FIGURE 11-29 An integrated drive generator (IDG), an adapter flange, and a quick attach/detach (QAD) ring. (*Sundstrand Corporation.*)

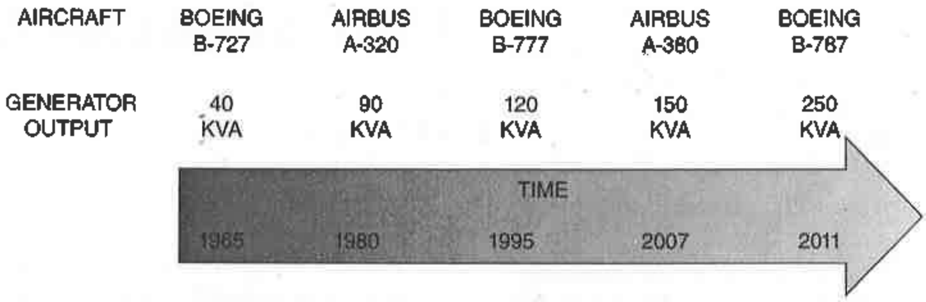


FIGURE 11-30 AC generator output by aircraft and year.

Three electrical subassemblies make up the generator (alternator) portion of the IDG: the permanent magnet generator (PMG), the exciter generator and rectifier assembly, and the main generator. This generator (alternator) operates in the same way as the PMG described previously.

There has been a trend in the design of transport category aircraft that requires the production of more electrical power. The newest aircraft are often referred to as **the more electric airplane** because many of their hydraulic and pneumatic systems have been converted to operate using electricity. Many people consider the Boeing B-727 as the beginning of the modern age of air transportation. This aircraft employed ac generators with an output of 40 KVA. (KVA stands for kilovolt amperes and is a measure of power output similar to a watt.) As aircraft and electrical systems developed, the output of a typical ac generator increased. Figure 11-30 shows a timeline comparing aircraft and the output of their brushless ac generators. As can be seen, the modern aircraft generators have a much higher power output than earlier units. It should also be noted that modern transport category aircraft not only use high-power generators, they also have more generators than earlier aircraft.

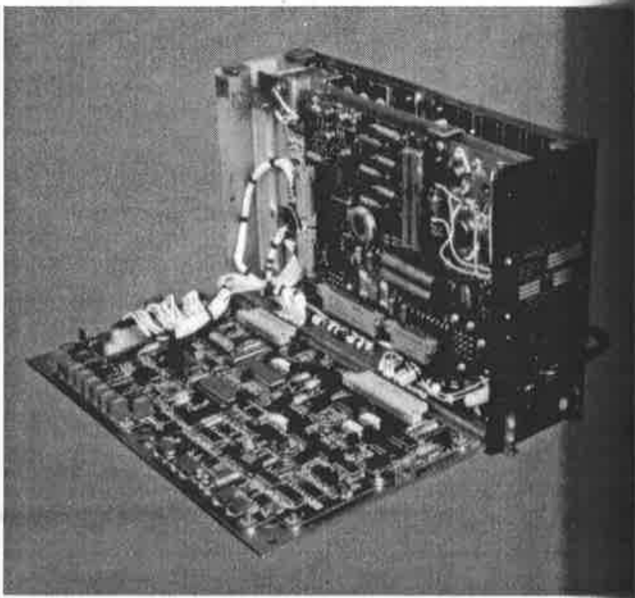


FIGURE 11-31 A typical generator control unit (GCU) (*Sundstrand Corporation.*)

Generator Cooling

Owing to their compact size, most ac generators require some means of cooling during operation. Older and/or less powerful generators are typically cooled by means of ram air forced through the units. Newer systems use oil as the cooling agent. The oil is sent from the CSD through the generator and then through an air/oil heat exchanger. The air cools the oil, which is once again cycled through the CSD and generator. The use of oil cooling allows for a higher-speed rotor within the generator section. A higher-speed rotor means a lighter, more compact generator that can produce the power required by modern aircraft.

Generator Control Units

Aircraft electric power control systems include functions such as voltage regulation, current limiting, protection for out-of-tolerance voltage and frequency conditions, and crew alerting. The major component used to perform these functions is called the **generator control unit** (GCU). A typical GCU is shown in Fig. 11-31. The GCU regulates generator output by sensing the aircraft system's voltage and comparing it with a reference signal. The voltage regulator then sends an adjusted current flow to the exciter field of the main generator. This, in turn, controls the main generator's output voltage.

Protection circuitry monitors various electrical system parameters including overvoltage and overcurrent conditions, frequency, phase sequence, and current differentials. If a fault occurs, the protection circuitry then operates corresponding electric relays in order to isolate defective components. In the case of a generator system failure, the GCU senses partial loss of electric power and automatically sends the appropriate signal to the **bus power control unit** (BPCU). In this event, the BPCU will automatically isolate any defective generator and reconnect the load bus to another power source. Power distribution and control, along with bus power control units, will be discussed in Chap. 12.

The Ram Air Turbine

Many modern transport category aircraft use a power backup system known as a **ram air turbine (RAT)**. In the event of a complete electrical generator system failure, the RAT is deployed to supply emergency electrical power. The RAT is a small wind turbine that is connected to a hydraulic pump, and/or electrical generator. When deployed, the RAT generates power from the airstream alongside the aircraft as long as the plane is in flight. If both primary and auxiliary power sources are inoperative, the RAT will power critical electric systems and flight controls.

In normal conditions the RAT is retracted into the fuselage (or wing), and is deployed manually or automatically following complete loss of power. In the time between power loss and RAT deployment, batteries are used to provide emergency electrical power. When deployed, as seen in Fig. 11-32, the RAT generates power due to the forward speed of the aircraft; the air passing through the RAT propeller causes the unit to windmill which in turn rotates a hydraulic pump. Most RATs produce only hydraulic power, which in turn is used to power a small electrical generator as well as critical hydraulic systems.

Many modern types of commercial airliners are equipped with RATs. The Airbus A-380 has the largest RAT propeller in the world at 5.3 ft [1.63 m] in diameter. A typical large RAT on a commercial aircraft can be capable of producing from 5 to 50 KVA, depending on the generator and speed of the aircraft. At low airspeed, the RAT will generate less power.

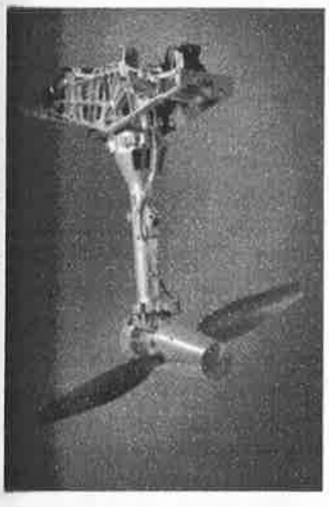


FIGURE 11-32 Ram air turbine.

INVERTERS

An **inverter** is a device for converting direct current into alternating current at the frequency and voltage required for particular purposes. Certain systems and equipment in aircraft electrical or electronic systems require 26-V 400-Hz ac power, and others require 115-V 400-Hz power. To provide this power, it is often necessary to employ an inverter.

Inverters are typically used on large aircraft for emergency situations only. In this case, the aircraft employs engine-driven generators (alternators) to supply needed ac power during normal operating conditions. If all ac generators should fail, the inverter would then be used to convert battery dc power into ac power available for essential ac loads.

Many light aircraft employ static inverters during normal operating conditions. These aircraft require a relatively small amount of alternating current and therefore utilize engine-driven dc alternators as their main electric power source. Most light aircraft produced over the last decade employ one or more inverters for the production of alternating current. These aircraft use alternating current to power a variety of components, including engine and flight instruments, heated windshields, and lighting circuits. In some cases, these components are feasible only if operated by ac power; therefore, the inverter is essential. There are two basic types of inverters, rotary and static. Modern aircraft employ static inverters because of their reliability, efficiency, and weight savings over rotary inverters.

Rotary Inverters

For many years inverters were simply special types of motor-generators; that is, a constant-speed motor was employed to drive an alternator that was designed to produce the particular type of power required.

A typical **rotary inverter** consists of a dc motor driving an ac generator. The rotors of the motor and the alternator are mounted on the same shaft and rotate as one unit. A cooling fan is typically mounted on the shaft to provide for air cooling.

Rotary inverters utilize an input voltage of 26 to 29 V dc. The output is 115 V, single-phase; 115 V, three-phase; and 200 V, three-phase. Frequency is 400 Hz for all phases.

Maintenance of rotary inverters is similar to that for motors and generators. Maintenance practices are set forth in the manufacturer's maintenance or service manual.

Because of their excess weight and high maintenance requirements, rotary inverters have been replaced by static inverters on almost all aircraft. Most likely the only aircraft currently flying with rotary inverters are antique aircraft that wish to maintain original equipment for historic purposes.

Static Inverters

A **static inverter**, or **inverter**, is an electrical power converter that changes direct current to alternating current using solid-state circuitry, transformers, switching transistors, and control circuits. Modern static inverters have no moving parts and are used in a wide range of applications, from small switching power supplies in computers, to large electric utility applications; inverters are commonly used to supply ac power from dc sources such as solar panels or batteries. The inverter performs the opposite function of a rectifier. The electrical inverter is a high-power electronic oscillator. (It creates an "oscillating" current flow from a direct or stable current flow.) Due to the miniaturization of electronic circuits, low-power inverters can now be constructed extremely small and lightweight. Static inverters have become commonplace to provide power for a multitude of applications on all types of aircraft. High-power inverters are found on transport category aircraft for backup supply of alternating current; for example, the Airbus A-380 employs a 2.5 KVA emergency inverter.

The internal circuitry of a **static inverter** contains standard electric and electronic components, such as an oscillator circuit, transistors, capacitors, and transformers. By means of the oscillator circuit, the inverter develops the 400-Hz frequency for which it is designed. This current is passed through a transformer and filtered to produce the proper waveshape and voltage. The unit shown in Fig. 11-33 utilizes an input voltage of 18 to 30 V dc and produces an output of 15-V single-phase alternating current with a frequency of 400 Hz. The unit weighs 18.5 lb [8.4 kg].

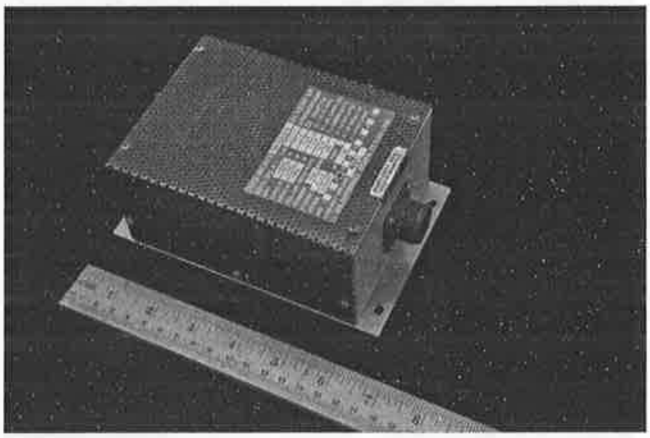


FIGURE 11-33 A static inverter. (*Bendix Corporation, Electric and Power Division.*)

Static inverters are easily removed for testing. If they require repair, they should be sent to an approved facility that is equipped to perform the work required.

Because of the miniaturization of electronic components, static inverters have become relatively small and lightweight. This has made it possible for light single-engine aircraft to employ an ac electrical system. An electroluminescent (EL) panel is a high-efficiency lighting system powered by alternating current. The panel is constructed of phosphorous material laminated between two clear plastic layers, as shown in Fig. 11-34. The phosphorous material glows when connected to an ac voltage. The front plastic layer is painted black except where stencils of appropriate letters or numbers are placed. The letters and numbers therefore remain clear in order to transmit the light from the glowing phosphorous material. Figure 11-35 shows a typical static inverter and EL panel.

VARIABLE-SPEED CONSTANT-FREQUENCY POWER SYSTEMS

In an effort to simplify and improve the production of ac power for aircraft and to get away from the need for hydromechanical constant-speed drives, a number of systems have been devised for producing 400-Hz three-phase electric power through electronic circuitry. This has been made possible by the great advances in solid-state technology developed in recent years.

Variable-speed constant-frequency generators are typically referred to as **VSCF** systems. Basically, the systems employ a generator driven at a variable speed, thus producing a variable-frequency output. The rotational speed of the generator is a direct function of the engine rpm. No constant-speed drive (CSD) mechanism is needed for VSCF systems. The elimination of the mechanical CSD improves reliability of the systems and offers more flexibility on installation of the generator. The generator's variable-frequency output current is

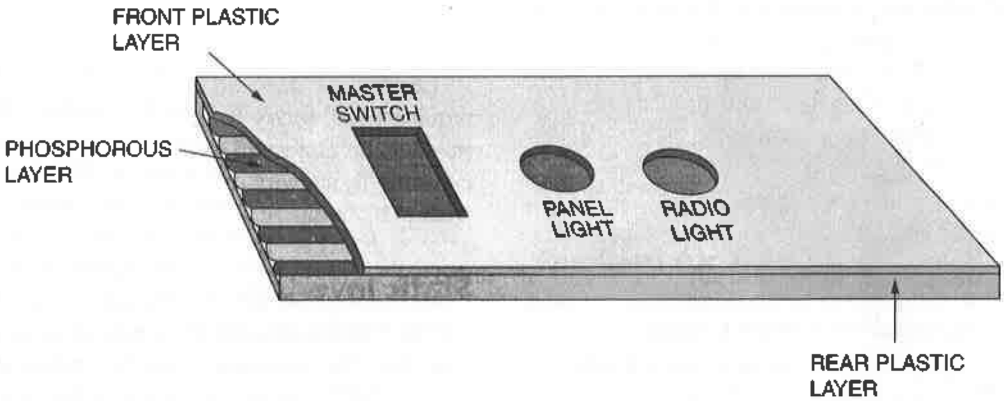


FIGURE 11-34 An electroluminescent panel.

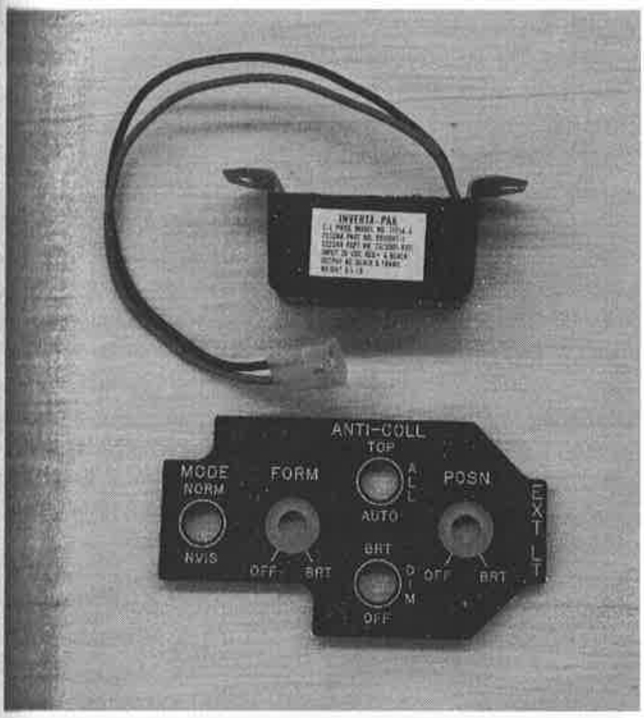


FIGURE 11-35 An electroluminescent panel and associated static inverter.

FIGURE 11-36 A 600-A power transistor. (*Westinghouse Electric Corporation.*)

converted to a constant-frequency 400-Hz alternating current by means of solid-state circuitry. This makes the electric power suitable for aircraft use. Several modern aircraft currently use VSCF systems as primary and secondary ac power sources. VSCF systems are found on virtually all transport category aircraft designed in the last 20 years, and many corporate and commuter aircraft.

Utilizing state-of-the-art electronic components, the VSCF systems improve reliability over the mechanical-hydraulic units of the constant-speed drive. One VSCF system produced by Sundstrand Corporation contains only two moving parts, the oil pump and the generator rotor. There are no other parts to wear or require periodic overhaul. A major breakthrough in component design for the VSCF systems was the development of the 600-A power transistor shown in Fig. 11-36. This transistor has made possible VSCF systems capable of 110-kVA output.

The VSCF systems also offer greater flexibility than the typical CSD and generator configuration. The generator must still be mounted to the engine drive mechanism; however, the control units of the VSCF system can be mounted virtually anywhere on the aircraft. Elimination of the CSD therefore allows for a more compact engine nacelle. A typical integrated unit is shown in Fig. 11-37. The major subassemblies are shown in Fig. 11-38; the high-power inverter assembly is shown in Fig. 11-39; and Fig. 11-40 shows the bottom view of the inverter and the modular power pole. As seen in this figure, the 600-A power transistors are mounted in one stack and, in this case, are capable of a 60-kVA output.

Figure 11-41 is a block diagram showing the principal elements of a VSCF system found on the Boeing 737 aircraft. The brushless ac generator is similar to those described

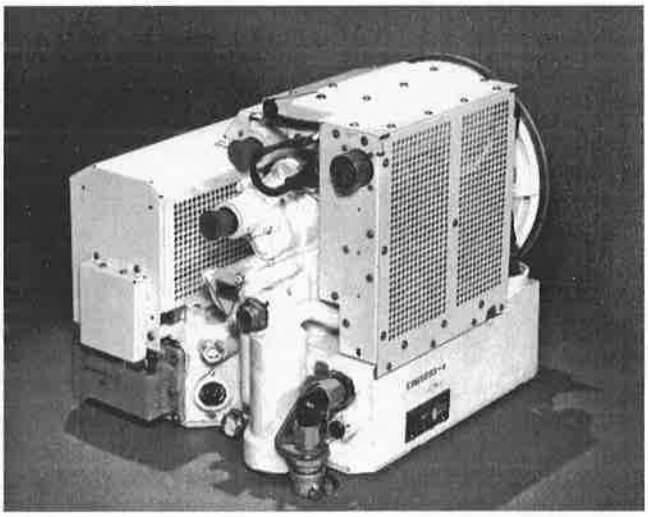


FIGURE 11-37 An integrated VSCF system. (*Westinghouse Electric Corporation.*)

previously; however, since it is driven directly by the engine, its rotational speed and output frequency will vary as engine speed varies. The variable three-phase power is fed to the full-wave rectifier within the VSCF converter, where it is changed into direct current and filtered. This direct current is fed to the inverter circuitry, where it is formed into square-wave outputs that are separated and summed to produce three-phase 400-Hz alternating current. The functions of the VSCF converter are similar to those of a typical static inverter. The generator converter control unit (GCCU) provides VSCF control and protection through the use of a voltage regulator and built-in test circuitry.

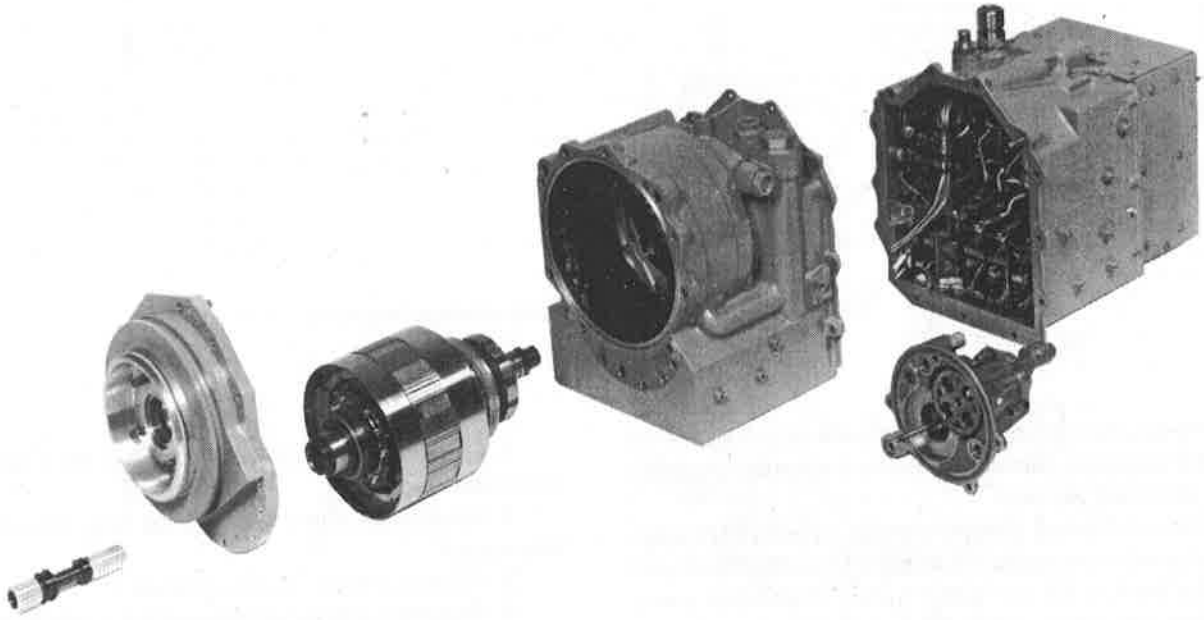


FIGURE 11-38 The major subassemblies of a VSCF system. (*Westinghouse Electric Corporation.*)

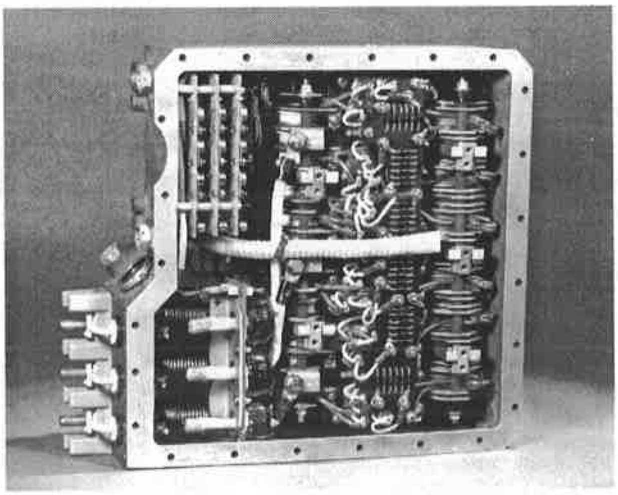


FIGURE 11-39 The power inverter assembly of a VSCF system. (*Westinghouse Electric Corporation.*)

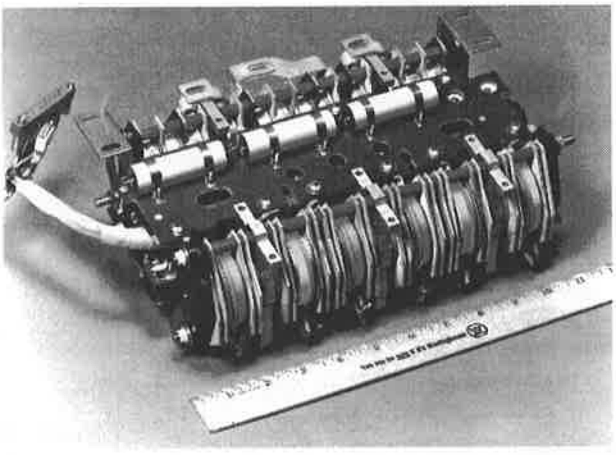


FIGURE 11-40 The main power pole assembly of a VSCF inverter. (*Westinghouse Electric Corporation.*)

The B-737 VSCF components are cooled by means of spray oil for the generator, spray oil and forced air for the converter assembly, and convection cooling for the GCCU. This system produces 115/200 V three-phase 400 Hz ac and is capable of a continuous 60-kVA output, or 80 kVA for 5 s. The input speed range is 4630 to 8600 rpm. The power factor limits range from .75 lag to .95 lead. The generator, converter, and GCCU together weigh only 145 lb. [65.8 kg].

The maintainability of the VSCF system is enhanced through the use of the aircraft's fault annunciator system and built-in test equipment located directly on the converter assembly. The built-in test (BIT) feature is designed to operate at two levels. Flight-line technicians use the first test level by activating a switch on the unit. Adjacent to the switch are two lights labeled "VSCF fault detected" and "Aircraft open phase trip." This test will inform the technician if the fault lies in the VSCF components or the aircraft wiring. The second test level is used by technicians repairing the VSCF system once it has been removed from the aircraft.

Currently, VSCF systems are in limited use; however, if the projected reliability and operating costs are accurate, VSCF systems will be the next-generation electric power supply systems for modern aircraft.

Variable Frequency Generators

The latest transport category aircraft generators are designed to output a variable frequency alternating current; these units are called **variable frequency generators (VFG)**. Since turbine engines operate at a relatively constant rpm, any generator connected to this engine will also rotate at a relatively constant rpm. This allows engineers to produce an ac generator directly driven by the turbine engine. The output frequency of these generators will typically range between approximately 350 and 800 Hz. Of course, the electrical loads connected to this variable frequency alternating current

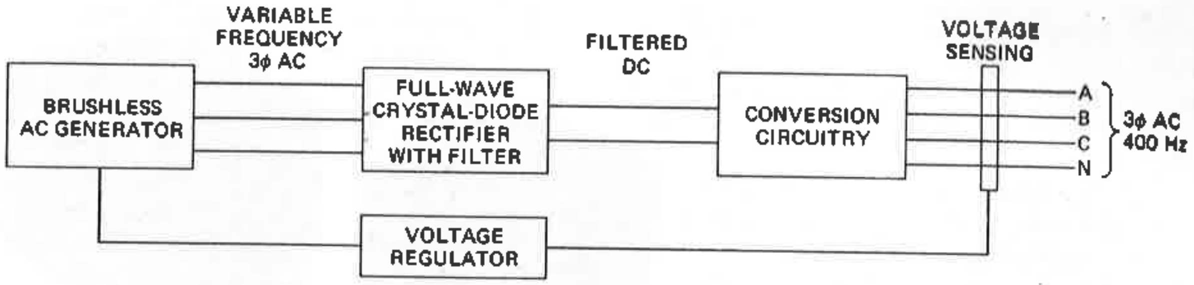


FIGURE 11-41 A block diagram of a variable-speed constant-frequency power system.

must be designed to operate on a variable frequency; or the variable frequency can be modified to a constant frequency using electronic circuitry.

Three commercial aircraft, recently introduced, employ VFGs for either emergency or main power units. The Boeing 777 uses the RAT for emergency backup ac electrical power. This unit will output 115 V AC at a variable frequency of 392 to 510 Hz. The frequency is a function of the RAT speed. The total power output of this unit is 7.5 KVA; much less than the main engine generators which output a maximum of 120 KVA. It should be noted that the frequency range of this emergency generator can only change approximately 25 percent; this variance will still allow all critical ac systems to operate in case of an emergency. The standard operating frequency of the B-777 ac equipment is 400 Hz. Both the Airbus A-380 and the Boeing B-787 employ VFGs as a primary power source. The A-380 has four main generators capable of 115 V ac output with a frequency range of 370 to 770 Hz, and a maximum power of 150 KVA. The two APU generators found on this aircraft use VSCF generators with an output of 120 KVA, 115 V ac at a constant frequency of 400 Hz.

The Boeing 787 is by far the most electric airplane currently flying. This aircraft employs four main starter generators and two APU starter generators; combined, these six units can produce a total of 1.45 MW of power. The **starter generators (SG)** found on the B-787 are multipurpose units used for engine starting as well as generation of alternating current. These SGs are similar to those discussed in the last chapter; however, these units are much more powerful, larger, and produce ac not dc. In the generating mode, the four main-engine SGs on the B-787 produce a maximum power of 250 KVA, 235 V ac at a variable frequency of 360 to 800 Hz. When one looks at the trends in aircraft design, it is obvious that variable frequency systems and the use of more electric power will shape the next generation aircraft.

REVIEW QUESTIONS

1. Describe the operation of a typical aircraft dc alternator.
2. What is the difference between the rotor and the stator in a dc alternator?
3. Explain the voltage control circuit for a typical dc alternator.
4. What is the purpose of the slip rings found in a dc alternator?
5. What is a three-phase armature?
6. Compare a delta winding with a Y winding.
7. In a three-phase system, how many degrees separate the phases?
8. How many diodes are used in a three-phase, full-wave rectifier?
9. Describe a three-phase alternator for light aircraft.
10. By what means are alternators for light aircraft driven?
11. Describe the tests that may be made on a small alternator in order to determine that it will operate satisfactorily.
12. What is the advantage of using a solid-state ACU?
13. What are the key points that describe the operation of a solid-state ACU?
14. How is voltage adjusted when a transistorized voltage regulator is used?
15. Why is it not necessary to include a reverse-current cutout relay in a system using an alternator?
16. What is the function of the zener diode in a transistorized voltage control circuit?
17. Describe the function of the alternator master switch.
18. Describe the differences between aircraft and automotive alternators.
19. Describe the theory of operation for a transport category aircraft's brushless alternator.
20. Explain how field excitation is accomplished in a brushless generator.
21. What is meant by the term PMG?
22. What factor must be controlled when ac generators are operated in parallel?
23. What is an integrated drive generator?
24. How are large ac alternators typically cooled?
25. What is the meaning of *kVA*?
26. What is the purpose of the GCU?
27. Explain the use of an APU driven alternator.
28. Describe the output of a variable frequency ac generator.
29. What is a *ram air turbine* (RAT) and on what type of aircraft are they used?

30. Which transport-category aircraft uses a starter generator?

31. How is it possible to keep an alternator at a constant speed when the engine by which it is driven changes rpm?

32. Give a brief explanation of the operation of a CSD.

33. By what means does a CSD sense oil loss or an overtemperature condition?

34. How can a technician determine if an IDG has the correct oil level?

35. Explain the basic principles of a variable-speed constant-frequency electric power system.

36. What is the advantage of a VSCF system?

37. Explain the purpose of an inverter.

38. What is the advantage of a static inverter?

39. Describe the principle of a static inverter.

Power Distribution Systems 12

INTRODUCTION

Modern aircraft require a consistent and reliable supply of electric power. There are four common sources of electric power used during normal aircraft operations. These sources are dc alternators, dc generators, ac alternators (generators), and the aircraft's storage battery. As discussed in Chap. 11, the aircraft's battery is typically used for emergency operations and any intermittent system overloads. DC alternators are typically used on piston engine aircraft. DC starter-generators are used on medium-sized turbine-powered aircraft. AC alternators are used on transport-category aircraft and some large business jets. Some form of electrical distribution system must be employed on every aircraft containing an electrical system. A simple power distribution system consists of a basic copper conductor, called a **bus bar** or **bus**. This type of system is found on most single-engine aircraft. The bus is a conductor designed to carry the entire electrical load and distribute that load to the individual power users. Each electric power user is connected to the bus through a fuse or circuit breaker.

On almost all aircraft the bus bar is connected to the positive output terminal of the generator and/or battery. The negative voltage is distributed through the metal structure of the aircraft. The metal airframe (negative side of the voltage) is often referred to as the **ground**; hence this type of distribution is often called a **negative-ground system**. In all negative-ground aircraft, the positive voltage is distributed to any given piece of electrical equipment through an insulated wire, and the negative voltage is connected through the airframe. Since only one wire (and the ground) is needed to operate electrical equipment, this is known as a **single-wire system**. Single-wire systems are possible only where the airframe is constructed from a conductive material, such as aluminum. On composite aircraft, some type of ground (negative) conductor is required. In some cases two wires (one positive, one negative) are routed through the aircraft to each power user; in other cases a ground plane is added to the structure of the aircraft. In this case, the composite aircraft will carry the negative voltage to all loads in a similar fashion as an aluminum aircraft. Power distribution on composite aircraft will be discussed later in this chapter.

Larger, more complex aircraft typically contain several bus bars or power distribution centers. Each bus has the specific task of distributing electric power to a given group of electrical loads. Distribution centers are often categorized as ac and dc, left and right, and essential and nonessential. On multiengine aircraft each engine-driven alternator typically employs its own distribution bus. These generator buses are then connected to their respective loads via distribution buses and associated bus ties.

As described earlier, alternators or generators are used on nearly every aircraft to produce electric power. Since both units operate similarly, the terms *alternator* and *generator* are used interchangeably throughout the aircraft industry. Although there are obvious differences between alternators and generators, in this chapter the reader should consider the terms synonymous.

REQUIREMENTS FOR POWER DISTRIBUTION SYSTEMS

General Requirements

The general requirements for power distribution systems on normal, utility, and acrobatic aircraft are set forth by **FAR Part 23**. **FAR Part 25** establishes the requirements for transport-category aircraft. The specific design details of any aircraft are agreed upon by the manufacturer and the FAA prior to aircraft certification. The federal aviation regulations (FARs) set forth only basic guidelines upon which an aircraft's certification is based.

The electric power system is one of the most critical systems found on modern aircraft. A complete electrical system failure would be catastrophic. The following guidelines related to electric power systems are designed to prevent such a failure.

Electric power sources must function properly when connected in combination or independently, except that alternators may depend on a battery for initial excitation or for stabilization. No failure or malfunction of any electric power source may impair the ability of any remaining source to supply load circuits essential for safe operation of the aircraft, except that an alternator that depends on a battery for initial excitation or for stabilization may be stopped by failure of that battery.

Each electric power source control must allow for independent operation of each source. However, controls associated with alternators that depend on a battery for initial excitation do not need to provide independent operation between the alternator and its battery. A design of this type makes it possible to disconnect an alternator in a multi-alternator (parallel) system without affecting the operation of other alternators in the system. Of course, with one alternator or generator disconnected, there will be a subsequent load increase on the active generator(s).

There must be at least one generator in an electrical system if the system supplies power to circuits that are essential for safe operation of the aircraft. Each generator must be able to deliver its continuous rated power. If the design of the generator and its associated circuit is such that a reverse current could flow from the battery to the generator, a reverse-current cutout relay must be provided in the circuit to disconnect the generator from the other generators and the battery when enough reverse current exists to damage the system. Alternator systems do not require a reverse-current cutout relay because the diode rectifiers in the alternators prevent a reverse current flow.

Generator voltage control equipment must be able to regulate the generator output within rated limits on a continuous and dependable basis. Each generator or alternator must have an overvoltage control designed and installed to prevent damage to the electrical system, or equipment supplied by the system, that could result if the generator were to develop an overvoltage condition. There must be a means to warn the flight crew immediately in case any generator in the system should fail.

There must be a means to indicate to appropriate flight crew members the electrical quantities in the system essential for safe operation of the aircraft. Generally, one or more ammeters and/or voltmeters are required. Often on twin-engine aircraft one ammeter is used with the capability of being switched to monitor either generator output current or battery current. As previously discussed, any ammeter that measures battery current must be capable of both positive and negative current readings, because the battery can either supply or receive current. Those ammeters used to measure generator output need only indicate positive current values; the current flows from the generator to the aircraft bus. On many newer aircraft, ammeters and voltmeters have become part of an integrated display. In this case the alternator monitoring is typically shown on a flat panel display.

If provisions are made for connecting an external power source to the aircraft and that external power can be electrically connected to equipment other than that used for engine starting, means must be provided to ensure that no external power source having a reverse polarity or a reverse phase sequence can supply power to the aircraft's electric power system. This is usually accomplished by the use of a plug with different-sized contacts. This makes it impossible to insert the plug incorrectly.

On many aircraft a diode is used to prevent any reversed-polarity current from entering the external power receptacle. The diode is placed in series with the circuit that controls the external power contactor (solenoid). If the external power system supplies current of incorrect polarity, the diode will be reverse-biased, and the contactor will not close. This occurs because a reverse-biased diode acts as an open switch; an open in the contactor circuit prevents the contactor from closing. Therefore, any reversed-polarity external power supplied to the receptacle will never be connected to the power distribution system.

The power sources and the electrical system must be able to supply the following power loads in probable operating combinations and for probable durations:

1. Loads connected to the system with the system functioning normally
2. Essential loads, after failure of any one prime mover, power converter, or energy storage device (battery)
3. Essential loads after the failure of any one engine on two-engine aircraft
4. Essential loads after the failure of any two engines on aircraft with three or more engines
5. Essential loads for which an alternate source of power is required, after any failure or malfunction in any one power supply system, distribution system, or other utilization system

Further requirements for electrical systems in transport-category aircraft specify that the generating capacity for the system and the number and kinds of power sources must be determined by an elaborate electrical **load analysis**. The generating system includes electric power sources, main power buses, transmission cables, and associated control, regulation, and protective devices. The system must be designed so that power sources function properly when independent and when connected in combination with other sources. No failure or malfunction of any power source can create a hazard or impair the ability of remaining sources to supply essential loads. The design of the system must be such that the system voltage and frequency, as applicable, at the terminals of all essential load equipment can be maintained within the limits for which the equipment is designed, during any probable operating condition. System transients (variations in voltage and frequency) due to switching, fault clearing, or other causes must not make essential loads inoperative and must not cause a smoke or fire hazard.

There must be means accessible in flight to appropriate crew members for the individual and collective disconnection of the electric power sources from the system. The system must include instruments such as voltmeters, ammeters, and frequency meters to indicate to appropriate crew members that the generating system is providing the electrical quantities essential for the safe operation of the system.

It must be shown by analysis, tests, or both that the aircraft can be operated safely in **VFR (visual flight rules)** conditions for a period of not less than 5 min with the normal electric power sources, excluding the battery, inoperative. Most commercial aircraft will far exceed this 5-min minimum. For example, a Boeing 737 with a fully charged battery can operate all essential electrical systems for approximately 30 min without supplemental power from any generator.

Need for Protective Devices

Short circuits in electrical systems constitute a serious fire hazard and also may cause the destruction of electric wiring and damage to units of electric equipment. For these reasons adequate protective devices and systems must be provided. Such devices include fuses, circuit breakers, and cutout relays.

In the generating system, the protective devices must be of a type that will de-energize faulty power sources and power transmission equipment and disconnect them from their associated buses with sufficient rapidity to provide protection against hazardous overvoltage, over current, and other malfunctions.

All resettable circuit protective devices should be so designed that when an overload or circuit fault exists, they will open the circuit irrespective of the position of the operating control. This means, of course, that a circuit protective device must not be of a type that can be overridden manually. This type of circuit breaker is said to be **trip-free**. Figure 12-1 shows several common aircraft circuit breakers. Protective devices must be clearly identified and accessible for resetting in flight if they are in an essential circuit. Resetting a circuit breaker can be done only after the fault is corrected.

When fuses are used in an aircraft electrical system, spare fuses must be provided for use in flight in a quantity equal to at least 50 percent of the number of fuses of each rating required for complete circuit protection. If only one fuse of a particular rating is used in an aircraft system, then one spare should be carried for that rating.

Protective devices are not required in the main circuits of starter motors or in circuits where no hazard is presented by their omission. Each circuit for **essential loads** must have individual circuit protection; however, individual protection for each circuit in an essential-load system is not required. The circuit breaker panel for a typical light twin-engine

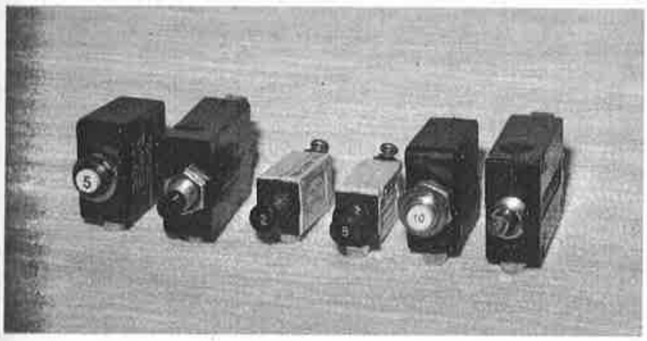


FIGURE 12-1 Common aircraft circuit breakers.

FIGURE 12-2 Circuit breaker panel, twin-engine Piper aircraft.

aircraft is shown in Fig. 12-2; the circuit breakers are located on the lower right side of the instrument panel directly in front of the copilot.

All fuses, circuit breakers, switches, and other electric controls in an airplane must be clearly identified so that the pilot or some other member of the crew can quickly and easily perform in flight any necessary service to a unit. A **master switch** must be provided that will make it possible to disconnect all power sources from the distribution system. By means of relays, the actual disconnection should be made as near to the power source as possible.

On many aircraft more than one master switch can be employed to allow for the isolation of certain electric equipment. For example, an avionics master switch controls the electric power to all avionics equipment. The master switch control panel from a Cirrus SR22 is shown in Fig. 12-3. This aircraft has two battery and two alternator switches; on this plane battery/alternator #2 is considered the master, or primary system. Battery/alternator #1 is the secondary system. There is also a separate **avionics** switch used to control the electronic navigation, communication, and instrument systems. This is typically accomplished through a solenoid that controls power to an avionics bus bar. Other master switches are commonly used to operate individual generators and galley power (if applicable).

FIGURE 12-3 A master switch control panel for a Cirrus SR22.

Electrical Load

The **electrical load** of an aircraft is determined by the load requirements of the electric units or systems that can be operated simultaneously. It is essential that the electrical load of any aircraft be known by the owner or operator, or at least by the person responsible for maintenance of the aircraft. No electric equipment can be added to an aircraft's electrical system until or unless the total load is computed, and it is found that the electric power source for the aircraft has sufficient capacity to operate the additional equipment.

To determine the electrical load of an aircraft, an **electrical-load analysis** is made. One way to do this is by adding all the possible loads that can be operating at any one time. (Electrical-load analysis is discussed in detail in the next section.) Loads may be **continuous** or **intermittent**, depending on the nature of the operation. Examples of continuous loads are navigation lights, the flashing beacon, the radio receiver, radio navigation equipment, electric instruments, electric fuel pumps, electric vacuum pumps, and the air-conditioning system. These are examples of systems that can be operated continuously during flight.

Intermittent loads are those that are operated for 2 min or less and are then turned off. Examples of intermittent loads are landing gear motors, flaps actuators, emergency electric-driven hydraulic pumps, trim motors, and landing lights. These units and circuits for other electrically operated devices are normally operated for a very short period of time, and hence considered intermittent loads.

In computing the electrical load for an aircraft, all circuits that can or may be operated at any one time must be considered. The total **probable continuous load** is the basis for selecting the capacity of the power source. It is recommended that the probable continuous load not be more than 80 percent of the generator capacity on aircraft where special placards or monitoring devices are not installed. This permits the generator or alternator to supply the load and also keep the battery charged.

Aircraft that employ a system to monitor the charging status can operate continuous electrical loads up to 100 percent of the generator capacity. In this case some means of indicating an alternator failure is also required. Most aircraft today employ a means to monitor alternator output; this can be accomplished by an ammeter only; or some aircraft use both ammeter and voltmeter indications as seen in Fig. 12-4. If a failure occurs in the charging system, a warning indictor will illuminate on the instrument panel and the pilot can then verify system operation using the ammeter and/or voltmeter.

During periods when a heavy intermittent load such as landing gear is operated, an overload will probably exist, and the overload will be met for a short time by the battery and generator together. The operator of the aircraft should understand that prolonged operation under overload conditions will cause the battery to discharge to the extent that it cannot provide emergency electric power.

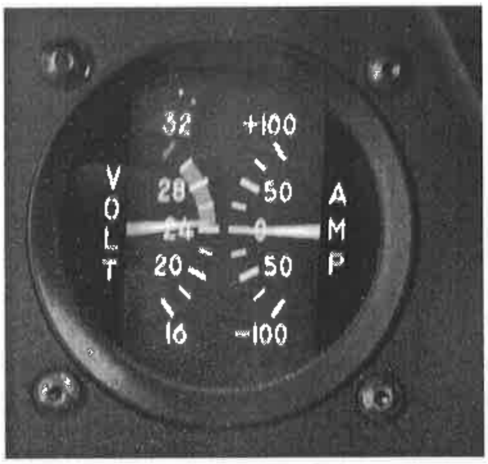


FIGURE 12-4 Voltmeter and ammeter on a modern single-engine aircraft.

On twin-engine aircraft where two generators are used to supply the electric power, the capacity of the two generators operating together is used when power requirements are computed. The probable continuous load is not excessive if the two generators can supply the power. When the total continuous load is greater than the capability of one generator to supply, it is necessary to provide for load reduction if one of the generators or one engine fails. The load should be reduced as soon as possible to a level that can be supplied by the operating generator.

The load condition during operation can be determined by observing the ammeter and voltmeter. When the ammeter is connected between the battery and the battery bus so that it will indicate CHARGE or DISCHARGE, it will be known that the system is not overloaded as long as the ammeter shows a charge condition. In this case a voltmeter connected to the main power bus will show that the system is operating at the rated system voltage. If there is an overload, the ammeter will show a discharge, and the voltmeter will give a low reading the value of which is determined by the amount of the overload.

When the ammeter is connected in the generator output lead and the system is not current-limited, an overload will be indicated when the ammeter reading is above the 100 percent mark. The ammeter should be "**red-lined**" so the pilot can determine easily when an overload exists. Most modern generator or alternator circuits contain an automatic means of controlling any overload condition; therefore, generator overloads typically do not exist.

When the ammeter is connected in the generator output lead and no output current is being produced, the ammeter will indicate zero current flow. On single-engine aircraft this indicates that the battery is supplying all the electric power. On multiengine systems, if only one alternator fails, the battery and the other generator(s) will supply the needed electric power. If this condition overloads the operating generator(s), the pilot may then shut off some nonessential equipment and reduce the load to a suitable level.

The principal concern of the aviation maintenance technician with respect to electrical load in an aircraft is a situation where it is desired to add electric equipment. If the addition of such equipment has been tested and approved by the FAA for a particular installation, instructions will be available from the manufacturer of the equipment or the aircraft setting forth all requirements for the installation. These instructions should be followed carefully.

Electrical-Load Analysis

Prior to installing any electric equipment in an aircraft, the technician must perform an **electrical-load analysis**. This is done to ensure that the aircraft's electric power system will not be overloaded by the addition of the new equipment. The goal is to compare the sum of all continuous electrical loads with the generator's (alternator's) maximum output. If the total continuous load is less than the rated generator output, more equipment may be added; however, the maximum generator output may never be exceeded by a continuous load.

There are basically two means to determine an aircraft's electrical load: via measurement or via summation of the individual loads. To measure electrical loads, an accurate ammeter must be placed in the generator output lead. The airplane ammeter is typically incapable of giving readings to an accuracy of 0.5 A, which is desirable for this test. Start the aircraft engine, and allow the battery to regain full charge. Next, turn on all the aircraft's continuous electric equipment, and monitor the ammeter. The ammeter will measure the total electrical load. This value can then be compared with the generator's rated output.

To find the total electrical load through summation, each individual electric current load must be known. The aircraft's service manual may provide this information, or it can be obtained from the data plate of each individual unit. In either case be sure to sum all continuous electrical loads. Then compare the generator's maximum rated output with the sum of the electrical loads. The total continuous load must always be equal to or less than the generator's maximum rated output. If "extra" capacity is available from the generator, more electric equipment can be added without a need for restricting the operation of certain electrical loads. If restriction(s) are necessary, a placard must be located on the aircraft's instrument panel to alert the pilot to each restriction. When summing electrical loads, be sure to use actual current draws, not circuit breaker (or fuse) ratings. A circuit breaker must be capable of sustaining a higher value than the actual load; therefore, an inaccurate sum will be obtained when using circuit breaker values.

If it becomes necessary to add equipment that may exceed the generator's maximum output, placards can be used to inform the pilot of the appropriate load configurations. That is, a placard will give the pilot the necessary load data to ensure that the electric power limits are not exceeded. For example a placard may read, "Do not operate the air conditioner and windshield heat simultaneously." This placard would be placed near the windshield heat and air conditioner control switches. Another option to prevent a potential charging system overload would be to replace the alternator/generator with one of larger capacity. If the aircraft is approved for more than one alternator through the original or supplemental type certificate, a larger capacity charging system may be available. In this case, the alternator, alternator control unit, associated wiring, and other related controls can be changed as needed. This in turn will allow for the addition of electrical equipment as approved for that aircraft.

A Simple Electrical System

A simple electrical system for a light aircraft consists of a battery circuit, an alternator circuit with associated controls, an engine starter circuit, a bus bar with circuit breakers, control switches, an ammeter, lighting circuits, and radio circuits. A schematic diagram of the basic power distribution system is shown in Fig. 12-5. The high-current-carrying cables in this system are connected from the battery to the main battery relay, from the battery relay to the starter relay, and from the starter relay to the starter. The ground leads for the starter and the battery are also of heavy cable. On this diagram these high-current circuits are drawn in bold.

The main alternator power cables are also considerably larger than the normal circuit wiring; however, they are usually smaller than the cables required to carry full battery current for engine starting. This is because the battery is used for starting the engine, and the starting current can easily exceed 200 A; alternator output current is often 100 A or less on light aircraft. During operation of the aircraft, the battery is connected to the system but is not supplying power. Instead, it is taking power from the alternator in order to maintain a charge. All the normal load currents are supplied by the alternator during flight. The distribution bus receives power from the alternator and/or battery during different operating modes. The bus then distributes the electric current through the individual circuit breakers to their respective loads. As shown in the schematic (see Fig. 12-5), the circuit breakers are connected directly to the distribution bus. This is done to prevent any accidental short to ground of an unprotected wire. It is always desirable to protect as much wiring as possible. Any wires that are not protected by a fuse or circuit breaker must be as short as practical and protected by insulated covers or "boots" at all terminal connections.

Although the schematic diagram in Fig. 12-5 shows an entire aircraft electrical system, this is not typical. Most manufacturers prefer to divide aircraft schematics into individual systems. This becomes a necessity when dealing more complex electrical systems. If an entire electrical system were represented in one schematic, the diagram would be extremely cluttered and too difficult to read. The following paragraphs will discuss schematic diagrams of several power distribution systems. Individual circuits, as they may be represented in a typical aircraft maintenance manual, will be presented in Chap. 13.

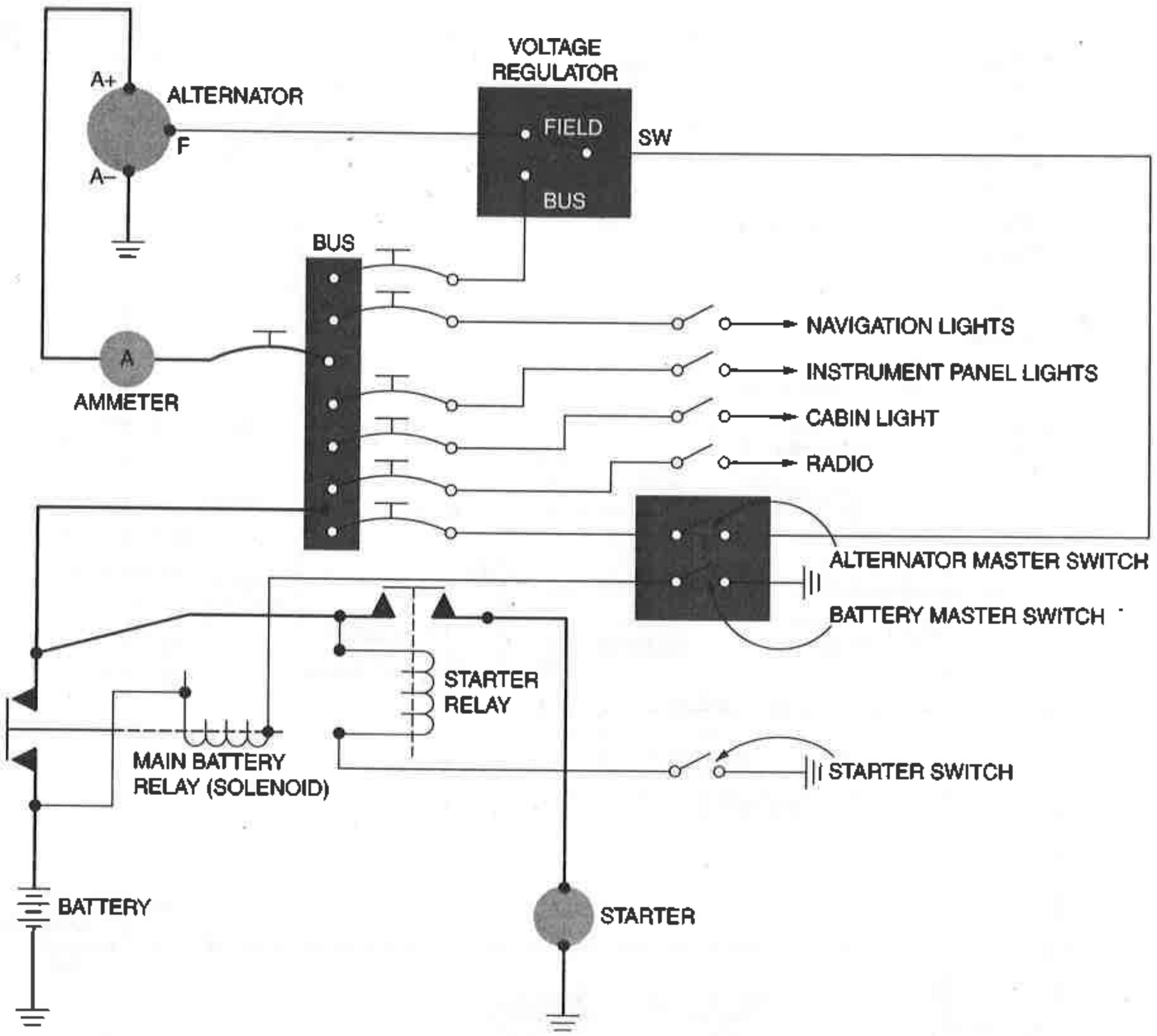


FIGURE 12-5 Basic power distribution system.

MAIN POWER DISTRIBUTION SYSTEMS

Single-Engine Aircraft

The Piper Tomahawk aircraft power distribution systems are shown in Fig. 12-6. This system is similar to many light single-engine aircraft such as the Cessna 152 and 172, the Piper Warrior, and other trainer aircraft built prior to the year 2000. In general, these aircraft were designed with one 12-V lead-acid battery and one alternator that produced a 14-V output. A typical alternator for single-engine aircraft can produce a maximum of 120 A. Most single-engine aircraft built after the year 2000 are much more reliant on electrical systems and therefore employ a more complex power distribution structure. These aircraft typically operate on a battery voltage of 24 V, alternator voltage of 28 V. In the Piper Tomahawk, and in most other light aircraft, the master solenoid coil is switched on the negative side of the circuit. The master switch contains two independent poles and throws. The battery master (on the left half of the switch), connects the ground (negative voltage) to the master solenoid. The solenoid's negative lead is switched to ensure proper system operation in case of an electrical short to ground. That is, if wire number P2A should short to ground, the master solenoid will remain closed. If the solenoid is closed, battery power remains connected to the distribution bus, thus creating no immediate danger. Therefore if wire P2A should accidentally short to ground during flight, the only consequence will be the inability to turn off the battery at the end of the flight. The alternator master switch (on the right side of the combination master switch), connects the voltage regulator to the bus, turning on the alternator. In many aircraft the alternator side of the master switch can be operated only if the battery master is also turned on. This is done to ensure that the battery is connected to the bus prior to the alternator.

There are two notes listed on the bottom left side of this diagram. Always refer to any notes or effective serial numbers prior to using a schematic for maintenance purposes.

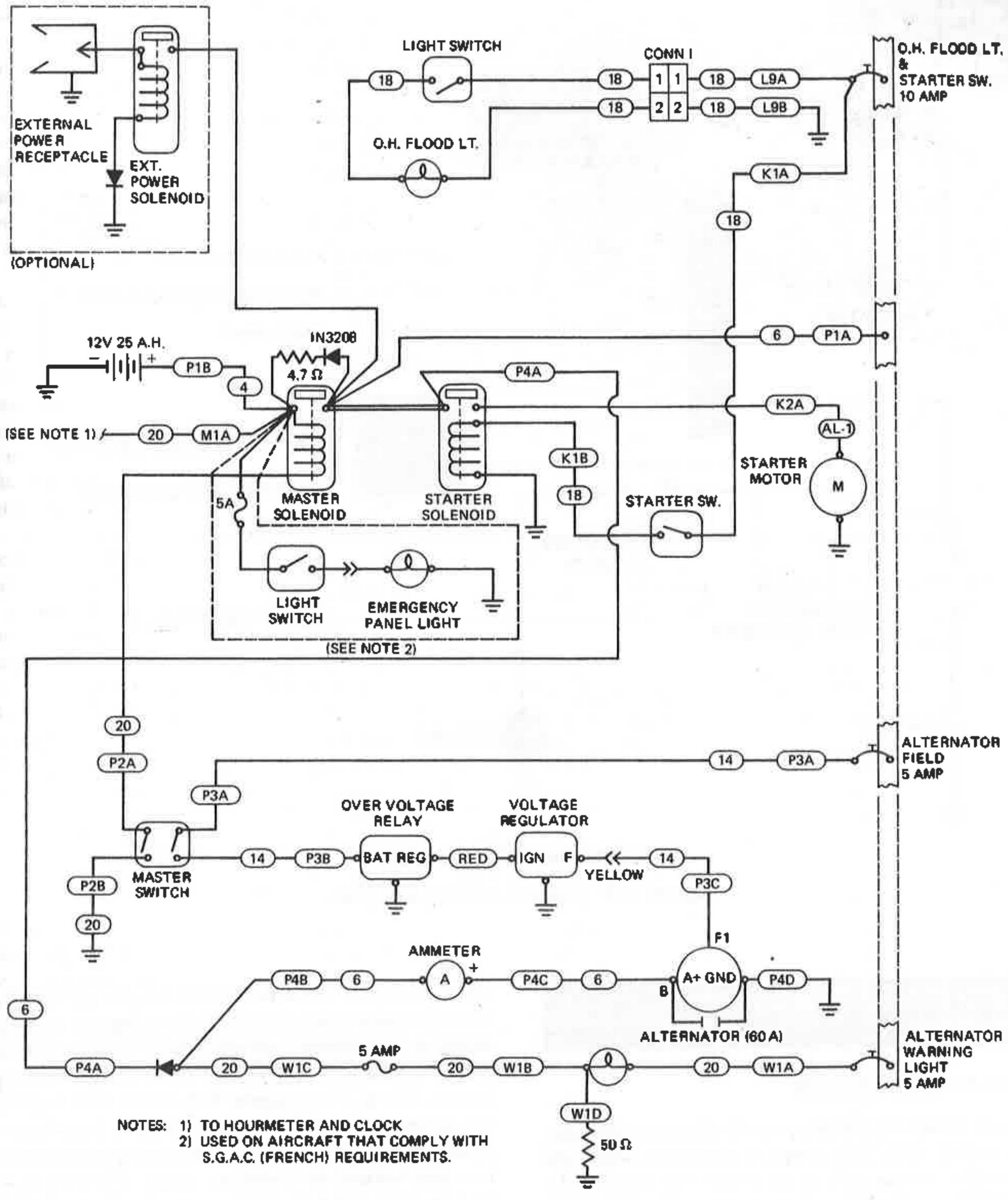


FIGURE 12-6 Typical single-engine aircraft power distribution system. (*Piper Aircraft Corporation.*)

The More Electronic Single-Engine Aircraft

The Cirrus model SR20 is a modern single-engine aircraft which is heavily reliant on electricity to power many critical flight and navigation systems. For this reason the SR20 contains a more elaborate electrical system than the Piper Tomahawk previously discussed. The SR20 electrical system contains two batteries and two alternators to help ensure the flow of electrical current and improve aircraft reliability. This "extra security" created by duplicate power systems is necessary because the instrument panel of this aircraft is totally dependent on digital electronics for operation. The instrument panel of a typical Cirrus single-engine aircraft is shown in Fig. 12-7. If all electrical systems would fail, there are only a few basic instruments that would provide mechanical backup and a critical situation could easily occur.

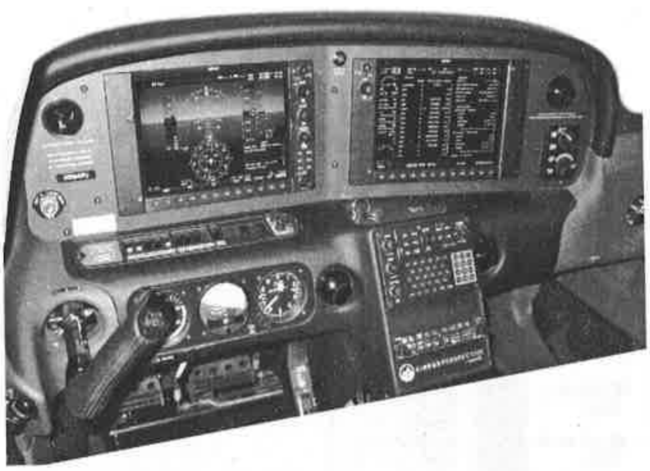


FIGURE 12-7 Cirrus SR20 instrument panel. See also color insert.

Please refer to the simplified diagram of the Cirrus aircraft shown in Fig. 12-8 during the discussions. Typical of most highly electronic aircraft, the Cirrus power system is divided into a **main** and **essential** distribution system. This aircraft operates using two 24-V batteries and two alternators that produce approximately 28 V dc during normal operation. The main alternator (ALT #1) produces a maximum of 100 A and the backup alternator (ALT #2) produces a maximum of 20 A. (The exact amperage may depend on aircraft serial number.) Battery 1 is the main battery used for engine starting and is similar to other lead-acid aircraft batteries. The two alternators and main battery are shown on the left side of the diagram.

Battery 2 is a smaller unit comprised of two sealed 12-V lead-acid batteries. The two 12-V batteries are wired in series to create the effect of one 24-V battery. These batteries are located in the aft portion of the fuselage and must be replaced after 2 years of service or 500 flight hours (see Fig. 12-9). At the bottom of the diagram (Fig. 12-8), it can be seen that battery 2 is connected to the essential bus 1 through battery relay 2 whenever the battery 2 switch is ON. The master switch panel (bottom left of diagram) shows two independent battery master switches, two alternator master switches, and one **avionics master** switch. The avionics master controls a relay that will turn on/off all nonessential avionics equipment. The battery masters control their respective batteries through a relay, or contactor. The alternators are controlled by their respective master switches through the alternator control unit (ACU) 1 and 2. Each module controls field current to its given alternator for control of alternator operation.

The distribution bus arrangement in Fig. 12-8 is relatively complex for a single-engine aircraft; there are nine independent buses. The main and essential distribution buses are used as the primary power supply points. The main bus will distribute the majority of the electrical power; however, the critical loads are fed through the essential bus. To provide a level of safety, battery 1 can power the essential bus through main bus, but the essential bus cannot power the main. In the center of the diagram there are two diodes used to prevent any reverse current flow from the essential to the main bus in the event of a system failure. There are also two 50-A circuit breakers to isolate either bus if needed due to an over-current situation. During normal flight, the main bus is powered by alternator 1 and the essential bus is powered by alternator 2. A logic module (near the center top of the diagram) receives input signals from three current sensors. If the sensors detect an abnormal current flow, the logic module can open one or more contactors or relays to isolate portions of the system. The module will also illuminate a warning indicator on the instrument panel.

Most of the electrical loads of the Cirrus SR20 are connected to the secondary buses located in the bottom right of the diagram. These secondary buses are fed from the main and essential distribution buses (upper center of the diagram). There are circuit breakers located in the feeder cables between the main and secondary buses. Some heavy electrical loads may be connected directly to the main bus because they require high current. These loads may include an air-conditioner system or high-power landing light.

The Cirrus system just described is typical of aircraft that require a high level of electrical reliability. The structure is designed to allow for one or more portions of the electrical system to fail, be completely isolated, and other systems to function normally. Critical electrical loads must be the least likely to fail and many systems can receive power from more than one power source. In the past this level of reliability was only available on multiengine aircraft; however, with the new generation of highly electronic airplane it is critical to have a dependable source of electrical power.

Twin-Engine Aircraft

A simplified power distribution schematic of a typical light twin-engine aircraft is shown in Fig. 12-10. This system employs a diode in series with the wire connecting the main and emergency power distribution buses. This diode will allow current flow from the main bus to the emergency bus, but not in the reverse direction. This is done to isolate the main bus in the event that it should short to ground. In that configuration the emergency bus could still receive battery power without being affected by the short circuit.

This schematic also contains a diode in parallel with the battery relay coil. If a diode is placed in parallel with an electromagnetic coil, it is used to "clip voltage spikes." As explained in Chap. 6, when a current starts to flow in a coil, or when the current flow is stopped, the inductance of the coil creates a voltage opposing the applied voltage. Thus whenever the switch is opened or closed within the relay or solenoid coil circuit, a **voltage spike** or **transient voltage** is produced. This reverse-polarity voltage spike will damage sensitive electronic equipment if it is allowed to enter the electrical system. The diode in parallel with the relay's coil will short together any reverse-polarity voltage spike; however, the applied voltage will be unaffected. A bidirectional zener diode can also be used for this purpose. The zener diode

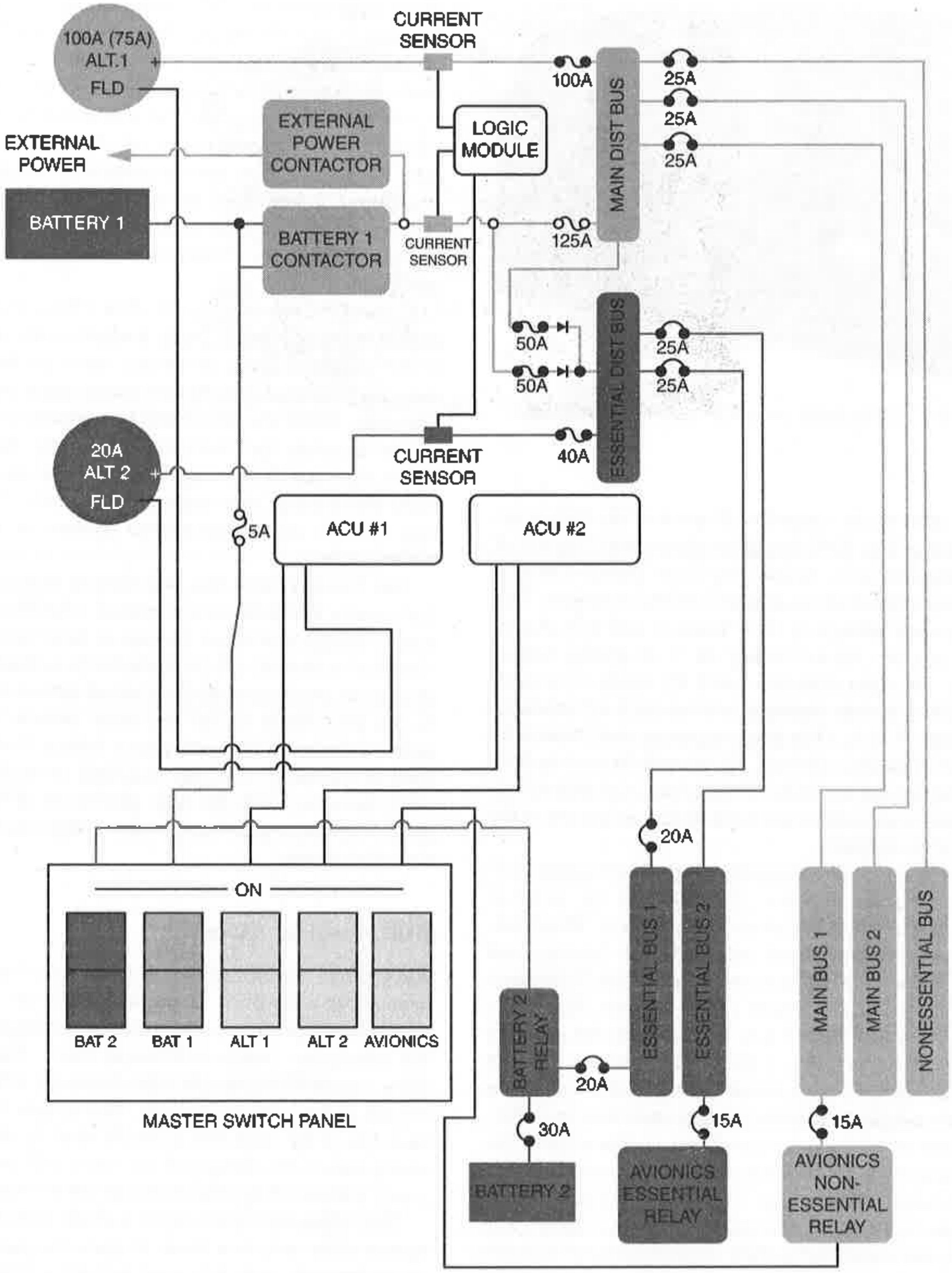


FIGURE 12-8 Cirrus SR20 power distribution system. See also color insert.

conducts and short-circuits the relatively high-value transient voltage. The lower system voltage is unaffected. Remember, the zener diode is a voltage-sensitive device.

In general, diodes of all types are becoming more popular in aircraft power distribution systems. If a diode is placed in parallel with a coil, it is used to prevent damage from induced voltage spikes. If a diode is placed in series, it is used to create a one-way current path between units.

The power distribution system for a light twin-engine Piper airplane is shown in Fig. 12-11. Since the airplane is equipped with all the avionics equipment necessary for electronic navigation and optimum flight performance, it is necessary for the alternators to have a comparatively high capacity.

The electrical system shown in Fig. 12-11 includes a 24-V, 17-Ah battery enclosed in a sealed stainless-steel battery box.

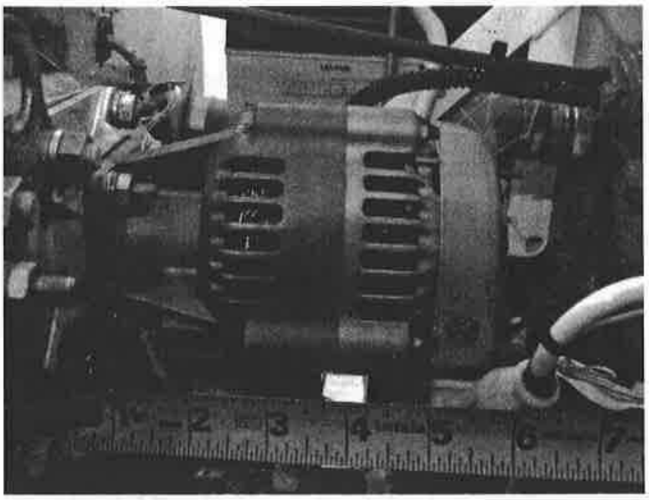


FIGURE 12-9 Backup alternator installed on a single-engine Cirrus aircraft.

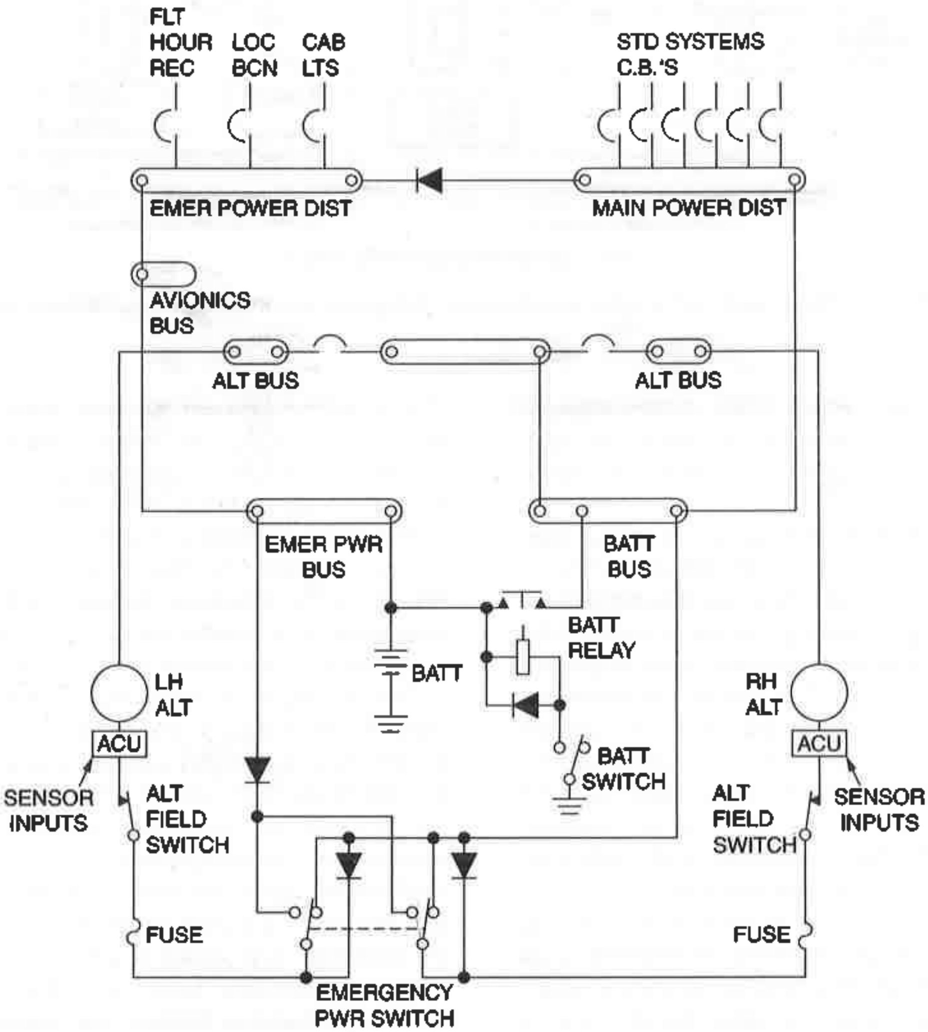


FIGURE 12-10 Typical light twin-engine aircraft power distribution system.

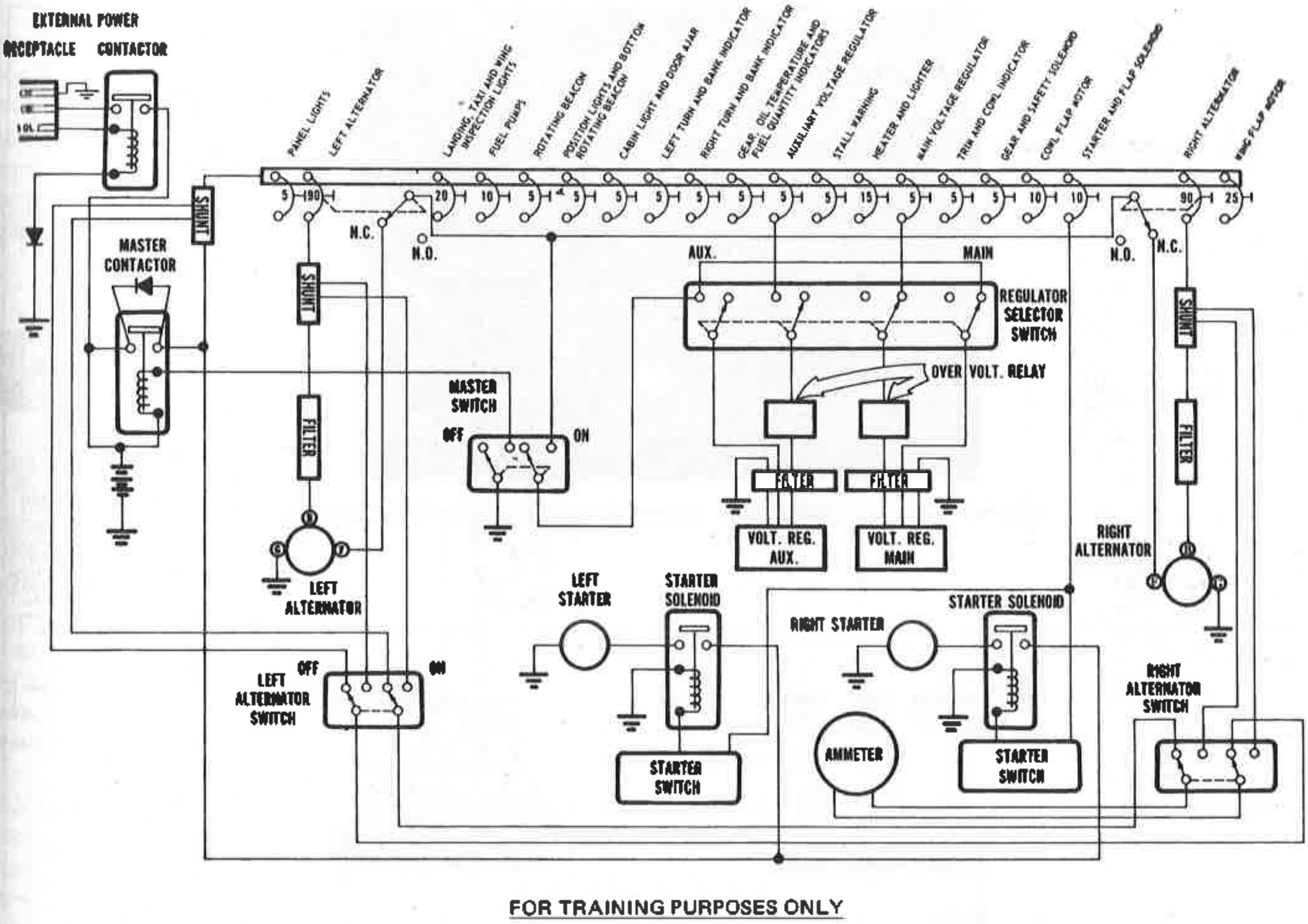


FIGURE 12-11 Typical light twin-engine aircraft power distribution system. (*Piper Aircraft Corporation.*)

Two 24-V, 70-A alternators driven by the engines supply all the normal power requirements of the aircraft and its equipment. The battery supplies power for starting the engines and for emergency peak loads.

The alternators are paralleled by using one voltage regulator to control the field current for both alternators. The circuit diagram in Fig. 12-11 shows how this is accomplished.

An overvoltage relay in the system serves as a safety valve in case either one or both of the alternators should produce dangerously excessive voltage. This condition would exist in the case of failure of the voltage regulator. In the event that the main voltage regulator fails and the overvoltage relay disconnects the alternator fields from the system, an auxiliary voltage regulator is available. Failure of the alternators can be detected by a discharge indication for the battery and a zero output on both alternator test positions.

The output of each alternator is checked by activating a PRESS-TO-TEST switch and observing the ammeter in the overhead switch panel. The test switches are shown as LEFT ALTERNATOR SWITCH and RIGHT ALTERNATOR SWITCH in the circuit diagram in Fig. 12-11.

Electrical switches for the various systems, including the MASTER SWITCH, are located on the aircraft instrument panel. The circuit breakers, located below the switches, automatically open their respective circuits in case of an overload. The circuit breakers can be reset merely by pressing the RESET button. If a circuit breaker continues to disconnect, the trouble should be located and repaired before another attempt is made to operate the circuit.

The power distribution system for a twin engine-turbine-powered airplane, the Beechcraft King Air, is shown in Fig. 12-12. This schematic diagram is presented to show the complexity of a modern aircraft electrical system and the many functions that require electric power.

The two-engine-driven starter-generators receive power from the main battery bus for starting purposes. During the generator mode, the starter-generator output current is directed to the right and left generator buses, respectively. The two generator buses are connected to the **feed buses** (numbers 1 to 4) through diodes and circuit breakers. This arrangement allows for both generators to power the four feed buses during normal operations or remain isolated during accidental short circuits to ground.

The two generator buses are connected to the isolation bus through **isolation limiters**. The isolation limiters, which are often referred to as **current limiters**, are simply high-amperage fuses. The isolation limiters can carry 325 A before opening. These isolation limiters open during overload conditions. For example, if an overload exists (a direct connection to ground) on the right generator bus, the right-side isolation

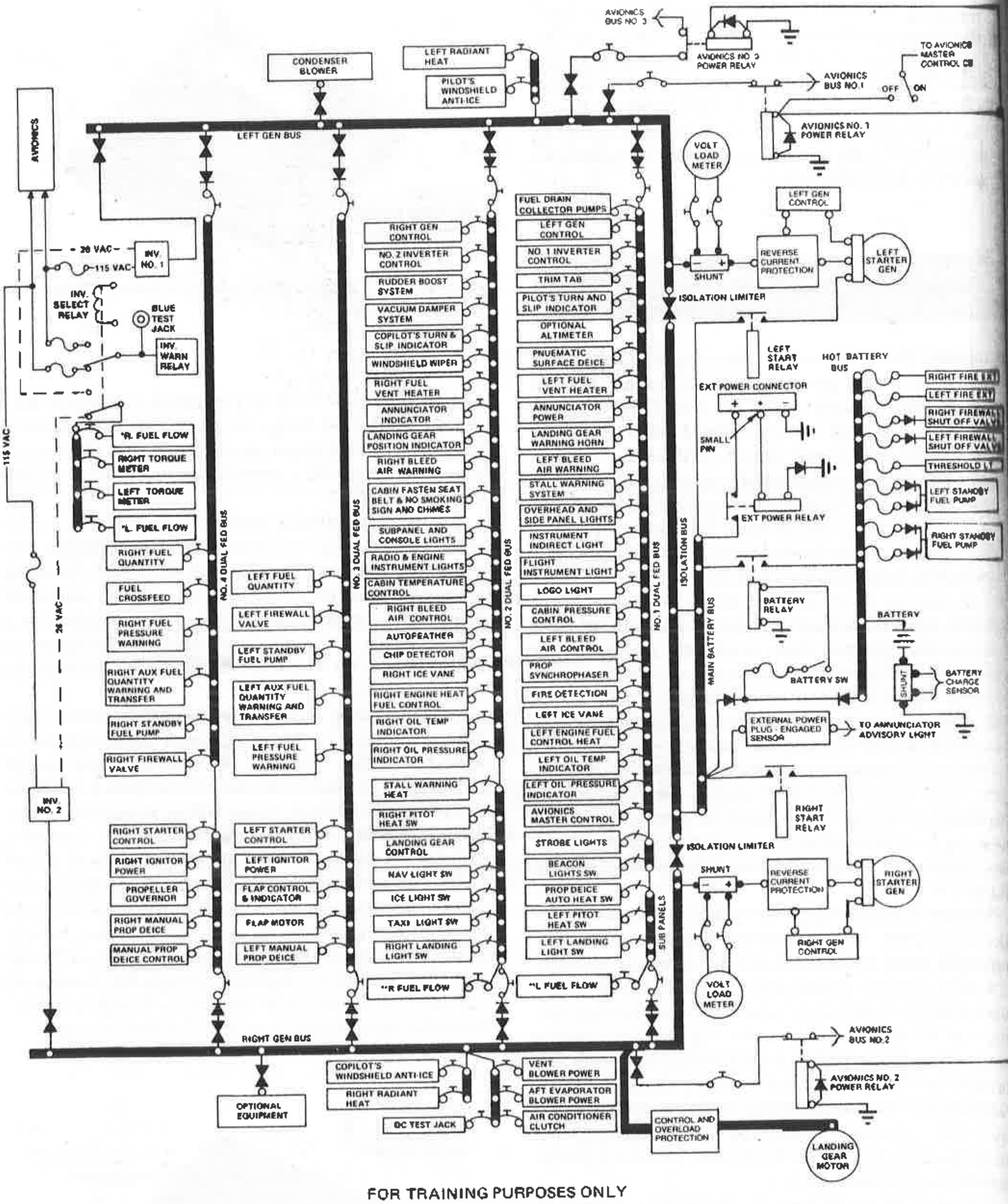


FIGURE 12-12 Power distribution system for a twin-engine turboprop aircraft. (*Beech Aircraft Corporation.*)

limiter will open and disconnect the battery (via the battery and isolation buses) from the right generator bus. At the same time, the right generator will be disconnected from the right generator bus by the right generator control unit. The diodes placed between the right generator bus and the four feed buses will be reverse-biased in this event and therefore will isolate the feed buses and prevent current flow from the feed buses to the right generator bus. The right generator bus is therefore completely isolated, and the rest of the electrical system operates normally. Under these conditions the right generator cannot supply power to the system, and all nonessential loads must be turned off to conserve power.

The King Air electrical system is typical of those found on moderately sized corporate aircraft. Isolation of overloaded circuits and distribution buses becomes essential for safe aircraft operation. Each of the aircraft's electrical loads may be powered by a minimum of two different means (the right and left generators). All essential electrical loads may be powered by one of three different means, the right or left generator or the aircraft battery.

POWER DISTRIBUTION ON COMPOSITE AIRCRAFT

Composite aircraft present an interesting challenge when it comes to electric power distribution, control of static electricity, and lightning strikes. The possibility of system interference from **high energy radiated fields (HERF)** is also enhanced in composite aircraft. HERF energy can easily transmit through nonprotected composite materials. For these reasons, most composite aircraft are completely covered by a conductive layer, and all metal fasteners and electrical ground connections are bonded to this layer. In other words, a conductive metal mesh is molded into the composite structure to create an electrical shield around the aircraft. Many different types of conductive materials are used including nickel-coated graphite cloth, aluminized fiberglass, and metal meshes. The most common metal mesh is aluminum; however, copper is used for certain composite materials. In each of these designs it is important that all independent sections of the aircraft be connected, **bonded**, electrically. This is often accomplished through the use of bonding jumpers; short wires used to electrically connect one component of the aircraft to another. Many composite aircraft require this electrical bond be tested at regular intervals to ensure that a low resistance is sustained between different components of the aircraft.

Composite materials have too high of a resistance to easily carry current. To counteract this high-resistance effect, a **ground plane** is integrated into the composite airframe. The most probable ground plane is made of an aluminum mesh material, as previously mentioned. This material is similar to an aluminum window screen. The aluminum mesh is bonded into the composite material during the manufacturing process. The ground plane is located toward the inside of the aircraft structure for case of bonding to electric equipment. The mesh may run throughout the airframe, including structural parts, bulk-heads, floorboards, instrument panels, and electric equipment shelves.

Two methods are used to connect electric equipment to the ground plane, **direct electrical bonding** and **indirect electrical bonding**. The direct method is used where electric equipment is mounted adjacent to the ground plane. To properly ground a component when the direct method is used, one must first remove a thin layer of composite material, paint, or any resistive coating to expose the wire mesh. The wire mesh is then coated with an anticorrosive agent, and the electric component is mounted directly to the ground plane.

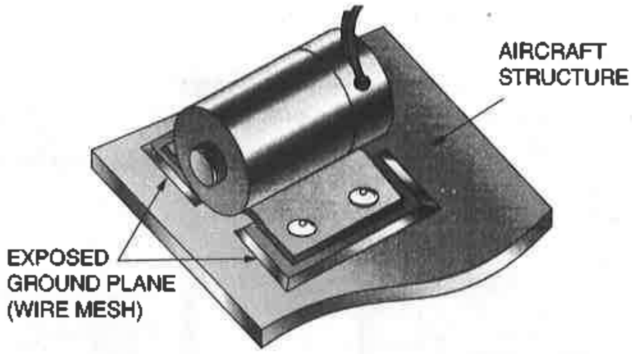


FIGURE 12-13 A typical direct electrical ground connection on a composite aircraft.

As seen in Fig. 12-13, it is very important to remove as little material as possible during this process and still provide a sufficient area for a proper ground connection. The exposed area is refinished with a protective coating after component installation.

The indirect method is more common and used in areas of the aircraft that are not adjacent to the ground plane. The indirect method uses a flexible metal strap called a **bonding jumper** to connect the ground plane to the electric component. The bonding jumper is attached to the ground plane in a manner similar to the one described above. The jumper is then attached to the component requiring an electrical ground (see Fig. 12-14).

Another indirect method of connecting electrical equipment to the negative side of the power source (ground) is through a metallic structure. On some composite aircraft certain areas are made of aluminum to facilitate the distribution of electrical current. Areas such as an equipment rack, instrument panel, or firewall can be made of a conductive material (aluminum) and the electrical equipment ground can be connected directly to that metal. The aluminum provides a current path to ground and becomes the structure for mounting the equipment. Of course, the aluminum must be connected to the main electrical ground circuit of the aircraft. This can be accomplished through the screen mesh embedded in the composite structure or through a separate conductor routed back to a negative distribution point.

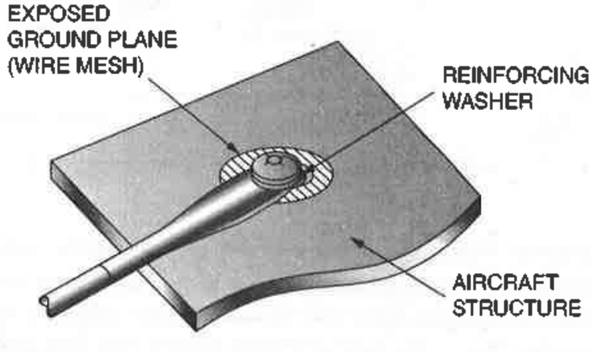


FIGURE 12-14 Connecting a bonding jumper to a composite aircraft.

In general, composite aircraft require both positive and negative electrical distribution; and the screen mesh is only used for electrical systems with very low current. Since the screen mesh bonded to the composite material is designed to be lightweight, it can only carry a low level of current; therefore, all heavy current loads will be connected with both a positive and negative wire. The positive wire will be routed identical to those found on an aluminum aircraft; the negative voltage wire will be routed back to a nearby negative distribution point. Figure 12-15 shows a typical distribution point for the negative voltage of a composite aircraft. This negative distribution bus is mounted to the engine side of the firewall on this Cirrus SR20 aircraft. Electrical loads such as the engine starter, alternator, and landing light circuit, as well as electrical bonding for the engine and related systems are all routed to this distribution point.

Lightning protection for a composite aircraft requires the installation of aluminum wire mesh which is interwoven in the inner ply of the aircraft skin. If lightning strikes the aircraft, the current is distributed over a large area through the aluminum wire. Since lightning typically enters the airframe at one extremity and leaves at another, the aluminum wire covers the entire structure of the aircraft. All sections of this lightning diversion wire must be connected by a low-resistance attachment. The lightning protection wire must not be used for electrical grounding. Only the aircraft's ground plane is designed to carry the current of electric equipment.

The distribution of the positive voltage for composite aircraft is virtually identical with such distribution on aircraft. The positive voltage distribution on the Cirrus SR20 aircraft previously discussed contains the standard bus bars, circuit

FIGURE 12-15 A typical ground (negative voltage) distribution point found on a composite aircraft. See also color insert.

protection, and electrical controls found on a typical metal aircraft. The power distribution system of an all composite business jet will be discussed in the next section.

VERY LIGHT JET ELECTRICAL POWER SYSTEMS

One of the most modern aircraft designs at the time of this writing was in the category of aircraft known as **very light jets (VLJ)**. These aircraft are typically constructed using composite materials as well as advanced avionics and automatic flight systems. The design concept is to save weight, improve efficiencies, and maintain the adequate safety needed for high-speed aircraft. One such aircraft, the Embraer Phenom VLJ introduced in 2008, has a typical capacity of four to six passengers and can be easily flown with only one pilot.

This type of aircraft typically employs two starter-generators that produce a 28-V dc output and one or more lead-acid batteries. The general description of the Phenom power distribution system presented here is typical of other very light jets currently available. The **Electrical Power Generation and Distribution System (EPGDS)** generates and supplies direct current to the aircraft electrical loads. The EPGDS is divided into the power-generating systems and the power distribution systems. The power-generating system is composed of two engine-driven 325-A starter-generators, one external power connection, and the related flight deck and automatic controls. There is also emergency power supplied by two 27 Ah valve-regulated lead–acid batteries. Each battery is charged through the respective primary power distribution channel. In the event of total main power loss, the battery system guarantees 45 min of dc power supplied to the emergency bus. The EPGDS also supplies automatic and manual controls to the flight crew.

The simplified schematic of the Phenom power distribution system is shown in Fig. 12-16; please refer to this diagram during the following discussions. The primary power distribution system is composed of a **central bus**, an **emergency bus**, and a **shed bus**. They are installed inside three independent power distribution units (left, right, and emergency) as indicated by the dotted lines on the diagram. The power distribution units contain all necessary controls for operation of the systems. The distribution functions are divided into three units in order to provide redundancy. The distribution units are small LRUs which contain a total of 13 electrical contactors (solenoids) and a variety of fuses and circuit breakers. The electrical bus bars and distribution wiring are routed in separate bundles to improve system segregation; hence improving reliability of the two redundant systems.

The hot battery buses (near the bottom of the diagram) are always connected to their respective batteries and should therefore never lose power. The most critical systems, such as fire extinguisher systems, would be connected to one of these buses. Other critical systems are connected to the emergency bus (lower left side of diagram). As can be seen in the diagram, the emergency bus can receive power from

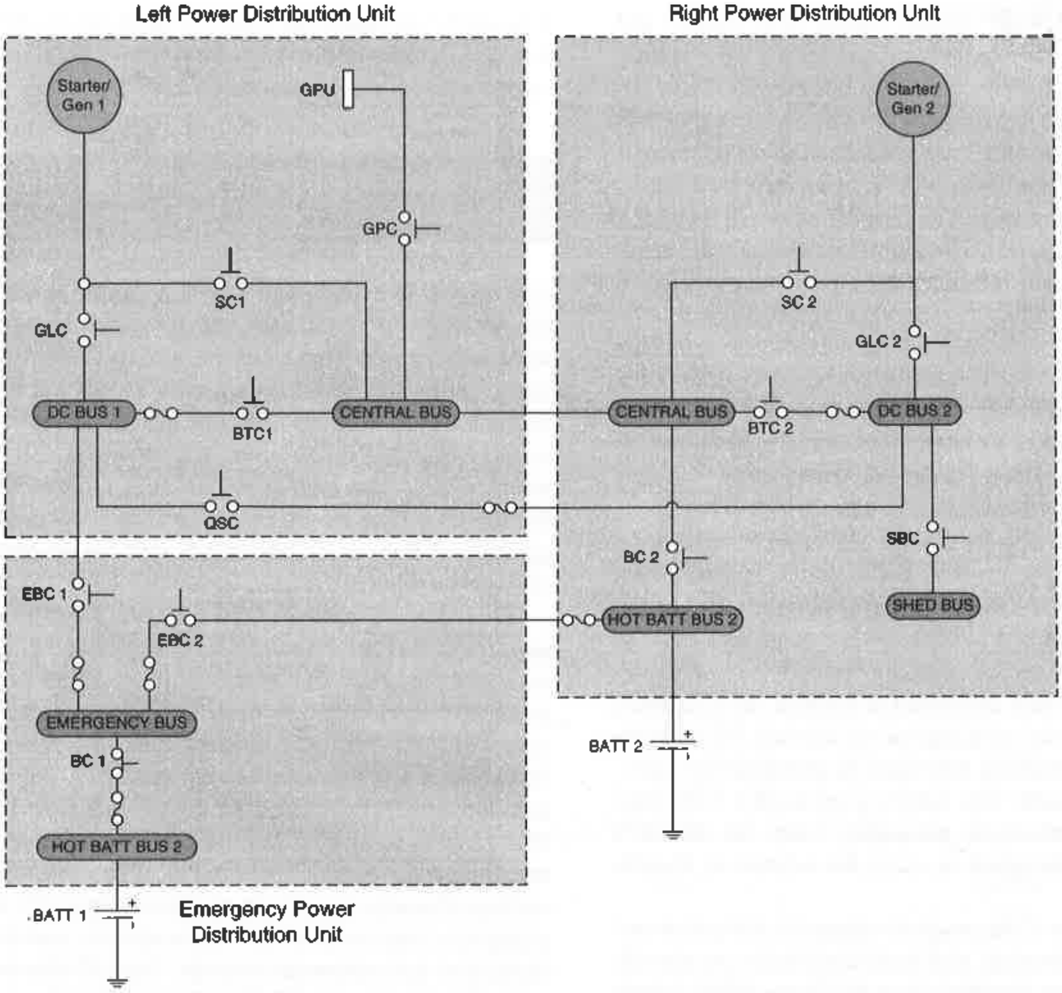


FIGURE 12-16 Modern light jet aircraft power distribution system.

either battery through the respective **emergency bus contactor (EBC)** 1 or 2. This aircraft also contains a static inverter connected to the dc shed bus. This inverter converts the 28 V dc to common household 120 V, 60 Hz ac for passenger use. The inverter is connected to the shed bus because it can easily be disconnected without consequences to flight safety. The shed bus is disconnected in the event of a generator failure.

The EPGDS is designed for automatic operation. However, manual control capability is provided to override some automatic control features. Specifically, the flight crew can manually control generator line contactors 1 and 2 through the respective engine switch, battery contactor 1 and 2 through the respective battery switch, bus tie contactor 1 and 2 through the bus tie switch, and the ground power contactor. The flight crew also has the ability to manually force the operation of the emergency power system.

LARGE-AIRCRAFT ELECTRICAL SYSTEMS

Large-aircraft electrical systems have many similarities to those systems found on small aircraft. On large aircraft there is typically one or two batteries and two or more ac generators (alternators), which supply power to several distribution buses. The ac generators are connected to the ac buses. The dc battery is connected directly to the battery or emergency bus. The ac power produced by the generators is converted to direct current where needed for special applications. Essential lighting, flight control systems, and communication and navigation radios are high-priority electrical systems. Galley power, nonessential lighting, and various other comfort systems are considered low-priority electrical systems. These nonessential systems are usually turned off during a partial generator system failure. In the case of a complete generator failure, the battery will supply power for all essential electric equipment. A fully charged battery will normally supply approximately 20 to 30 min of emergency power.

Power Distribution Systems

Modern large aircraft use both ac and dc electric power. The output of a typical generator is **three-phase 115 V ac**; this is converted by **transformer-rectifier units** (TRUs) where dc power is needed. A TRU incorporates a step-down transformer and a full-wave rectifier; its output is 28 V dc. Most large aircraft contain two or more static inverters, which are used for emergency situations (generator failure).

Each inverter is capable of converting direct current, supplied by the battery, into ac power, which is distributed by the essential ac bus. The static inverters supply a relatively small amount of ac power; however, their output is adequate to power all essential ac equipment. Ram air turbines (RATs) are also used to power emergency generators on most modern transport-category aircraft. The RAT is deployed from the fuselage in the event of a catastrophic electrical system failure. The turbine is used to power a small emergency generator and critical hydraulic systems. See Chap. 11 for more information on RATs.

There are two basic configurations that are used to distribute electric power, the **split-bus system** and the **parallel system.** The split-bus system is used on most twin-engine commercial aircraft, such as the Boeing 737, 757, 767, 777, and 787; and the Airbus Industrie A-320, 330, and 300. In a split-bus system the engine-driven generators can never be connected to the same distribution bus simultaneously. Under normal conditions each generator supplies power only to its associated loads.

In a parallel electrical system, the entire electrical load is equally shared by all the working generators. Parallel ac power distribution systems are typically found on commercial aircraft containing three or more engines, such as the Boeing 727 and early 747s, and the McDonnell Douglas DC-10 and MD-11. Parallel systems are typically found on older aircraft with three or more engines. A modified parallel system is used on some modern four-engine aircraft, such as the Boeing 747-400. This modified parallel system is called a split parallel system, because all generators can operate in parallel or be isolated. The right-side generators and the left-side generators can be connected, or they can be separated from each other by means of a split system breaker.

The Split-Bus System

The **split-bus electrical system** contains two completely isolated power-generating systems. Each system, the left and the right, contains its own ac generator, transformer-rectifiers, and distribution buses. The right and the left generators power their respective loads independently of other system operations. In the event of a generator failure, the operating generator is connected in such a manner as to feed all the essential electrical loads, or the APU (auxiliary power unit) generator may be employed to carry the electrical load of the inoperative generator.

Figure 12-17 shows a simplified schematic of a typical split-bus system. This schematic shows the **external power contactor** (EPC) closed and a ground power supply connected to the aircraft. The **bus tie breakers** (BTBs), 1 and 2, are closed, connecting external power to both transfer buses and their respective electrical loads. In this configuration the **generator breakers** (GBs) are open, thus disconnecting the generators from the electrical system.

It should be noted that the various contactors, such as the BTBs and GBs, are controlling three-phase current. The contactors are therefore actually made up of a set of three contacts, one contact to open or close the "hot" wire for each phase.

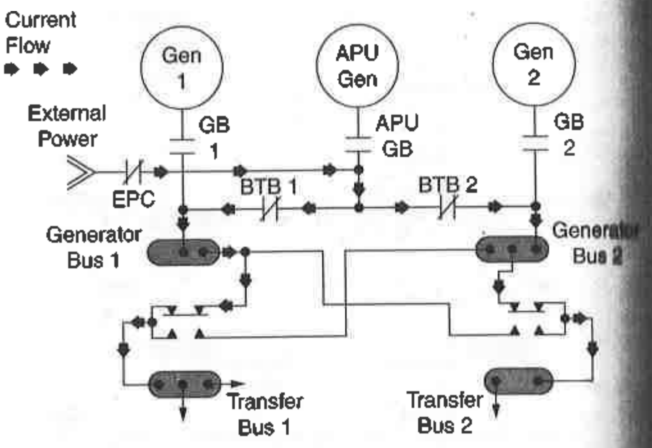


FIGURE 12-17 A typical split-bus system for a large aircraft. (*Sundstrand Corporation.*)

In some cases the contactors may have four contacts, one for each phase and one for the neutral wire. The buses also consist of three distinct units, one for each phase. The power distribution diagrams presented here are simplified diagrams and do not show the actual wiring for each phase of the ac power generated.

In the case where the APU would be used to supply electric power to the entire aircraft, the EPC would open and the APU generator breaker would close. This would distribute the electric power from the APU generator to both transfer buses.

If both engine-driven generators are operating, the current flow is from each generator to its respective transfer bus, as illustrated in Fig. 12-18. At this time BTBs 1 and 2 are open, GBs 1 and 2 are closed, and the transfer relay is in its normal position. It can be seen from this distribution diagram that the two generators operate completely independently of each other.

If one engine-driven generator fails, the opposite generator is connected to both transfer buses in order to power the entire electrical system. Under this configuration, nonessential loads are automatically removed from the system in order

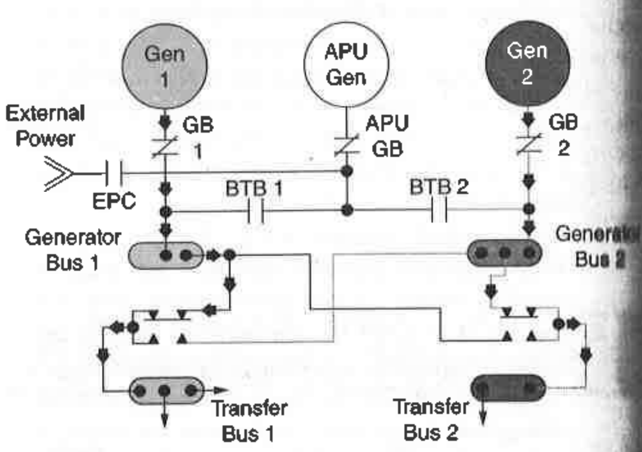


FIGURE 12-18 Spilt-bus system with both generators operating. (*Sundstrand Corporation.*)

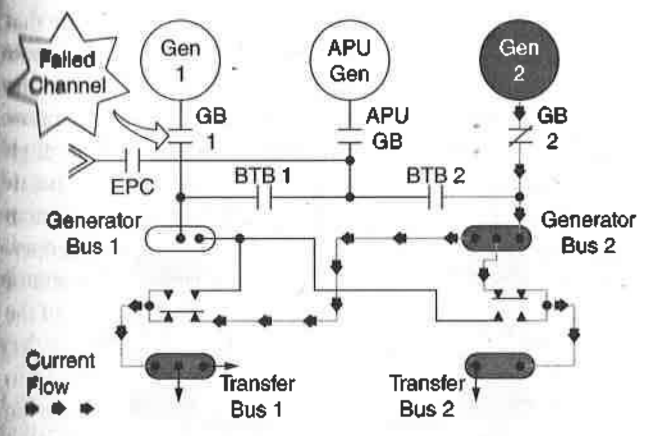


FIGURE 12-19 Split-bus system with generator 1 failed. (*Sundstrand Corporation.*)

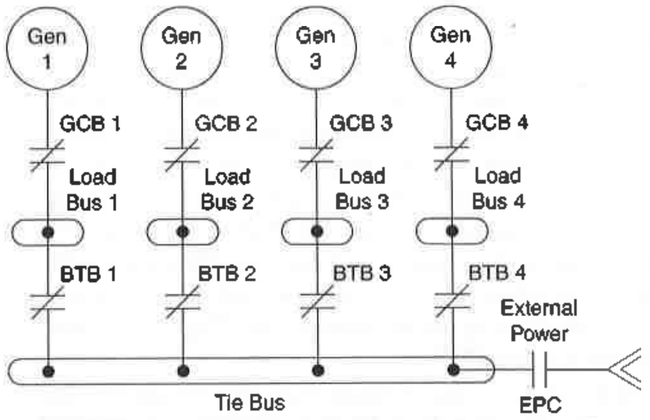


FIGURE 12-20 A four-generator, parallel power distribution system. (*Sundstrand Corporation.*)

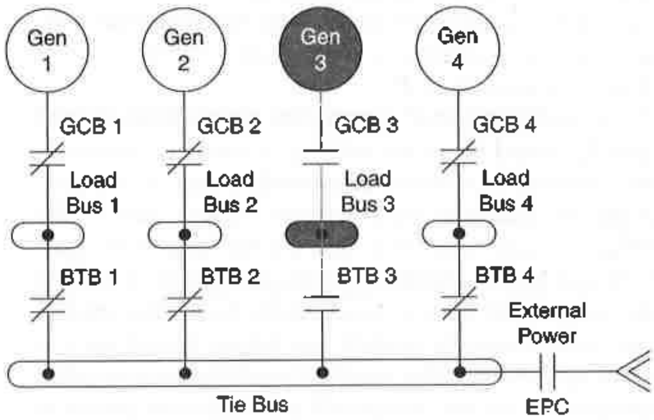


FIGURE 12-21 Parallel power distribution system with bus 3 isolated. (*Sundstrand Corporation.*)

to avoid a generator overload. The schematic in Fig. 12-19 shows a failure in generator 1. The current from generator 2 is divided to transfer buses 1 and 2 via the correct positioning of the transfer relays. In this case transfer relay 1 is automatically activated to its abnormal position, which connects generator bus 2 with transfer bus 1. At this same time GB 1 opens to disconnect the failed generator from the electrical system. This entire process is controlled automatically within several microseconds, and the flight continues uninterrupted.

On certain aircraft, if a primary generator fails, the flight crew may elect to employ the APU generator. In this situation the APU must be started and its generator connected by closing the APU generator breaker (GB). This automatically closes **BTB** 1 and repositions transfer relay 1 to its normal position. Thus the APU generator is connected to transfer bus 1, and once again two independent generators are operating to supply all the aircraft electrical power.

The major advantage of a split-bus system is than the generators operate independently; that is, generator output frequencies and phase relationships need not be so closely regulated. Parallel systems require strict operating limits. Split-bus systems are, in effect, more tolerant of frequency variance.

Parallel Electrical Systems

In a **parallel electric power distribution system**, all ac generators are connected to one distribution bus. This type of system maintains equal load sharing for three or more ac generators. Since the generators are connected in parallel to a common bus, all generator voltages, frequencies, and their phase sequence must be within very strict limits to ensure proper system operation.

The simplified block diagram in Fig. 12-20 represents a typical **four-generator parallel system**. This diagram shows a normal operating configuration; all four generator circuit breakers (GCBs) and bus tie breakers (BTBs) are closed. All four generators are synchronized and connected in parallel by the **tie bus**. The tie bus is often referred to as a **synchronizing bus**; its purpose is to connect the output of all operating generators. The **load buses** are used to distribute the generator current to the various electrical loads.

If one generator fails, its receptive GCB opens. This isolates that generator from its load bus; however, that load bus still continues to receive power while connected to the tie bus. In case of a load bus overload the bus is isolated by the opening of its GCB and BTB. This mode of failure is illustrated in Fig. 12-21. In this diagram, load bus 3 has been isolated. The likely suspicion is that load bus 3 has been shorted to ground and the bus power control unit has automatically tripped the appropriate contactors. This manner of isolation takes place whenever one or more load buses are faulty.

If two or more generators fail, their respective generator circuit breakers open, and they are isolated. The remaining generator(s) supply the power to the entire system. In this situation nonessential electrical loads are automatically disconnected from the system. This prevents an accidental overload of the operating generator(s).

Split Parallel System

A **split parallel electric power distribution system** is illustrated in Fig. 12-22. This system allows for flexibility in load distribution and yet maintains isolation between systems when needed. When closed, the split system breaker connects all generators together, thus paralleling the system.

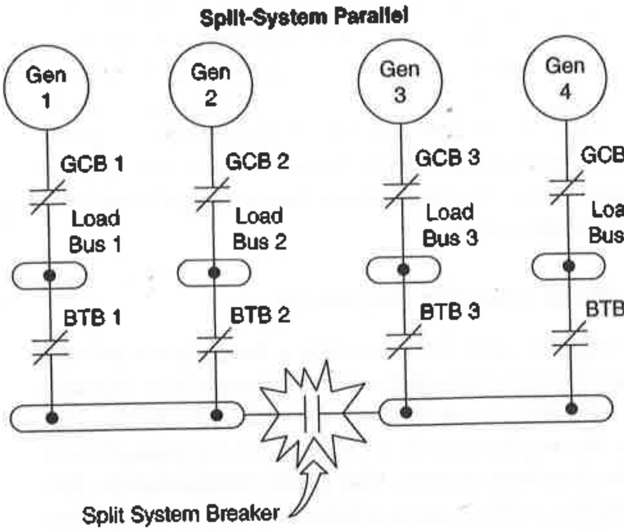


FIGURE 12-22 A split parallel power distribution system. (*Sundstrand Corporation.*)

When open, the split system breaker isolates the right- and left-hand systems, thus creating a more flexible parallel system.

A split parallel system was first used on the Boeing 747-400 aircraft; today this system is employed in most four-engine transport-category aircraft. As seen in Fig. 12-23, this system employs four engine-driven generators and two auxiliary power unit (APU) generators, and it can accept two separate external power sources (EXT 1 and EXT 2). The B-747-400 uses an automated power distribution control system that features a no-break power transfer. The no-break power transfer will be discussed later in this chapter. As seen in the schematic of the system, the four integrated drive generators (IDGs) are connected to their respective ac buses through generator control breakers (GCBs). The ac buses are paralleled through the bus tie breakers (BTBs) and the split system breaker (SSB). When the SSB is open, the right system operates independently of the left. With this system any generator can supply power to any load bus, and any combination of the IDGs can operate in parallel.

The external power or APU power can be connected to the ac buses through their associated contactors. The ac **ground-handling** (GH) buses are powered by closing the ground-handling relay (GHR) to either the APU or EXT power. The dc GH buses receive power from the transformer-rectifier (TR) located directly above them on the diagram (Fig. 12-23). The ground-handling buses are used to power lighting and miscellaneous equipment for cargo loading, aircraft fueling, and cleaning. The GH buses are not powered during normal flight.

The **ground service** (GS) buses are controlled from the flight attendants' station located at the number 2 left door of the aircraft. The control switch energizes the ground service relay (GSR), which connects the GS buses to whichever is currently on line, the APU or EXT power. The ground service buses are used to light the interior of the aircraft and power the main battery charger and other miscellaneous systems required for maintenance, cleaning, and initial start-up of the aircraft.

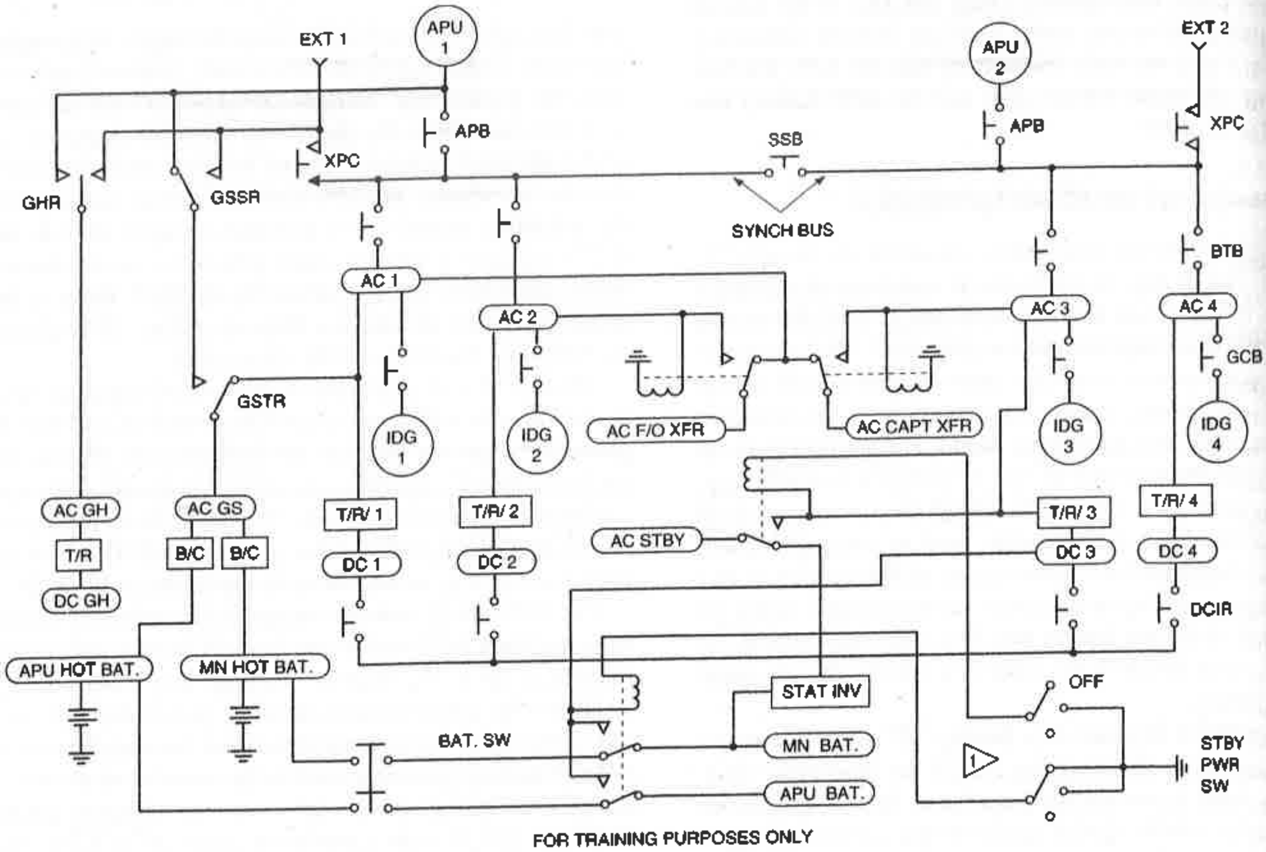


FIGURE 12-23 A split parallel power distribution system.

Virtually all transport-category aircraft contain one or more means to power the aircraft for ground handling and maintenance purposes. An aircraft of this size requires numerous ground operations, including cleaning and cargo loading. The ground-handling power allows crews to perform general tasks without powering various flight critical systems. The exact name and design of the ground-handling electrical systems will vary between aircraft; the systems just described are typical.

DC Electrical Systems

Large commercial aircraft employ both an ac power distribution system and a dc system. The dc system incorporates redundancy and isolation capabilities for safety. Loading of the dc buses is so arranged that a complete loss of power to one system is unlikely. During a partial system failure, the essential dc loads can be powered by any transformer-rectifier (TR) via the essential dc bus. In the event of a complete generator system failure, the essential dc power would be supplied by the aircraft's battery. An ac inverter would also be powered in an emergency situation in order to operate all essential ac loads.

The Boeing 747 DC Power Distribution

The 747-400 diagram (see Fig. 12-23) shows the four dc distribution buses each connected to its respective TR unit. During normal flight the dc buses are all connected because the direct current can easily be paralleled. If one dc bus experiences a fault, that bus is isolated by opening its respective **direct current interconnect relay (DCIR)**. If the aircraft is operating on battery power only (an extreme emergency situation), only the **main hot battery bus**, the **APU hot battery bus**, the **main battery bus**, and the **APU battery bus** will receive power.

The Boeing 727 DC Power Distribution

The complete power distribution system for the Boeing 727 is illustrated in Fig. 12-24. It can be seen from this diagram that the B-727 power distribution system is a parallel system containing three engine-driven ac generators. Each generator can be connected to carry the entire aircraft electrical load individually during emergency situations or synchronized with the other two generators during normal operation. In this aircraft the essential ac and dc power is normally supplied by generator 3; however, any generator may perform this function. The rotary switch used to control essential power is shown near the bottom center of the diagram. In this type of system, the most critical electrical loads would be connected to the hot battery bus. This bus is the least likely source to lose power in the event of a catastrophic electrical system failure.

A simplified diagram of a **Boeing 727** dc power distribution system is shown in Fig. 12-25. As illustrated, the 1 and 2 ac load buses and the essential ac bus are connected to TR units, which furnish power to the corresponding dc buses. The battery charger TR unit receives power from the ac transfer bus. This is a typical means of in-flight battery charging. DC buses 1 and 2 are connected together by a 100-A current limiter. DC bus 1 is tied to the essential dc bus through a diode that permits current flow only from dc bus 1 to the essential dc bus. The essential dc bus supplies current to the battery bus, the battery transfer bus, and the hot battery bus. The **hot battery bus** is always connected directly to the battery.

The More Electric Airplane

As aircraft designers strive to create a fuel-efficient aircraft, the use of lightweight solid state components have replaced many mechanical systems found on traditional aircraft. This change has also been made possible by the invention of more reliable electronic systems, high-power electric motors, better computer controls, and a multitude of redundant systems. In general, today's aircraft employ more electrical and electronic systems than any previous design. This design concept is often referred to as **the more electric** airplane. The first transport-category aircraft following these design concepts was released in the late 1990s; the Boeing 777. Since that time aircraft have increased the used of electrical systems and many experts predict that someday even turbine (jet) engines will be replaced by electric motors. Of course, there are years of development before a large aircraft could be powered solely by electricity; however, light propeller-driven two-seat aircraft have been developed and fly using only electric power.

The Boeing 777 Power Distribution System

This Boeing 777 aircraft is currently the largest twin-engine passenger aircraft in service. This aircraft, commonly referred to as "the triple seven" was introduced in 1995 and can carry over 300 passengers. The B-777 was the first to employ many of the electrical systems found on the most modern aircraft. In order to enhance available electrical power and maintain the reliability needed for a transport-category aircraft, the B-777 contains a total of eight generators; seven engine-driven generators and one driven by the RAT. Refer to the simplified power distribution diagram in Fig. 12-26 during the following discussion on the triple seven.

The B-777 uses a split-bus ac power distribution system; as well as, two additional ac backup generators and two dc generators explicitly available for flight controls. The electrical distribution is regulated, controlled, and protected through a modern computerized system. The two main ac generators are traditional integrated drive generators (IGDs) with an output of 115 V ac at 400 Hz and a maximum of 120 KVA.

The B-777 flight controls operate using electrical signals from the flight deck with no mechanical backup; commonly referred to as a "fly-by-wire" aircraft, this plane literally could not be flown without electrical power. For this reason, each engine drives a variable speed constant frequency (VSCF) backup generator used in the event of an electrical emergency. These generators use a converter circuit to supply 115 V ac, 400 Hz with a maximum output of 20 KVA. The two engines and related generators are located at the top

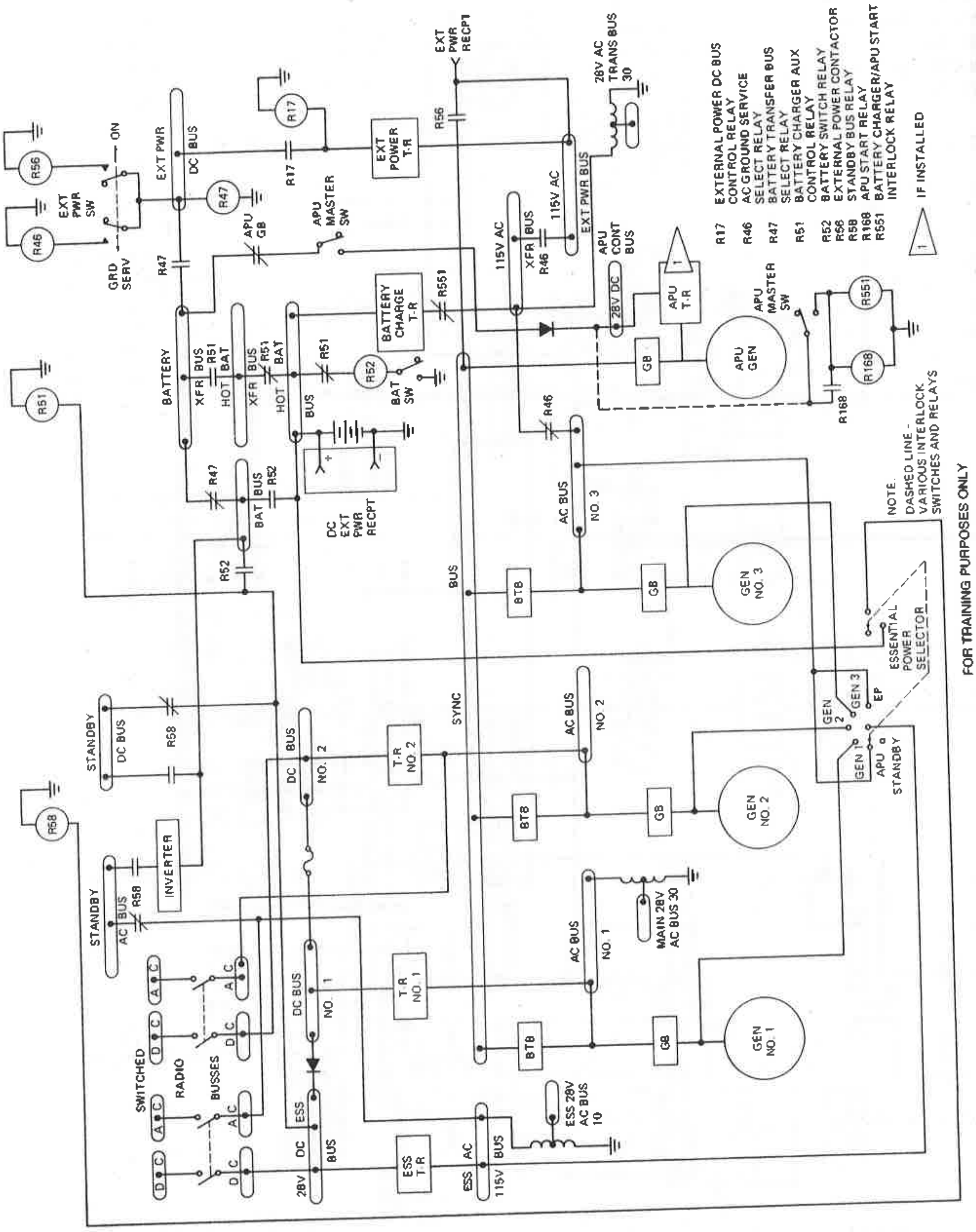


FIGURE 12-24 Boeing 727 power distribution system. *(Boeing Company.)*

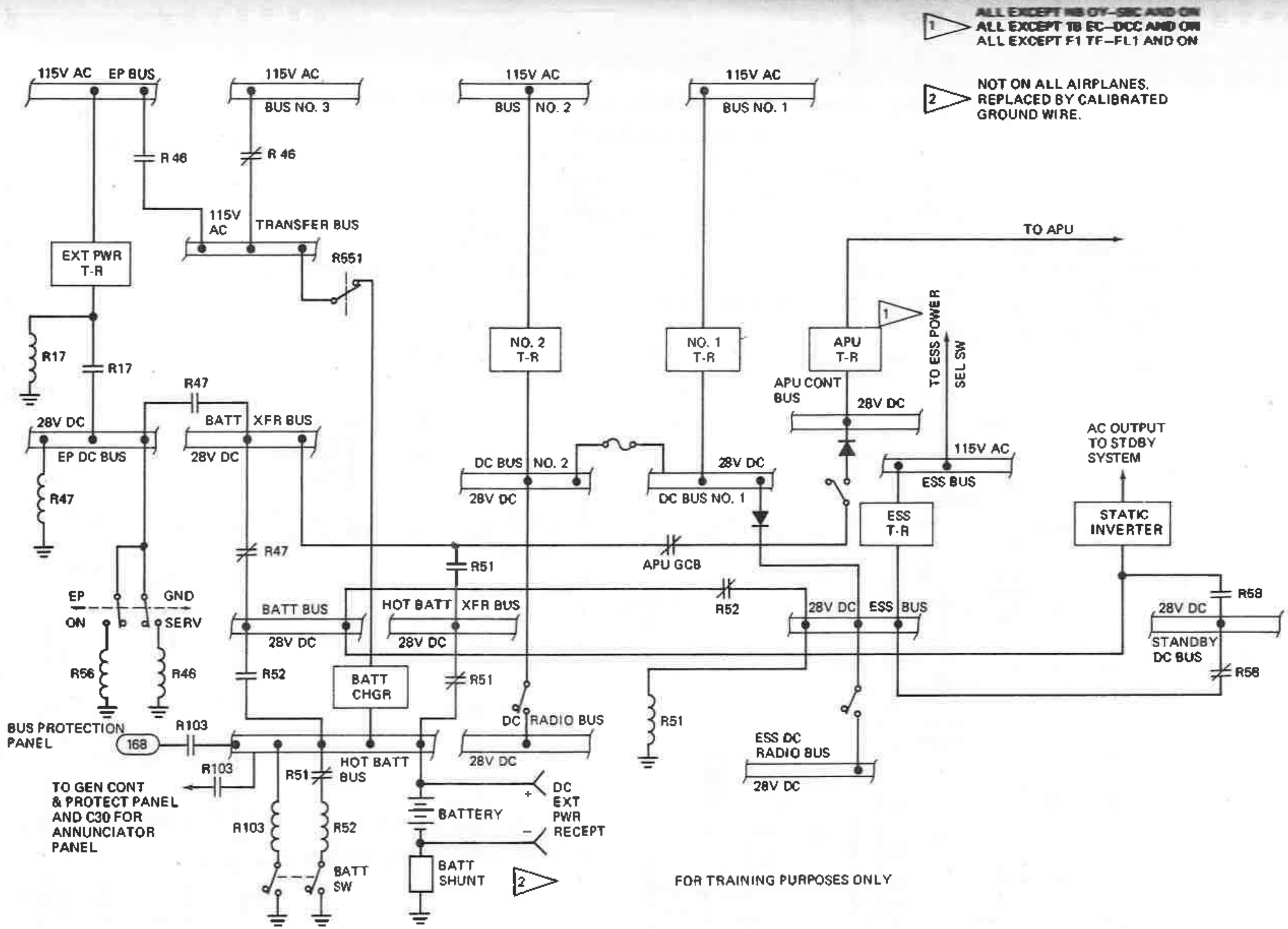


FIGURE 12-25 Boeing 727 dc power distribution system. (*Boeing Company*.)

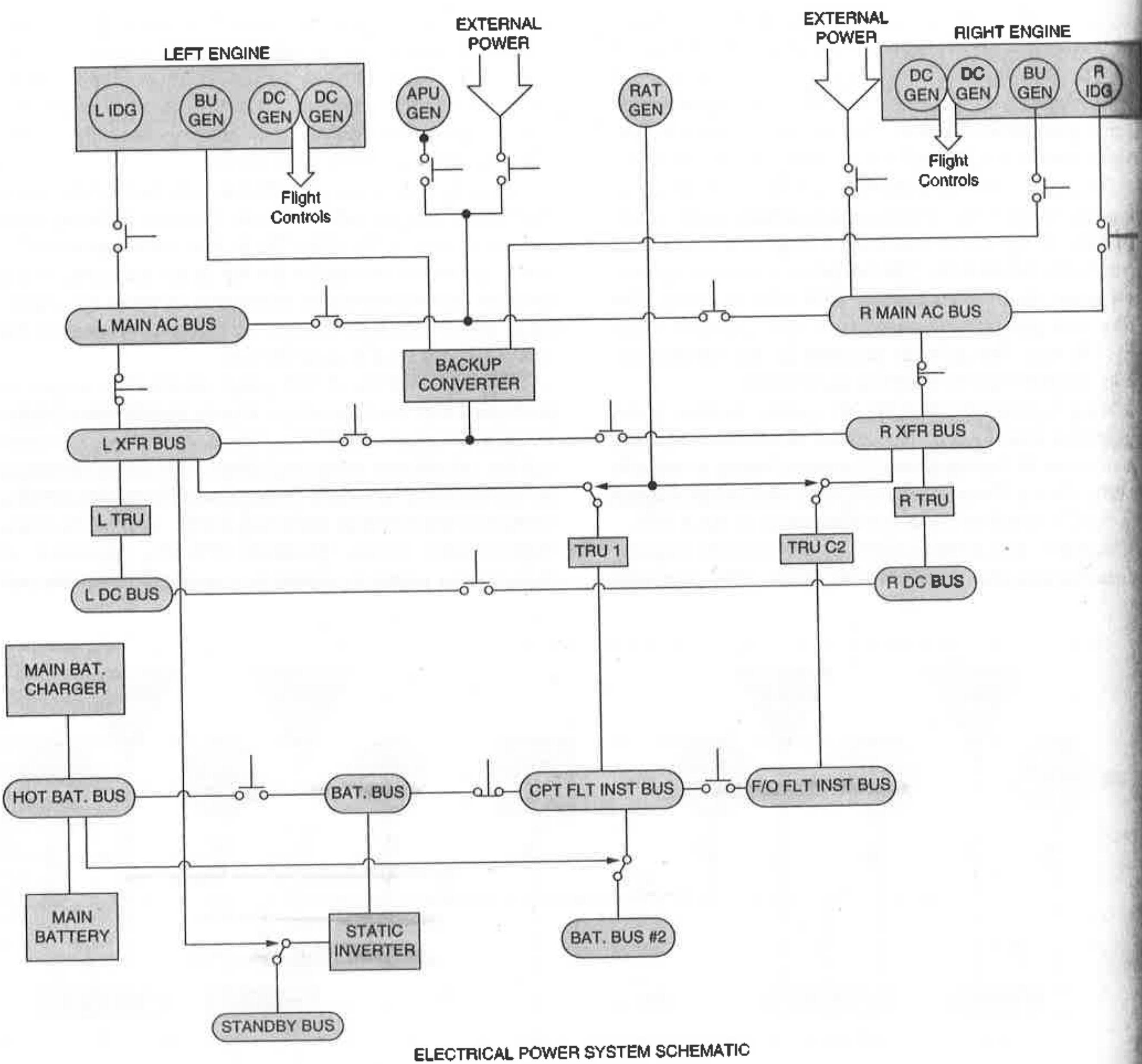


FIGURE 12-26 B-777 power distribution system.

of the diagram; notice that the backup generators connect directly to the electrical converter.

Each engine also drives two dc generators used to power three flight control power supply assemblies. Like most modern aircraft the APU can be operated in flight and its generator can be used for electrical power. Also the B-777 employs a ram air turbine (RAT) to generate 7.5 KVA of electrical power in case all engines fail. This design provides extreme redundancy for all critical flight controls.

All but the very heavy loads are controlled through the **Electronic Load Management System (ELMS).** There are several ELMS power control panels which contain the load switching units that distribute power. ELMS receives information from various systems and controls through a digital data bus in order to monitor, distribute, and protect electrical power. Heavy loads are controlled by the bus power control unit.

The dc power system of the B-777 employs five transformer rectifier units (TRUs) which receive power from the ac generators. Near the bottom center of the diagram, it can be seen that the captain's and first officer's flight instrument buses can receive power from several sources. These two buses are used to power critical flight instruments and are considered essential for flight safety. During normal flight, these instrument buses receive power from the TRU 1 or 2; they can also be powered directly from the main battery.

The A-380 Electrical Power System

The Airbus A-380 was introduced in 2007 as a long-range, high-capacity commercial aircraft; the plane can seat over 500 passengers. There are six engine-driven ac generators; four are driven by the main engines and two are driven by one APU mounted in the aircraft tail. Like most modern aircraft, the APU can operate on the ground and in flight. The main generators can output a maximum 150 KVA at 115 V ac. The generator output frequency will range from 370 to 770 Hz, depending on engine rpm; these are **variable frequency generators (VFGs)**. The two APU generators output a maximum of 120 KVA at a constant 400 Hz. The A-380 also has a RAT and a static inverter system for emergency ac power. Each generator operates independently of the others; hence the A-380 power distribution system is similar to a typical split-bus system. The ac power from one generator is never connected in parallel with other ac power. This allows each generator to operate in a wide frequency range (370–770 Hz). The ac loads powered by this variable frequency current must be designed accordingly.

During normal operation the dc system receives power through two main TRUs (TRU). Three 50 Ah batteries supply electricity for dc backup power. A separate battery is available for APU starting. Please refer to the power distribution diagram (Fig. 12-27) during the following discussions on the A-380.

The ship's main power is shown at the top of the diagram; sources include four engine-driven VFGs, APU generators A and B, and four external power options. While on the ground, external power can supply up to 90 KVA at 115 V ac and 400 Hz. The RAT generators (top/center of the diagram) can be used to feed emergency power to the ac essential bus. If all ac generators fail, the static inverter can supply emergency alternating current to the aircraft.

The bottom portion of the diagram contains the dc power distribution system with two main batteries and a separate battery for starting the APU. The dc load buses can be fed by the ac generators (located at the top of the diagram), or fed from the batteries during an emergency situation. Of course, all ac power must pass through the TRUs which convert the ac voltage from 115 V ac to 28 V dc.

Diagnostics of the A-380 power distribution system is performed with the help of two **Power Distribution Maintenance Computers (PDMCs)**. There are three access terminals for information using the PDMC. The access terminals are known as the **Onboard Maintenance Terminal (OMT)**, **Onboard Information Terminal (OIT)**, and the **Portable Maintenance Access Terminal (PMAT)**. Operation of these access points is similar to a personal computer and

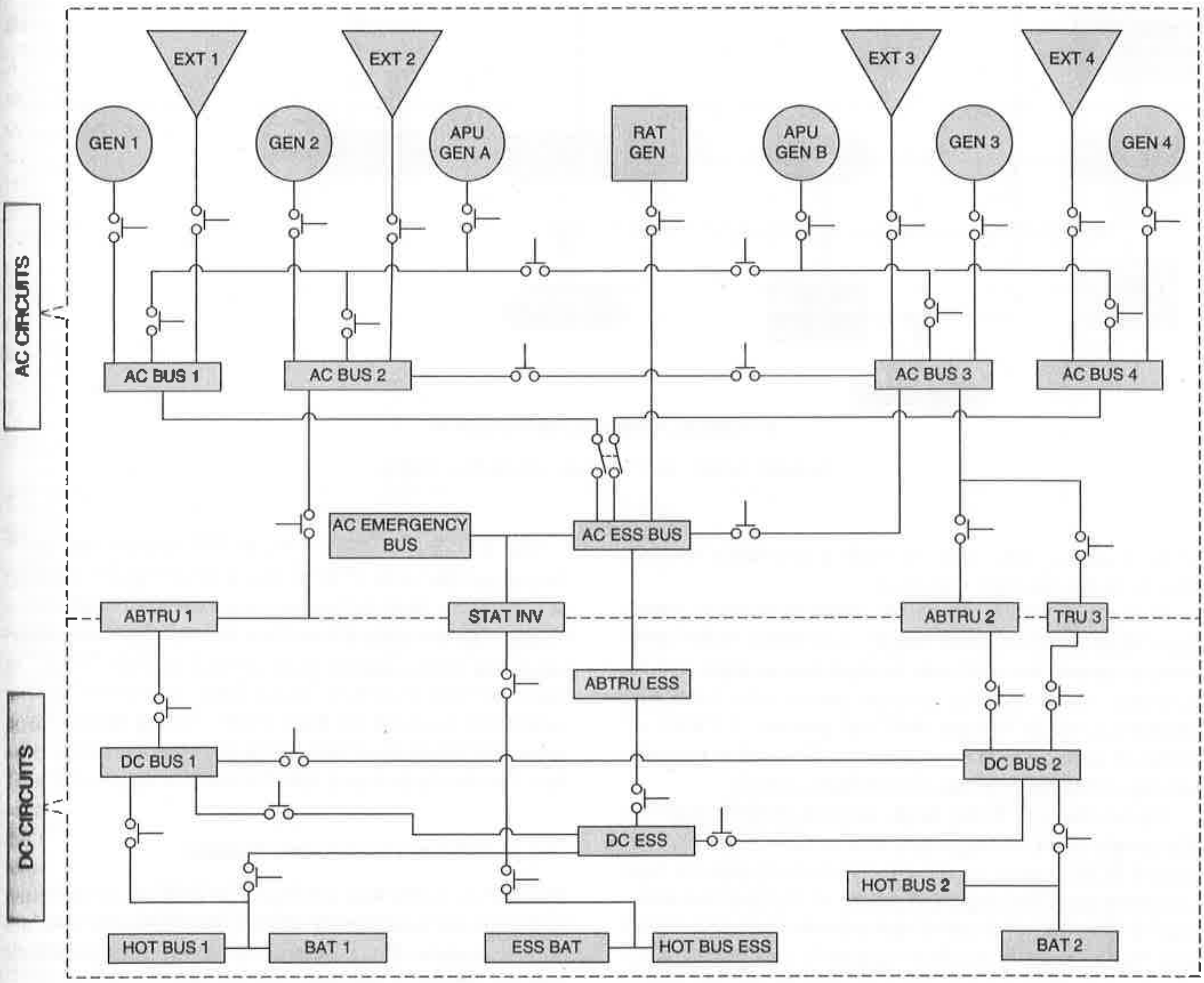


FIGURE 12-27 Airbus A-380 power distribution system.

allows technicians direct information about electrical power systems during maintenance. Automated maintenance systems will be presented in greater detail in Chap. 13.

The Boeing 787 Electrical Power System

The Boeing 787 is a twin-engine aircraft designed to carry up to 330 passengers and is by far the most electric aircraft ever built. Many of the other traditionally hydraulic and pneumatic systems, such as cabin air conditioning, pressurization, and wing ice protection have been replaced with electrical systems. Most of the hydraulic systems operate using hydraulic actuators driven by a high-power electric motor. Due to the size of this aircraft, many of the motors produce near 100 hp; along with other loads this creates a need for an unprecedented amount of electrical energy for an aircraft. The B-787 employs four starter-generators on the two main engines, and two APU starter-generators with a combined output of 1.45 MW of electrical power. While in generation mode the output power is 235 V ac at a variable frequency of 360 to 800 Hz. Using a 235-V system (instead of the traditional 115 V ac) allows for reduced current flows; reducing the size and weight of electrical components and wire.

Both starter-generators are used for a normal engine start; however, one unit can start an engine at a slower pace. Only one starter-generator is used for APU starts. In most cases electrical power from the external power system is used for engine starting. If ground power is not available, the APU is started using the ship's battery and the APU generator power can be used for starting the main engines.

A simplified diagram of the B-787 power distribution is shown in Fig. 12-28. Shown here are the three turbine

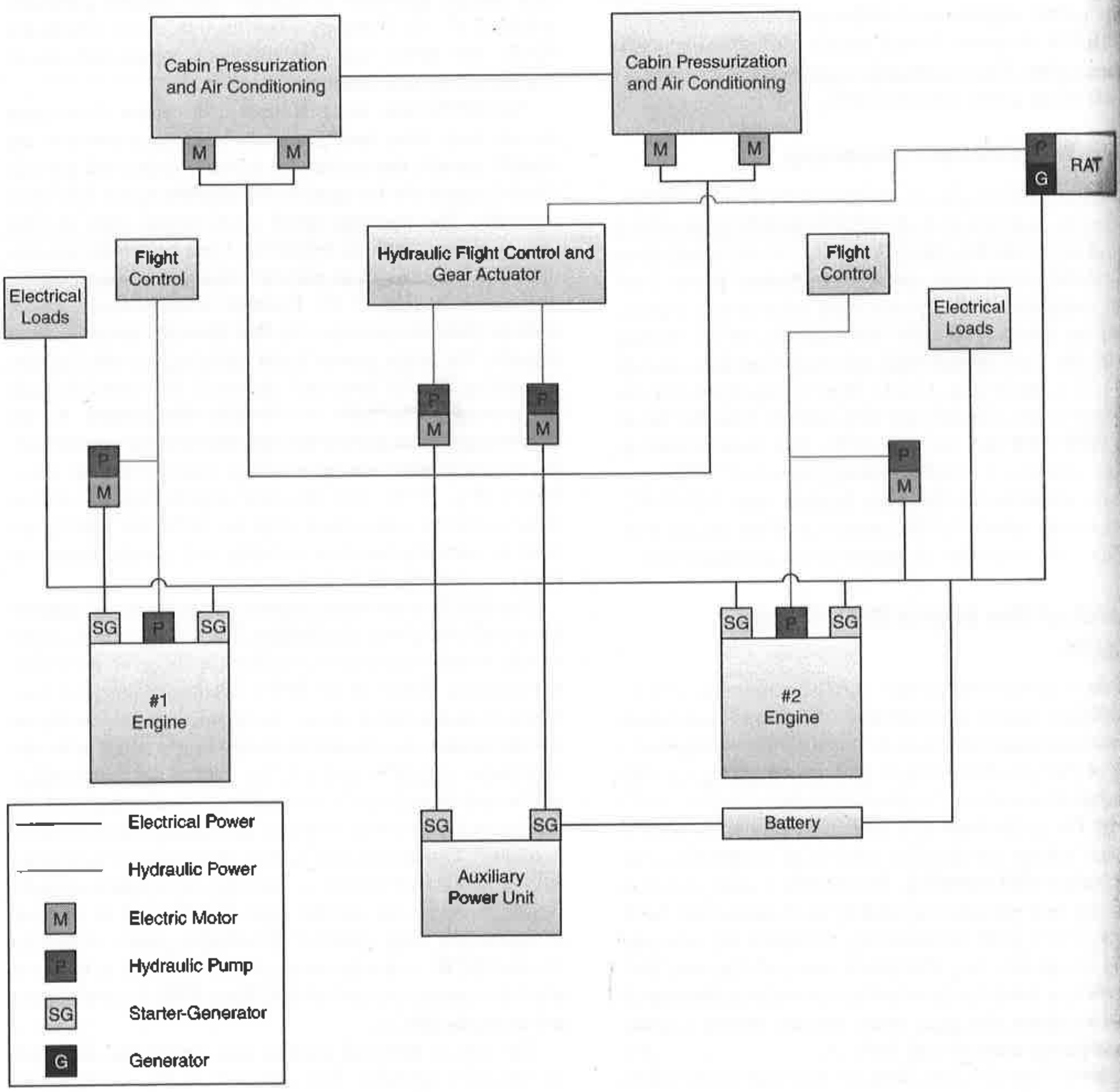


FIGURE 12-28 Boeing 787 power distribution system. See also color insert.

engines (bottom of the diagram); the APU and the main engines 1 and 2; each employ two starter-generators. On engine 1 and 2, the diagram also shows the engine-driven pumps (P) that produce the hydraulic pressure for certain flight controls. The center of the diagram represents the hydraulic fight control and gear actuators; hydraulic pressure for these units is provided by two pumps (P) driven by two electric motors (M). Four electric motors are also shown at the top of the diagram for powering the cabin pressurization and air-conditioning systems. This is the first transport-category aircraft that employs large horsepower electric motors for powering hydraulic and cabin environmental systems. In the top right corner of the diagram is the RAT; this unit supplies emergency power for both critical electric and hydraulic systems.

This aircraft has the capability to supply four different voltage values: 235 volt alternating current (V ac), 115 V ac, 270 volt direct current (V dc), and 28 V dc. The 115 V ac and 28 V dc power supplies most traditional systems. The 235 V ac and 270 V dc power is used mainly for high horsepower electric motors. This complexity requires a highly sophisticated electrical power control system.

Power Distribution Hierarchy

All aircraft electrical systems are designed with a **bus hierarchy**. That is, each system is designed so that the most critical components are the least likely to fail. On all aircraft the most critical components must operate from battery power. Less critical components can operate from other power sources, such as an aircraft generator. For example, on the Boeing 747-400 the least critical loads are connected to ac and dc buses 1, 2, 3, and 4 (Fig. 12-23). More critical loads may be connected to the captain's and first officer's **transfer buses** (AC CAPT XFR and AC F/O XFR). The most critical ac loads are connected to the **ac standby bus** (AC STBY); dc loads are connected to the **main battery bus** (MN BAT). This hierarchy allows for safe operation of the aircraft even in the unlikely event that all engine-driven generators fail.

Control of the Power Distribution Systems

On modern aircraft employing a parallel or split-bus system, a centralized means of controlling the power distribution between individual load buses is essential. For example, if a generator fails or a bus shorts to ground, the appropriate bus ties and generator circuit breakers must be set to the correct position. Or in the event of a system overload, the control unit must reduce the electrical load to an acceptable level. This is called **load shedding**. The aircraft's galley power is usually the first nonessential load to be disconnected. Also, the control unit must automatically reconnect any essential loads to an operable bus. This power manipulation must take place within a fraction of a second to ensure an uninterrupted flight. To achieve this goal, many aircraft employ a solid-state **bus power control unit** (BPCU).

The BPCU receives data from the generator control units (GCUs), the ground power control unit (GPCU), and the various bus ties and circuit breakers of the system. As discussed in Chap. 11, GCUs are used in conjunction with each aircraft generator to monitor and regulate generator activities. If a GCU detects a malfunction, it will inform the BPCU. The BPCU will then ensure the appropriate power distribution system configuration.

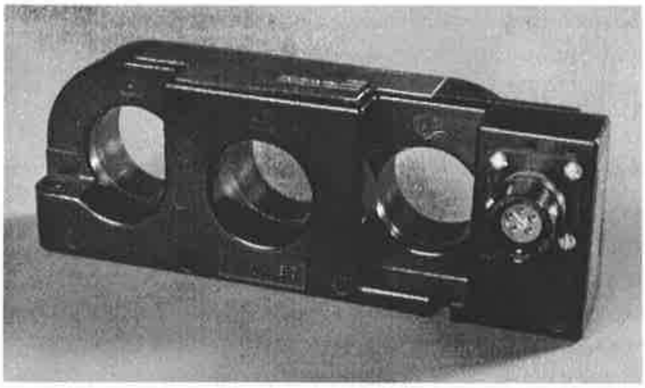


FIGURE 12-29 Current transformer. (*Sundstrand Corporation.*)

The BPCU also receives input information concerning system loads from **load controllers**. Load controllers are electric circuits that sense real system current and provide control signals for the generator's constant-speed drive rpm governor. The constant-speed drive output rpm in turn affects generator output frequency. Load controllers receive their input signals from current transformers, such as the one shown in Fig. 12-29. **Current transformers** consist of three inductive pickup coils that provide current-sensing signals. The main power leads carrying the three-phase alternating current from each generator are routed through the corresponding holes in a current transformer. As the alternating current travels through the wire, the corresponding magnetic field induces a voltage into the current transformer (Fig. 12-30). The electrical signals from the current transformer, in conjunction with the GCU and BPCU, are used to control protection circuitry and supply signals to load meters on the flightdeck.

The BPCU is the main control computer for all generator and electric power distribution. The BPCU receives input signals from several current transformers in order to monitor the electrical system. If the BPCU detects an abnormal condition, it opens and/or closes the appropriate bus tie and/or circuit breaker. As illustrated earlier in this chapter by the schematics of parallel and split-bus systems, circuit breakers are located throughout the aircraft's electrical system and are used to isolate or connect various generators and/or distribution buses. Circuit breakers operate automatically according to GCU and BPCU signals or manually via cockpit controls. Bus tie breakers are another type of unit used to connect or disconnect main electrical distribution points. A bus tie breaker (BTB) is similar to an electric solenoid in that it is used as a remote control switch. Each BTB is usually controlled by the BPCU.

The BPCU performs control, test, protection, and fault identification functions. The schematic in Fig. 12-31 shows the GCUs, the BPCU and its related sensors, and the current

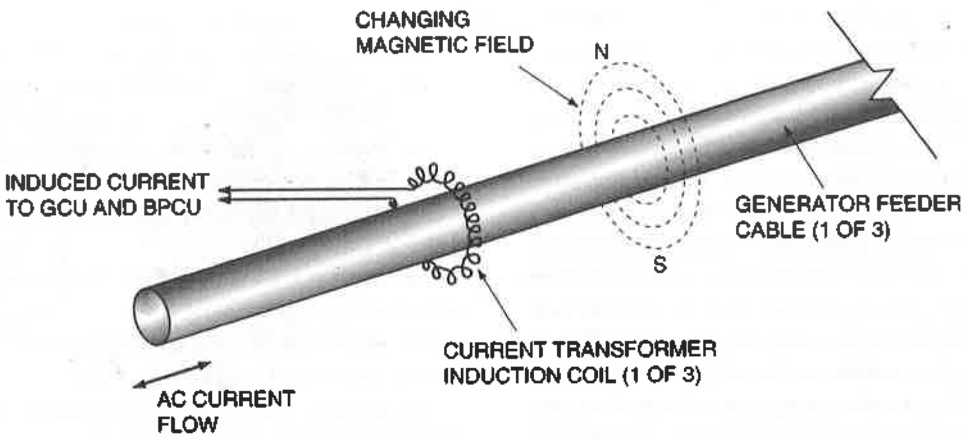


FIGURE 12-30 Current transformer induction coil.

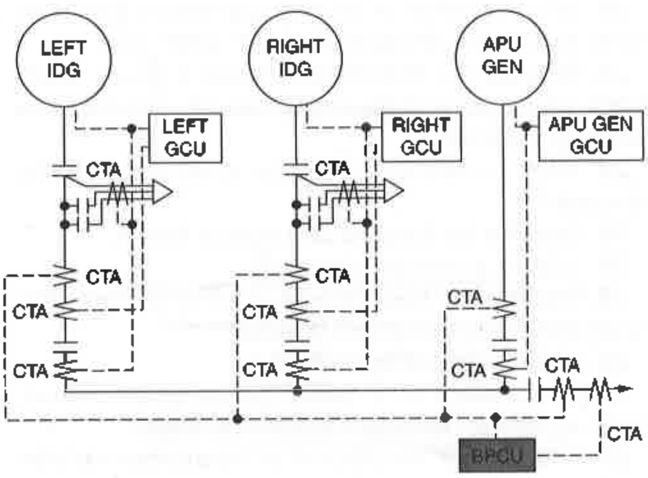


FIGURE 12-31 Schematic of a power distribution control system. (*Sundstrand Corporation.*)

transformer assemblies (CTAs). Figure 12-32 shows the generator breakers (GBs) and the bus tie breakers (BTBs), which are used to control system loads via signals from the BPCU.

BPCUs are basically small computers designed for a specific function. Each aircraft typically contains two BPCUs

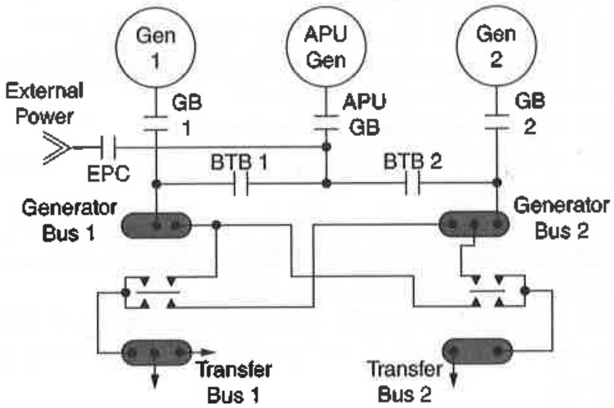


FIGURE 12-32 Power distribution control system showing generator breakers (GBs) and bus tie breakers (BTBs). (*Sundstrand Corporation.*)

for redundancy in the event of a failure. Each BPCU constantly monitors its input and output data using a digitally coded message. If a system fault occurs, the BPCU initiates the necessary corrective action and records the fault in a nonvolatile memory. The nonvolatile memory is part of the built-in test equipment (BITE) of the BPCU. Any fault data stored by the BITE system can be recalled at a later time by a line technician. This process greatly reduces maintenance time and enhances system reliability. Built-in test equipment is discussed in Chaps. 7 and 13.

Newer transport-category aircraft such as the B-777, 787, and A-380 incorporate highly complex electrical systems which employ elaborate controls. The trend on these aircraft is to subdivide regulation of electrical power into various control located at various sites throughout the aircraft. This allows for shorter runs of most power cables and saves weight.

The power distribution system of the B-777 is controlled through a modern **ELMS**. All electrical power goes through ELMS for distribution throughout the aircraft. There are several ELMS power control panels, which contain the load switching devices that distribute power. In order to monitor, distribute, and protect electrical power, ELMS receives data from various systems and flight deck control panels using an ARINC 629 data bus.

The electronic control circuitry needed for B-787 power distribution is contained in both the aft or forward equipment bays. The forward equipment bay distributes power to the majority of the electrical loads at 115 V ac or 28 V dc. The 235 V ac electrical equipment is supplied through the aft bay. There are 17 remote power distribution modules located in various sections of the aircraft to minimize the number of long-distance power cables. The remote power distribution modules (RPDMs) control over 1000 low- and medium-sized electrical loads. The RPDMs replace the traditional thermal circuit breakers and contactors found on older aircraft. Heavy loads, such as large motors, are switched by individual controllers.

The Airbus A-380 power distribution system is controlled through a series of contactors (solenoids) which connect/disconnect buses and power supplies. Pilot commands and automated instructions are sent to four power distribution subsystems for control of electrical power. The main distribution system is divided into two subsystems; primary and secondary. Primary distribution, for loads requiring 15 A or higher, is controlled through the **Primary Electrical Power Distribution Center (PEPDC)** located in the electrical equipment bay. The Secondary distribution system is controlled by two **Secondary Electrical Power Distribution Centers (SEPDCs)** and eight **Secondary Power Distribution Boxes (SPDBs)**. The secondary system controls and protects electrical circuits which consume less than 15 A of current. The distribution centers are located in various areas of the aircraft in order to reduce long runs of wire from one central location; this saves wiring complexity, weight, and increases reliability.

On most modern aircraft the automated power distribution system provides for a **no-break power transfer** (NBPT). A no-break power transfer means that the automated system can change the ac power source without a momentary interruption of electric power. For example, when external power is being used and the aircraft is preparing to depart the gate, the engines are started and the main generators are brought on line. During an NBPT, the generator control units monitor the power source currently on line (external power) and the power source requested by the flight crew (main generators). If the power requested is within specifications, both power supplies are paralleled for a split second, and no power interruption occurs. If the requested power is out of limits, the GCUs try to adjust the system and then connect the requested power to the buses. If the power system cannot be adjusted to the correct tolerance for paralleling, the requested power source will be rejected, or there will be a momentary power interruption.

REVIEW QUESTIONS

1. What is the purpose of a bus bar?

2. Describe a power distribution system for a large aircraft.

3. What FAR establishes the general requirements for aircraft power distribution systems?

4. What are the various means of monitoring a power distribution system?

5. Explain the purpose and use of an external power circuit.

6. What is the purpose of a diode in an external power contactor circuit?

7. Explain how to conduct an electrical-load analysis.

8. What loads are considered for an electrical-load analysis?

9. Discuss why an aircraft may contain more than one battery.

10. Discuss the need for protective devices in aircraft electrical systems.

11. Where should protective devices be located?

12. What is the purpose of a master switch?

13. What types of electrical loads may be considered as intermittent loads?

14. What must be done before adding electric equipment to an aircraft system?

15. What are the basic requirements for circuit protection identification?

16. Explain why an aircraft might contain more than one master switch.

17. When can a total continuous load equal 100 percent of alternator output?

18. Explain the difference between a *single-polarity* and *dual-polarity* ammeter circuit.

19. Why are electrical schematics within an aircraft's maintenance manual separated into different systems?

20. What elements of an electrical system would be found on a power distribution system schematic?

21. Describe the difference between a power distribution system on a single-engine aircraft and one on a twin-engine aircraft.

22. What is used to clip voltage spikes produced by solenoids?

23. Describe the function of a current limiter.

24. What is an *electrical ground*?

25. Describe the two methods used to connect electric equipment to the system ground.

26. What is a bonding jumper?

27. In the event of a partial power system failure, what happens to nonessential electrical loads?

28. What is the function of a transformer-rectifier unit?

29. Describe the basic operation of a split-bus power distribution system.

30. What types of aircraft typically employ a split-bus system?

31. Describe the operation of a parallel power distribution system.

32. What are the disadvantages of a parallel power distribution system?

33. Describe the basic dc power distribution system for a large commercial airliner.

34. What is the purpose of the hot battery bus?

35. What units are used to control the power distribution system found on large aircraft?

36. What is a no-break power transfer?

37. Explain the basic design concepts of the "more electric" airplane.

38. Why does the Cirrus SR20 have two alternators?

39. What are high energy radiated fields (HERFs); and how do aircraft protect against HERF?

40. Describe the unique nature of the AIRBUS A-380 and the Boeing B-777 and B-787 power distribution systems.

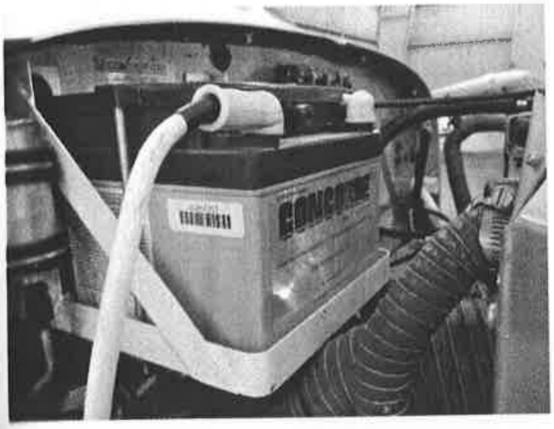


FIGURE 3-18 A 24-V lead-acid aircraft battery with self-contained battery box.

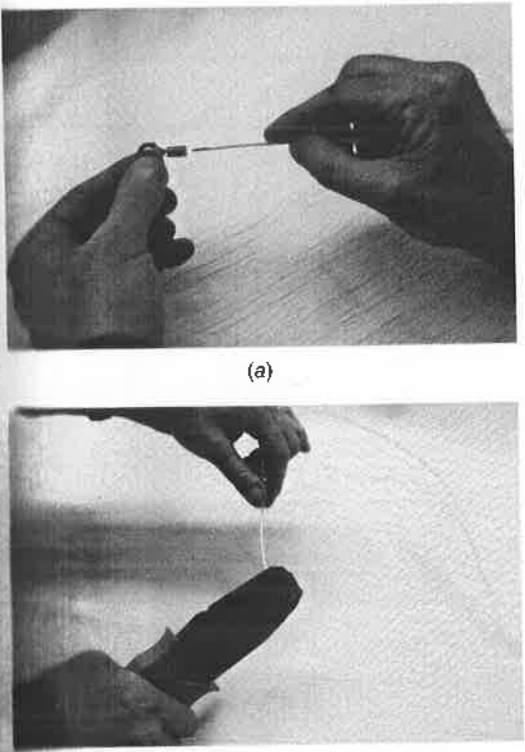


FIGURE 4-24 A typical crimped installation: (*a*) step one, prepare wire for installation; (*b*) step two, compress ring terminal using tool.

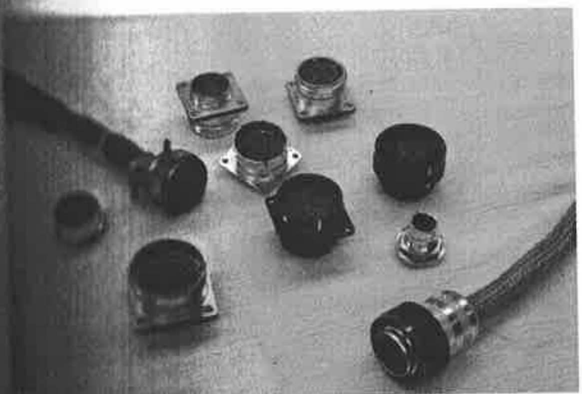


FIGURE 4-31 Common aircraft connectors.

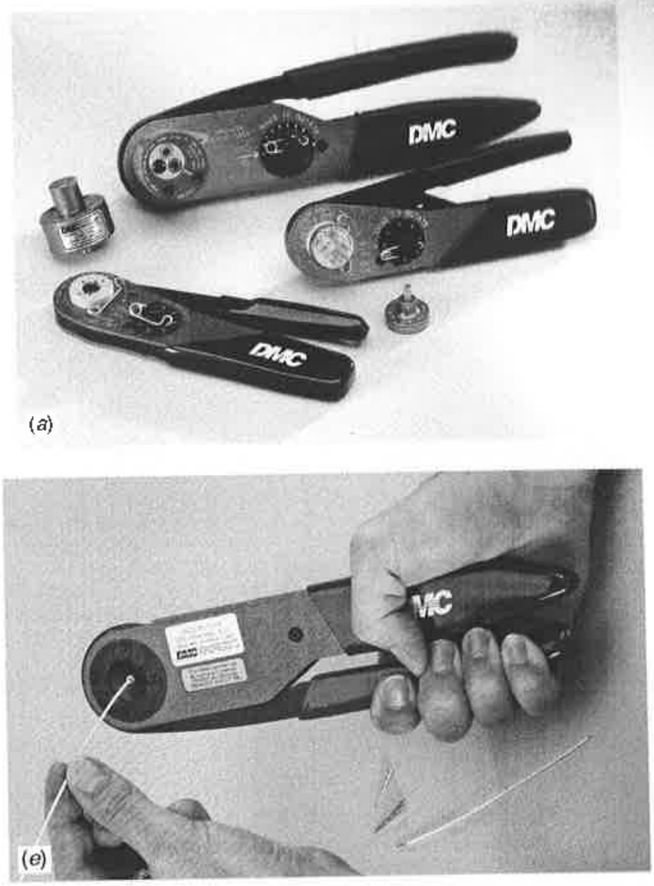


FIGURE 4-34 Common steps used during the crimping process. (a) Select the correct crimping tool and adaptors for the wire and pin being crimped. (*e*) Completely compress (squeeze) handles until tool automatically releases. (*Daniels Manufacturing Corporation.*)

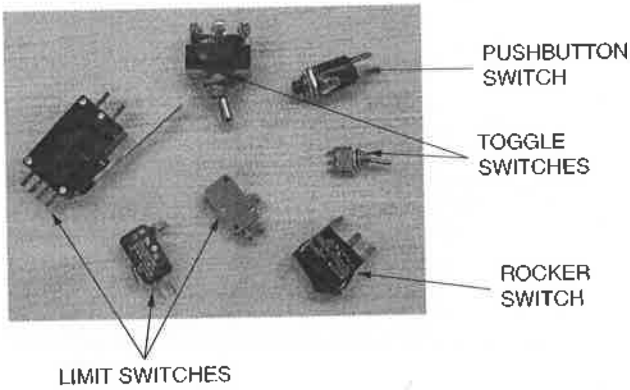


FIGURE 6-3 Common switch designs.

FIGURE 6-85 A modern instrument panel replaces conventional instruments with multiple flat panel displays.

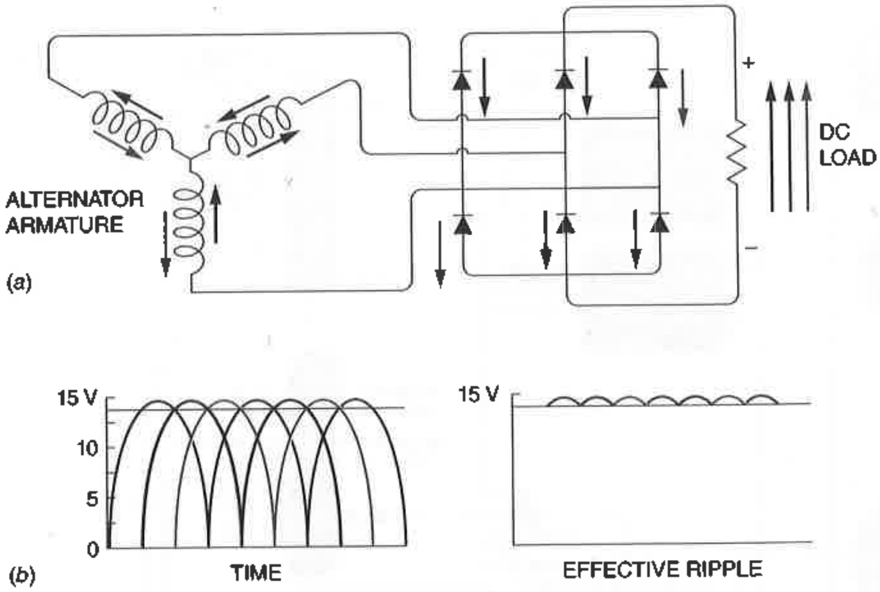


FIGURE 11-6 Rectification of a three-phase current.

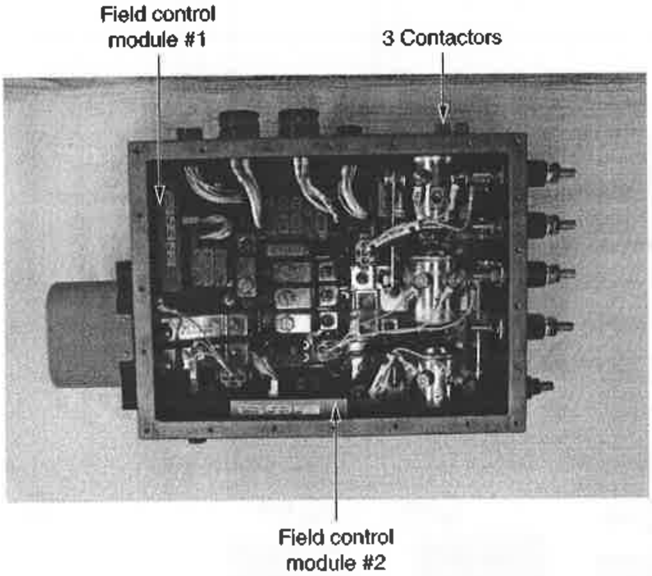


FIGURE 11-21 Cirrus aircraft master control unit (MCU).

FIGURE 12-7 Cirrus SR20 instrument panel.

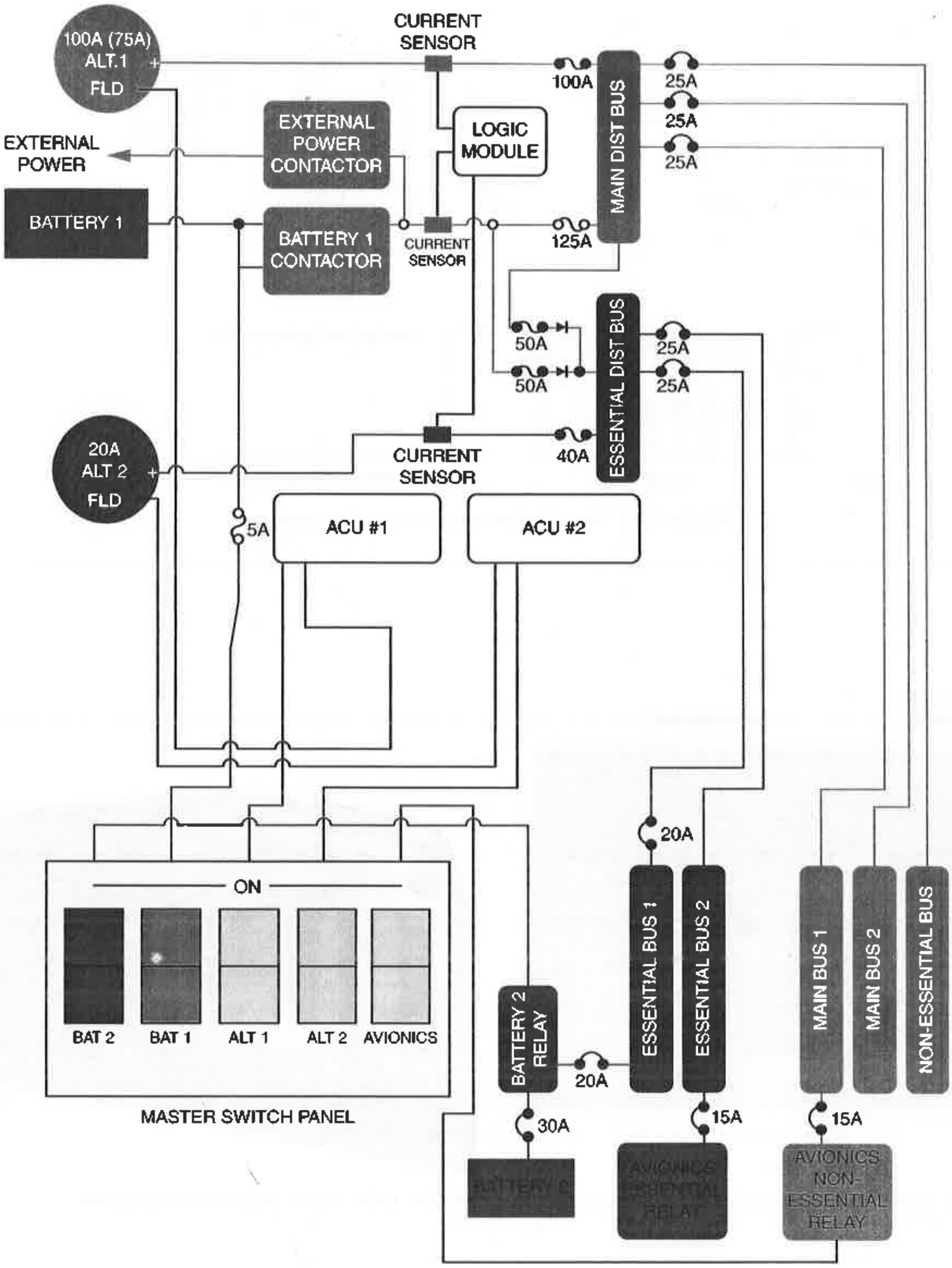


FIGURE 12-8 Cirrus SR20 power distribution system.

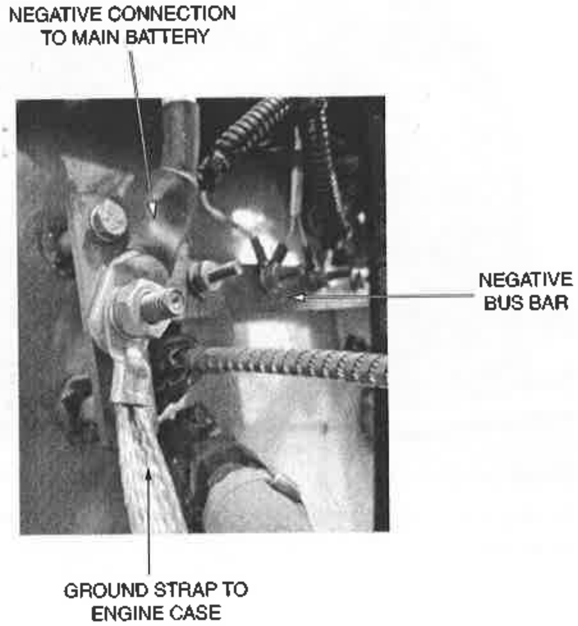


FIGURE 12-15 A typical ground (negative voltage) distribution point found on a composite aircraft.

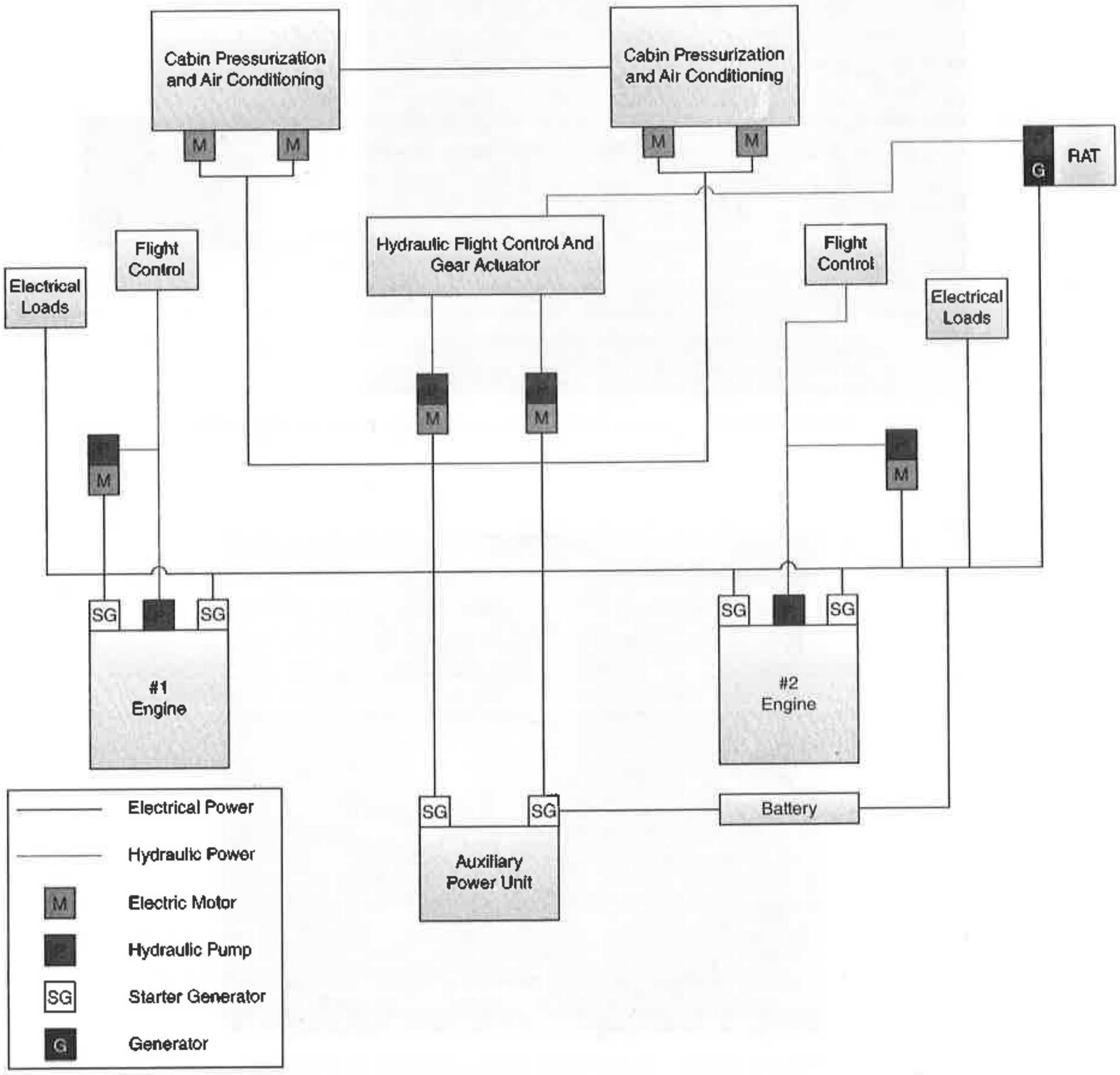


FIGURE 12-28 Boeing 787 power distribution system.

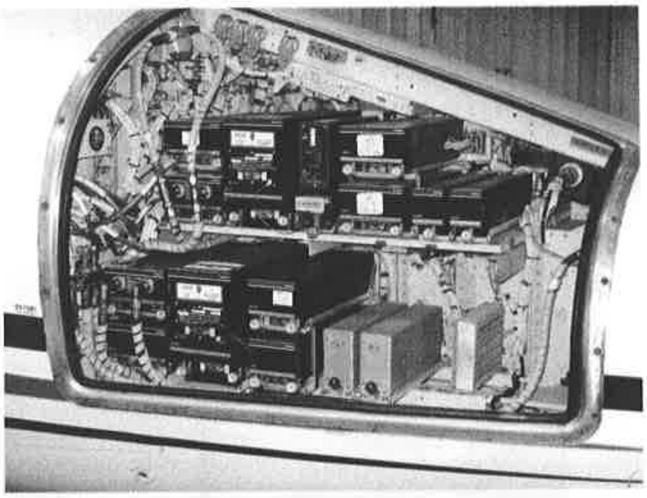


FIGURE 13-1 Forward equipment bay in the nose of a light jet aircraft.

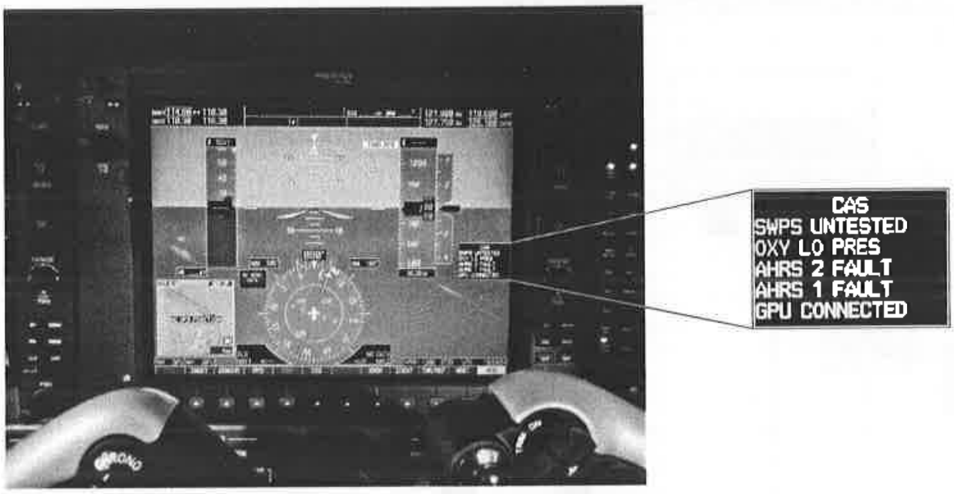


FIGURE 13-10 Caution data shown on a modern flat panel display.

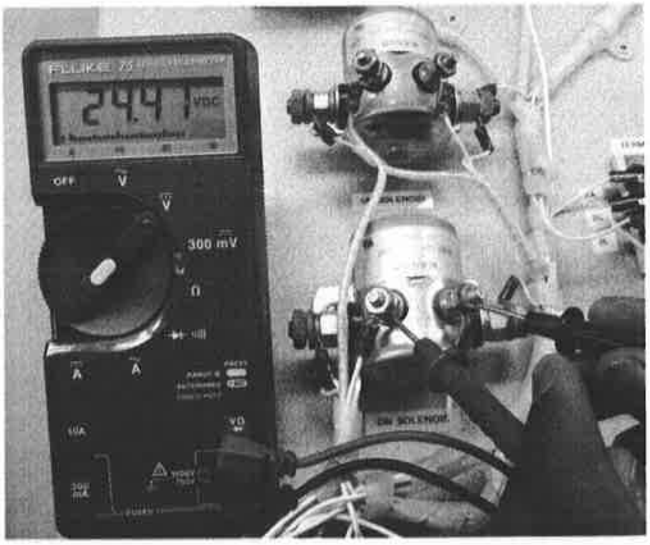
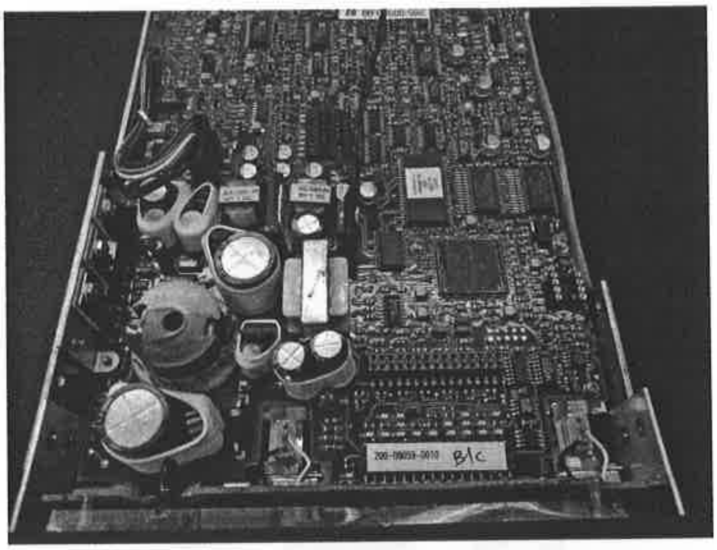


FIGURE 13-32 Digital multimeter connected to the terminals of a solenoid circuit to measure voltage.



(a)

(b)

FIGURE 14-49 Modern digital aircraft radio: (*a*) internal circuitry showing surface mounted integrated circuits; (*b*) digital display panel.

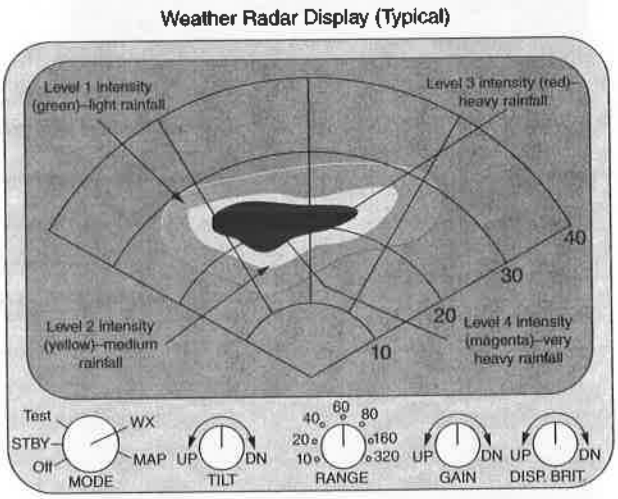


FIGURE 16-9 A typical color radar display. The range markings are typically white or blue. Level 1 storm activity (light rain), green; Level 2 storm activity (moderate rain), yellow; Level 3 storm activity (heavy rain), red; turbulence (extreme storm activity), magenta.

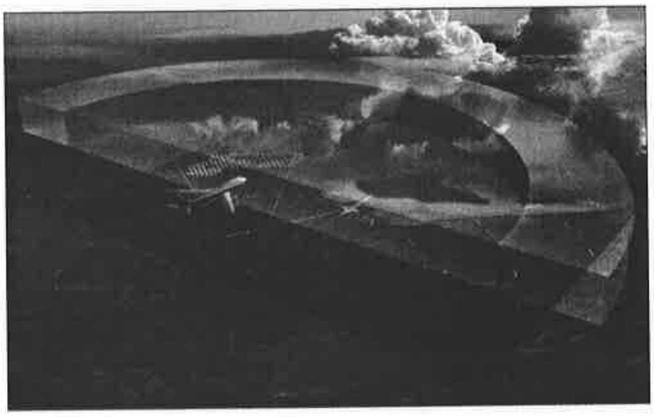


FIGURE 16-20 3-D aircraft weather radar. (*Honeywell.*)

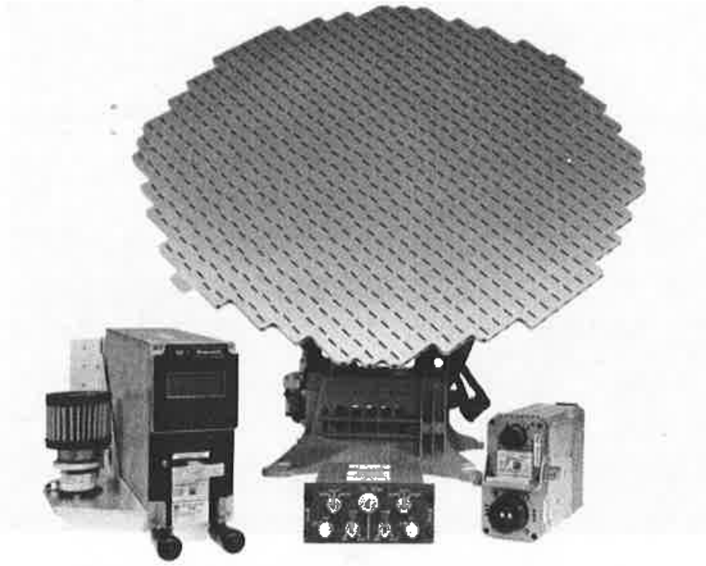


FIGURE 16-21 The RDT-4000 IntuVue 3-D radar system for a Boeing 737. (*Honeywell.*)

FIGURE 17-28 The AV80R portable multifunction display designed for light aircraft. (*Bendix King, by Honeywell.*)

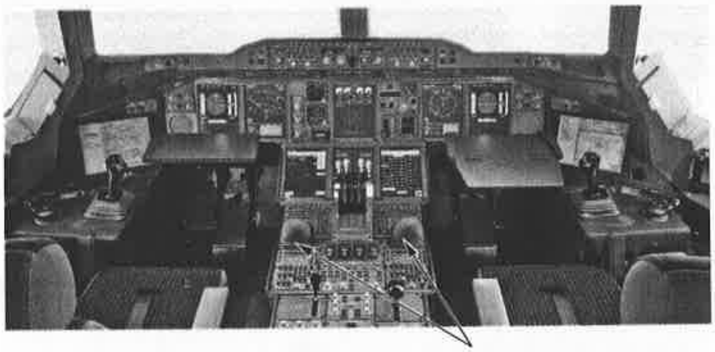


FIGURE 17-32 Airbus A-380 flight deck. (*Airbus S.A.S.*)

FIGURE 17-47 Control display unit (CDU).

Design and Maintenance of Aircraft Electrical Systems

13

INTRODUCTION

Modern aircraft depend upon the proper operation of their electrical systems for safe and satisfactory operation. Electrical systems are required for power-plant control, navigation, communications, flight control, lights, galley operation, and other functions. With many aircraft, flight operations cannot be conducted safely without certain **essential** electrical systems. On some of the most modern planes, it would be impossible to fly the aircraft without some source of electrical power. It is therefore apparent that the proper maintenance of aircraft requires that the electrical systems be kept in the best possible condition through inspections, testing, and the exercise of approved maintenance procedures.

To attain reliability in electrical systems, it is essential that great care be exercised in the selection of components and materials and that each part be installed in such a manner that it will not be subjected to damaging conditions of any kind. For commercial and other civil aircraft, the requirements for the installation and approval of electric components and materials are established by the Federal Aviation Administration (FAA) and published in Federal Aviation Regulations (FARs). The regulations and directives of the FAA should always be observed in the maintenance of civil aircraft. For specific types of aircraft and equipment, the manufacturer's overhaul and maintenance manuals should be followed. During the design and manufacture of aircraft, the manufacturer makes certain that the requirements of the FAA are met to assure safe aircraft that can pass the certification process. The purpose of this chapter is to present materials related to design and maintenance of common aircraft systems. Both simple systems found on light single-engine aircraft as well as complex computerized components will be presented.

REQUIREMENTS FOR ELECTRICAL SYSTEMS

General Requirements

In general, requirements for aircraft electrical systems are established to assure that the systems will perform their functions reliably and effectively. The requirements for normal, utility, and acrobatic aircraft are set forth in **FAR Part 23. FAR Part 25** gives the requirements for transport-category aircraft. Various changes are made in these requirements from time to time, and it is the responsibility of the FAA, manufacturers, and maintenance personnel to ensure that required changes are incorporated in certificated aircraft, as needed.

In this section it is not possible to list all current requirements in detail; however, we shall consider the principal factors that assure safe and effective electrical systems. For the current requirements related to inspection and maintenance of aircraft, the appropriate manufacturer's bulletins and FAR should be consulted.

Electrical systems for all aircraft must be adequate for the intended use. Electric power sources, their transmission cables, and associated control and protective devices must be able to furnish the required power at the proper voltage to each load circuit essential for the safe operation of the aircraft. Compliance with the foregoing requirement must be substantiated by an electrical-load analysis (measurement or summation) that accounts for the electrical loads applied to the system in probable combinations and for probable durations.

Electrical systems, when installed, must be free from hazards in themselves, in their methods of operation, and in their effects on other parts of the aircraft. They must be protected from fuel, oil, water, and other detrimental substances and from mechanical damage such as abrasion or physically applied force. The systems must be designed so that the risk of electric shock to the crew, passengers, and ground personnel is reduced to a minimum.

Whenever possible, electrical systems are designed so they will not be adversely affected by excess heat or fire. This can be accomplished through proper placement of wiring, use of firewalls and heat shields in engine compartments, and the use of special high-temperature wire insulation. Electrical equipment and systems must be designed so they are protected from over-current situations that may create smoke or fire. Also, the installation of electrical equipment must be in such a location as to minimize the possibility of fire caused by other aircraft systems.

Requirements for Transport Aircraft

All systems and equipment installed in **transport-category aircraft** must meet certain basic safety requirements, and these are set forth in FAR Part 25. All systems must be designed so they will perform their intended functions under foreseeable operating conditions. The electrical system and associated components, must be designed so that the occurrence of any failure condition that would prevent continued safe flight is unlikely. Any failure that would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions must be improbable.

Warning information must be provided to alert the crew to unsafe operating conditions, thus enabling them to take appropriate corrective action. Systems, controls, and associated monitoring and warning equipment must be designed to minimize crew errors that could cause additional hazards. Compliance with requirements must be shown by analysis and, where necessary, by appropriate ground, flight, or simulator tests. The analysis must consider possible modes of failure, including malfunctions and damage from external sources. It must deal with the probability of multiple failures and undetected failures and the resulting effects on the aircraft and occupants.

Installations

The electric equipment, controls, and wiring for an aircraft must be installed so that operation of any one unit or system of units will not adversely affect the simultaneous operation of any other electric unit or system essential to the safe operation of the aircraft. For this reason individual electric circuits are wired in parallel with respect to each other. If one circuit of a parallel group is turned off or fails, it will not affect the remaining circuits. It is also important to ensure that circuits critical to flight safety are fused separately. If only one critical circuit is connected to any given fuse or circuit breaker, its failure will not adversely affect other circuits. Individual control (on/off) switches must also be employed on all circuits critical to flight. That is, the appropriate crew member must be able to turn off or on any critical circuit without adversely affecting others. In short, each critical circuit must contain its own independent switch and circuit protective device.

Cables and wires must be grouped, routed, and spaced so that damage to essential circuits will be minimized if there are faults in heavy-current-carrying cables. This means that cables that might be subject to burning in case of a short circuit should not be grouped with essential-circuit cables, because the burning of a shorted cable could also damage an essential circuit to the extent that it would not be operable.

Figure 13-1 shows the equipment bay in the nose section of a corporate jet aircraft; the wiring is grouped, secured, and routed in such a manner as to protect the wire and allow

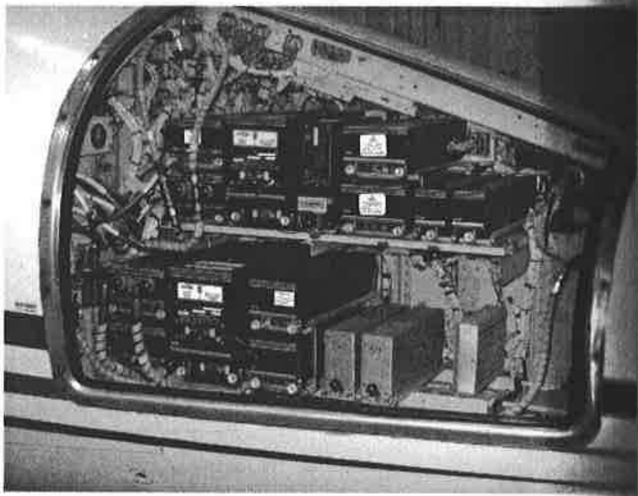


FIGURE 13-1 Forward equipment bay in the nose of a light jet aircraft. See also color insert.

removal and installation of the LRUs mounted in the area. The LRUs shown here are for operations of various navigation, communication, and autoflight functions.

The installations designed for an aircraft by the manufacturer are usually acceptable; however, changes are sometimes required after the aircraft has been in operation. These changes are called to the attention of the aircraft owner or operator by means of the manufacturer's service bulletins or Airworthiness Directives (AD) issued by the FAA.

Typical Schematic Diagrams

The maintenance publications for any aircraft must contain information explaining the operation of electrical systems. To fully understand the operation of any electrical system, the technician must become familiar with the wiring of that system. The **schematic diagram** is an electrical road map that identifies the various wires and electric components of a particular system. Electrical schematic diagrams for light aircraft are often contained in the **maintenance manual**. The maintenance manual also describes each system's operation and maintenance practices. The electrical schematics for larger, more complex aircraft are contained in a separate **wiring diagram manual**. Electrical systems that are not produced or installed by the aircraft's manufacturer are not typically included in these data. Schematics of "add-on" electric equipment must be obtained from the manufacturers of those particular items.

The terms **schematic diagram**, **schematic**, and **diagram** are all used to denote the map of an electrical system or component. Generally speaking these terms are used interchangeably throughout the industry. Many corporations and manufacturers do have specific guidelines as to what constitutes an electrical diagram and an electrical schematic; therefore, these definitions should be followed. However, in common practice most technicians use the simple term **diagram** or **schematic** to define the electrical road map. Their choice of which term to use is typically a matter of personal preference, not specific definition. For the most part, this text will use both terms interchangeably.

The manufacturers of corporate and transport-category aircraft typically follow the **Air Transport Association (ATA)** specifications for categorizing data in the maintenance and wiring diagram manuals. Some, but not all, general aviation aircraft manuals follow ATA specs. **ATA specification 2200** is a detailed number code of the various items found on a typical aircraft. ATA specification 2200 is a modern version of the former ATA specification 100. Since 2200 is relatively new, many older aircraft maintenance publications will follow ATA 100. For the most part these specifications are very similar; however, specification 2200 has greater flexibility and has been designed for use with digital media such as laptop computers and table-type devices.

ATA specification 2200 assigns specific components and systems to particular chapters of all maintenance publications and wiring diagrams. Knowledge of this standard will help technicians find a specific electrical schematic diagram or system description. Some of the various chapters that might apply to electrical systems include chapters **20 (standard practices airframe)**, **24 (electric power)**, 31 (indicating and recording systems), 33 (lighting), 34 (navigation), 39 (electrical/electronic panels and multipurpose components), 74 (engine ignition), and 77 (engine indicating). Keep in mind that this is only a partial list; virtually any part of an aircraft could have a related electrical or electronic system. Each of the ATA chapters is divided into sections that describes in detail the various parts of an aircraft system.

Schematic diagrams usually represent the electrical configurations of one or more systems. Schematics *do not* show physical configurations of components within an electrical system. That is, schematic diagrams do not represent the location of electric components within the aircraft or with respect to other components of the system. Most civilian aircraft schematics are generally similar; however, there are several differences in diagrams drawn by different manufacturers. Some schematics indicate wire size within the wire code number. This becomes helpful when replacing defective wires. Often the individual components of an electrical system are identified on the schematic; other diagrams number the components and use an identification list. There are literally hundreds of symbols used to represent the various components of aircraft electrical systems. For the most part, these symbols are standardized; however, some variance does occur among manufacturers. The appendix of this text includes the electrical and electronic symbols from various aircraft manufacturers.

Generally speaking complex aircraft require more elaborate wiring diagrams and detailed wire lists. For example, large transport-category aircraft typically use several levels of electrical diagrams. The most simple level may be the block diagram (see Fig. 13-2). The **block diagram** is used for general familiarization of an entire system and includes little detail. A technician would likely start the troubleshooting process with this diagram and eventually move to diagrams that contain more specific information. Eventually, a technician might need to understand details such as wire numbers or specific contact points within an electrical connector; for this information the manufacturer will supply more detail in one or more an electrical schematics or diagrams. Large complex aircraft also employ **wire lists** and **bundle lists** to help identify the routing of wires and bundles. These lists are often laid out as tables containing wire numbers, connector identification numbers, electrical contact information, and locations where that wire can be found on the aircraft. This information will be slightly different between manufacturers and even between aircraft types constructed by the same manufacturer. Whenever detailed troubleshooting of a system is necessary, it is often helpful to refer to wire or bundle lists.

The schematic diagram of an electrical system seldom identifies the electric wiring within a component or LRU. For example, a diagram of an aircraft starter circuit may represent the starter as an empty circle. The schematic diagram of the starter motor will show the internal wiring of the motor. **Line replaceable unit (LRU)** is often the term used to refer to an electric component, a communication radio, or a generator control unit. The schematics of these components are typically available from the manufacturers of the components. The term line replaceable unit (LRU) means that the component is easily removed and installed on the aircraft.

The major aircraft manufacturers represent electrical schematics slightly differently. Figures 13-3 and 13-4 show different schematics of a landing light system; there are

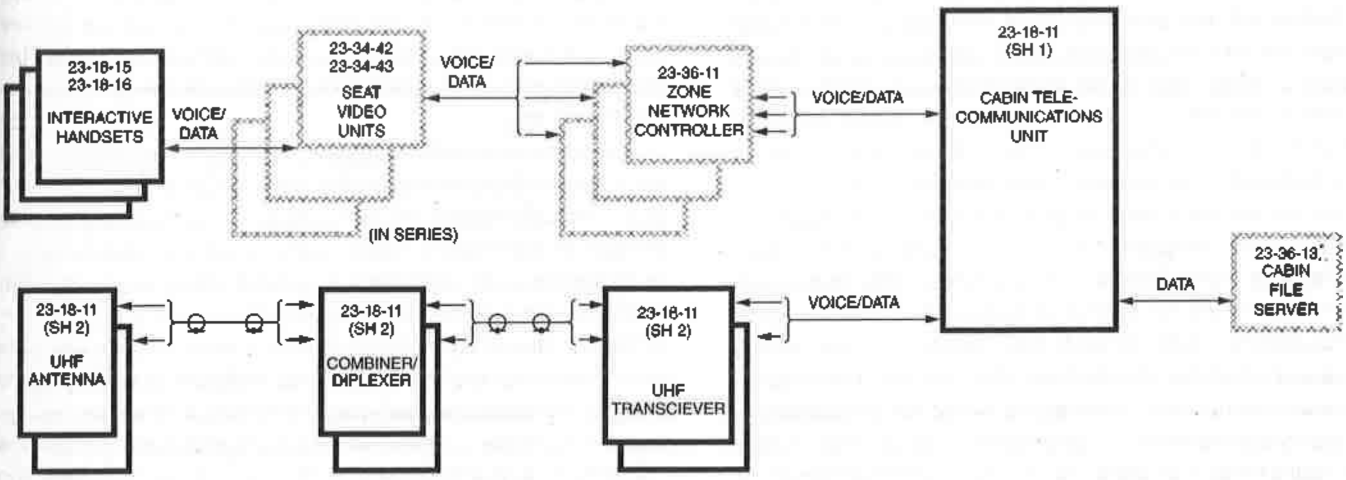


FIGURE 13-2 A typical block diagram.

GMA/ATA CODE & REF DES	PART NO.	DESCRIPTION 1 2 3 4 5 6 7	UNITS PER ASSY	INSTL ZONE	USABLE ON CODE
46-01-CB56		CIRCUIT BREAKER SWITCH, LANDING LIGHT/SEE CH 24/	1	240	
-DS20	4596	LIGHT ASSY, LANDING LIGHT........................	1	410	
-GS4	131270-3	GROUND STUD..	1	222	
-J61		RECEPTACLE, SUBPANEL DISCONNECT/SEE CHAPTER 91/.	1	231	
-P61		PLUG, SUBPANEL DISCONNECT/SEE CHAPTER 91/	1	231	

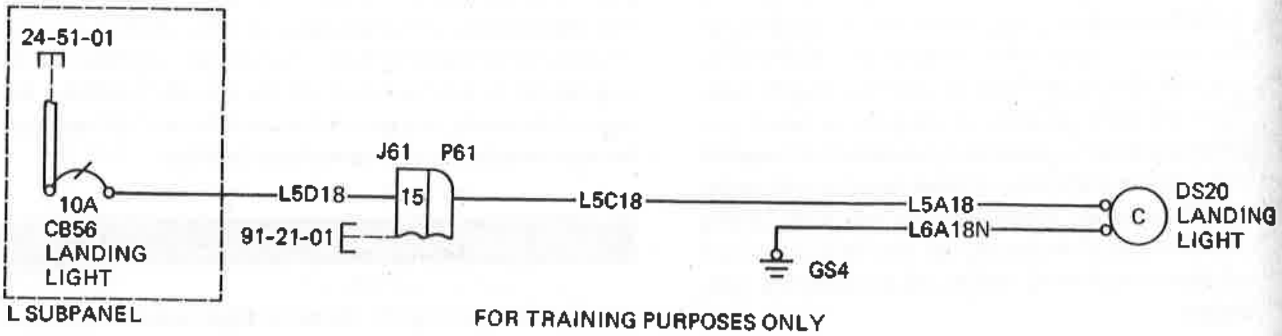


FIGURE 13-3 Beechcraft landing light circuit schematic. (*Beech Aircraft Corporation.*)

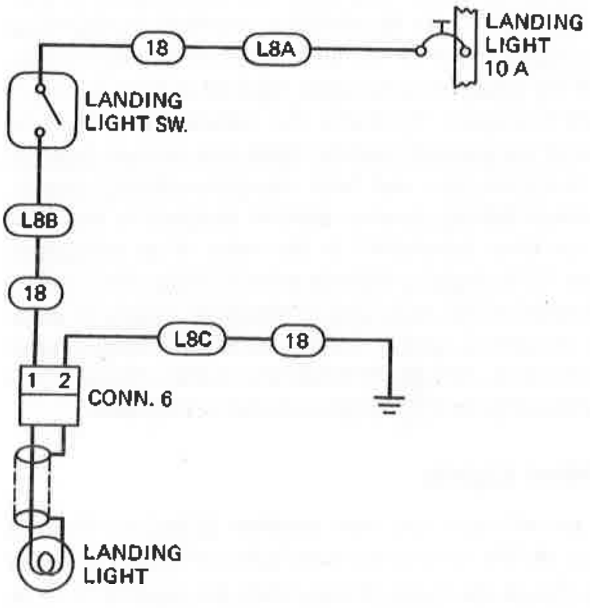


FIGURE 13-4 Piper landing light circuit schematic. (*Piper Aircraft Corporation.*)

several differences and several similarities. The Beechcraft schematic, Fig. 13-3, includes a component description, which lists applicable part numbers, the quantity of units, and the component installation zones. An **installation zone** indicates the location of a component within the aircraft. If the zone number is referenced to a zone code chart, the component's location can be identified. This becomes extremely important when dealing with complex aircraft containing several electric components in remote locations. Beechcraft indicates a circuit's wire size in the last two digits of the **wire code**. For example, L5 5A18 indicates an 18-gauge wire.

The Piper schematic diagram shown in Fig. 13-4 does not contain a separate component or wire table. All the information concerning the circuit is contained within the schematic. Each component is labeled, and the wire size is overlaid on the individual wires.

In general, all schematics are very similar; each contains the necessary information to convey the electrical layout of the circuit. Any design differences are illustrated in the schematic. For example, the Beechcraft controls the light by means of a circuit breaker switch; the Piper system connects the landing light to the connector plug by means of a shielded cable. These design differences are typical among various manufacturers. Always refer to the schematic diagram prior to servicing any electric circuit. If any portion of a schematic cannot be interpreted, contact the appropriate technical representative for assistance.

Electronic Maintenance Data

In today's electronic age, aircraft technicians have become increasingly dependent on digital data for maintenance processes. Also, over the past decade aircraft have become more complex and there is more maintenance documentation. This creates a challenge when dealing with maintenance information. In the past, aircraft manufacturers have printed literally tons of paper manuals covering inspection, maintenance, and repair of their electrical systems. Today paper documents have virtually all been replaced by computerized maintenance data in most maintenance facilities.

Modern computerized aircraft employ the capability to monitor and store maintenance data on aircraft engines, airframes, and electrical system performance and faults. The data from these computerized systems is fed to central maintenance computers and can be of great benefit during troubleshooting. The problem becomes how to categorize and analyze all this data. As modern aircraft have grown in complexity, electronic technical data has evolved as well. Today, even CD-ROM formats are no longer sufficient to support the multiple types of data available to a maintenance technician.

Modern aircraft technical data is often maintained directly by the original equipment manufacturer (OEM) and supplied to the maintenance technician through a secure online service. The OEM-managed technical data system provides "one stop" technical data storage and retrieval services for a maintenance provider. Included in a typical online service would be fault isolation manuals, maintenance documentation, and engineering diagrams along with a variety of other information. A technician can then access technical manuals using the web-based system and common personal computer or tablet-type device. Where in the past, maintenance providers were required to store and maintain multitudes of paper-based aircraft maintenance, troubleshooting, wiring diagram, and parts catalog manuals; these technical documents can now be accessed and maintained almost exclusively online and accessed as a web-based interface.

Modern database servers have relatively limitless storage space and flexibility. The move toward OEM data management control systems allows for the ability to link separate manuals (e.g., a maintenance manual and a wiring diagram manual) using hyperlinked keywords. This offers rapid cross-referencing as well as important revision and document control improvements. This web-based approach also makes it easier to maintain updates for all aircraft technical documents. The integration of computer workstations during hanger maintenance and portable electronic devices (laptops and tablet-type computers) on the flight deck has helped the frontline technician to improve the efficiencies of maintenance activities (see Fig. 13-5). One or more computer devices could now be considered the most important troubleshooting tool for a modern aircraft technician.

Identification Systems for Locating Electric Components

Virtually all manufacturers of corporate and transport-category aircraft have an identification system that is used to locate components on an aircraft from the electrical schematics. The systems may vary among manufacturers and even among different aircraft produced by the same company; so, always refer to the introduction of the wiring diagram manual to find the specific details. In general, the electric components and wiring found on schematics are each assigned a number. That number can be used to locate the part using the appropriate manuals.

Aircraft maintenance publications using electronic publications also take advantage of component location systems. In many cases component locations can be accessed with a simple click of the mouse. Hyperlinks are often used in various maintenance manuals to bring up component location data quickly and seamlessly. In some modern systems, location information includes 3-D images or photos of the component as it is installed on the aircraft. Someday this type of electronic component location system will no doubt become standard in all maintenance facilities.

FIGURE 13-5 Accessibility of online maintenance data for hanger maintenance activities.

AIRCRAFT LIGHTS

All aircraft approved for flying at night must be equipped with various types of lights. Among these are **position (or navigation) lights**, **anticollision lights**, **landing lights**, **instrument lights**, **warning lights**, and **cabin lights**. In addition, other lights may be needed or required. Among these are taxi lights, ice-detection lights, cargo compartment lights, and all the special-purpose lights required in large passenger aircraft. Emergency lighting is also mandatory for both the passenger compartment and the flight deck on most business jets, commuter-type, and large transport-category aircraft. Emergency lighting systems must be designed to allow for safe exit from the aircraft in the event of an emergency landing. All emergency lighting must be designed to operate independent of the main aircraft electrical system; in many cases, emergency lighting employs batteries dedicated solely for that system. All lighting equipment and installations must be approved by the FAA prior to aircraft certification.

Position Lights

Each aircraft must have three **position lights**: two forward and one aft. The forward position lights are usually mounted on the tips of the wings because they are required to be as far outward as possible. The right position light is green, and the left is red. The forward position lights must show light through a 110° angle from directly forward to the right and the left, as shown in Fig. 13-6.

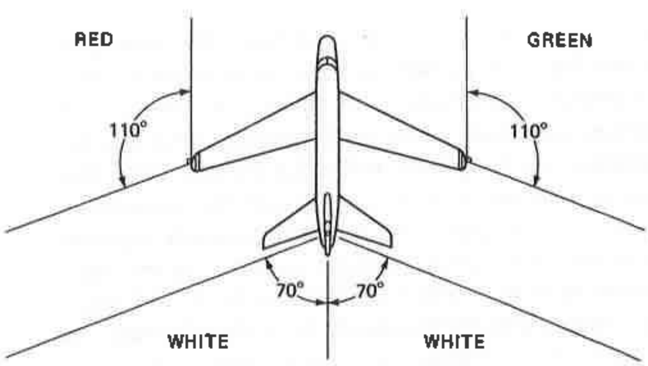


FIGURE 13-6 Arrangement of position lights.

The aft light is white and mounted as far to the rear as **possible.** It is common practice to mount the aft position light on the top of the vertical stabilizer (fin) or the aft tail cone. The aft position light must show light through an angle of 70° on each side of the centerline of the aircraft and to the rear.

The covers or color filters used on position lights must be of a material that is heat-resistant and will not shrink, fade, or become clouded or opaque.

All position lights must be in a single circuit and must be controlled by one switch. The power source is connected through one fuse or circuit breaker. It should be noted that the term *navigation lights* is often substituted for *position lights.*

The schematic in Fig. 13-7 represents a typical panel-and-position-light system. This aircraft employs transistorized dimming circuits to control the intensity of the radio and panel lights. This system is designed such that the navigation (position) lights and aircraft instrument panel lights are turned on simultaneously. Toward the top of the diagram, it can be seen that the **panel/nav.** light switches are mechanically linked; indicated by the dotted line. It can also be seen that the electrical components of each system are completely independent including all circuit breakers and wiring. This allows for a failure in one circuit with no adverse effect on the other.

Some modern aircraft now use **light-emitting diodes (LEDs)** for various lighting systems. LEDs are becoming very popular due to their light weight, rugged, high-efficiency design. A typical LED navigation wingtip light will consume approximately 0.35 A at 28 V dc; this same light using a traditional incandescent lamp would consume nearly 10 times as much power. A typical wingtip LED assembly is shown in Fig. 13-8. LEDs also have a high **mean time before failure (MTBF)**; the average life of a common LED is between 10 000 and 20 000 h of operation. This is much longer than a traditional incandescent lamp; hence aircraft downtime and maintenance costs are reduced using LEDs. Interior lights, position lights, and even landing lights are now all available using LED technologies. Many of the aircraft produced after the year 2005 have original designs using LED lighting, other older aircraft can take advantage of this technology with LED fixtures designed to be a direct replacement for older lights. It should be noted that many high-intensity or flashing LED lights require some type of power supply for operation. In many cases through the use of microelectronics, this power supply is contained within the light assembly.

Anticollision Lights

An **anticollision light** is designed to make the presence of an aircraft visible to pilots and crew members of other aircraft in the vicinity, particularly in areas of high-density aviation activity, at night, and in conditions of reduced visibility. The anticollision light is of high intensity and flashes on and off not less than 40 and no more than 100 cycles/min. There are two basic types of anticollision lights, **rotating beacons** and **strobelights**. Most modern aircraft employ strobe (flashing type) anticollision lights, since they use no moving parts and generally produce a brighter light. High-intensity flashing LEDs are also found on some aircraft.

A strobelight is a glass or quartz tube filled at low pressure with Xenon gas. The tube is caused to flash by applying a high voltage to two electrodes in the tube and triggering the tube with an additional circuit. The current used to fire the tube is stored in a capacitor by means of a charging circuit. This circuit converts the low voltage from the aircraft electrical system to a high voltage (300 to 500 V) to charge the storage capacitor. A trigger circuit then applies the trigger signal to the trigger terminal of the tube and causes it to fire. The duration of the flash caused by the capacitor discharge may be a little more or less than 0.001 s, but the intensity of the light is very high; thus the light can be seen for many miles. The strobe principle is the same as that of a photographer's electronic flash.

At least one anticollision light is required on all aircraft certified for night flight. Any aircraft certified after August 11, 1971, or any anticollision lights installed after that date must meet the anticollision-light requirements of AC 43.13-2A, chapter 4, paragraph 56.b.(1). These requirements stipulate that each anticollision-light system must illuminate a specific field of coverage. That is, each system must illuminate a given area around the aircraft. In order to meet this condition, most aircraft certified after August 11, 1971, employ three anticollision lights. The three lights are usually one red flashing light or rotating beacon located on top of the vertical stabilizer and two white flashing (strobe) lights on the wingtips. Since flashing-type anticollision lights produce a high-intensity light, the glass portion of any strobe lamp must be kept free from oil and grease in order to ensure proper operation. Even small amounts of oil will create hot spots on the glass and form cracks in the bulb.

The schematic in Fig. 13-9 illustrates the electrical system of a typical strobelight circuit. In this system one power supply is used to light two independent flashtubes. As illustrated in Fig. 13-9, shielded cable is used to connect the flashtubes to the strobe power supply. This prevents radio interference, which is created by the short pulse of current used to produce the intense flash.

Rotating beacons are another type of anticollision light typically found on older aircraft. These units contain a high-power incandescent lamp and a small dc motor that powers a reflector and/or lens assembly. The rotating beacon is designed so the reflector/lens is the actual rotating component and the lamp is stationary. The assembly also contains a gear reduction system between the motor and the rotating lens in order to create the required 40 to 100 flashes/min. This type of anticollision light contains multiple moving parts and is therefore less reliable than a modern flashing beacon; they also require more electrical power.

LED anticollision lights are now available as a replacement for older rotating beacons or quartz-halogen flashing units. Any replacement must be certificated by the FAA under Technical Standard Order TSO-C96a, which prescribes the minimum performance standards for anticollision light systems.

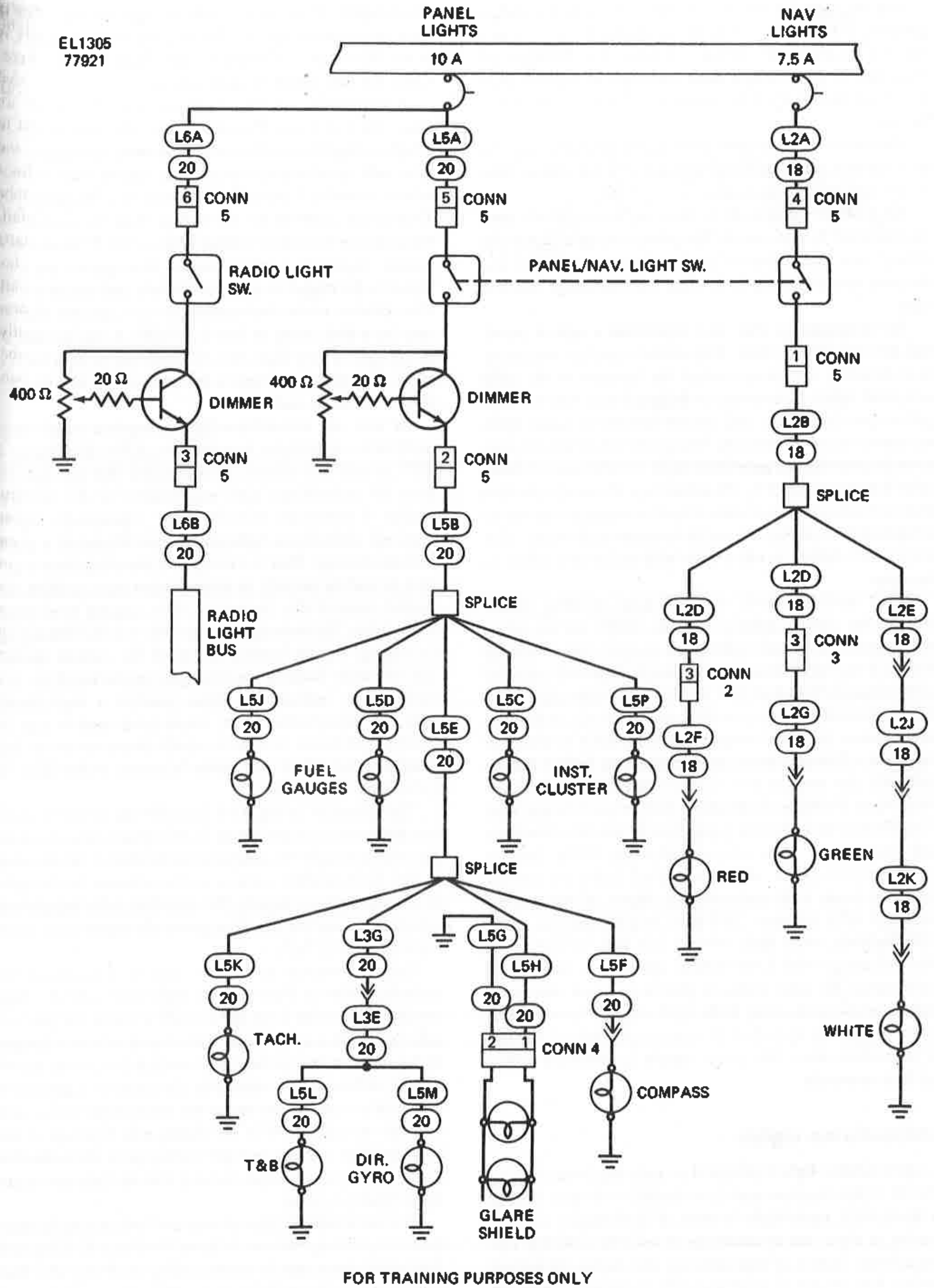


FIGURE 13-7 Panel-and-position-light circuit schematic. (*Piper Aircraft Corporation.*)

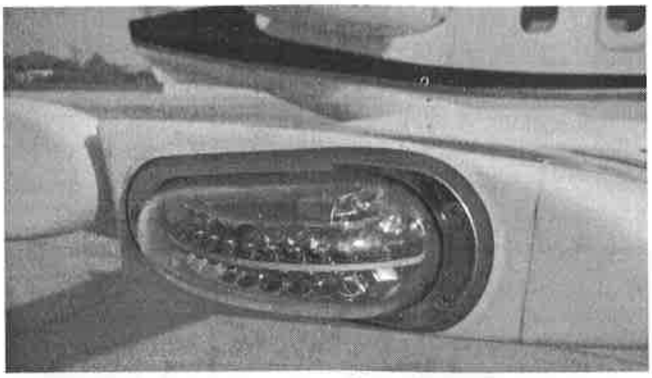


FIGURE 13-8 A modern LED wingtip light assembly.

The Whelen Corporation, a popular manufacturer of aircraft lighting, offers several LED anticollision light replacement units for various aircraft. The units have a self-contained power supply and employ LED technologies with a life expectancy of over 20 000 h. The major advantages of this technology over older systems are reduced weight, longer life, and reduced power consumption. The LED units require an average input current of 1.2 A at 14 V dc or 0.6 A at 28 V dc.

Landing Lights

Landing lights for an aircraft are required to provide adequate light to illuminate the runway when the aircraft is making a landing. A parabolic reflector is utilized to concentrate the light into a beam of the desired width.

Landing lights may be attached to the stationary part of the nose gear, installed in the leading edges of the wings, or installed in the engine cowl. Some large aircraft have landing lights in the leading edges of the wings and retractable lights in the lower surfaces of the wings. The leading-edge landing lights can be turned on several miles away from the landing site, and the retractable lights are turned on shortly before landing.

Retractable landing lights are extended by means of a small but powerful motor that is able to move the lights outward and forward against the force of the airstream. Or these lights can be mounted to a portion of the landing gear. The lights then automatically extend or retract with the gear mechanism.

Taxi lights can be employed on some aircraft to improve visibility during ground operations. Taxi lights are aimed slightly higher than landing lights in order to illuminate the area directly in front of the aircraft. Both landing and taxi lights are usually of very high wattage; therefore, they are often controlled via a switching solenoid or relay. Some landing and taxi lights operate at a high voltage in order to produce a high-intensity light. Xenon lamps are commonly used for high-intensity lights on modern aircraft. These light assemblies use a gas tube (not an incandescent bulb) made of fused quartz; this is necessary due to the intense heat produced during operation. The quartz tube is filled with a high-pressure Xenon gas. A power supply is needed to increase system voltage to a level that will create an arc between two electrodes located inside the sealed quartz tube. The actual light produced is caused by the arc and can be made directional with a reflector mounted to the lamp assembly. In some aircraft, the power supply and lamp assembly are one complete unit, on some installations the power supply is remotely mounted and the quartz tube light assembly is positioned as needed. Whenever installing a high-intensity lamp, it is important to keep the quartz tube clean. Dirt, oil, or grease on the tube can cause hot spots during operation and the lamp will crack and fail. Even the oil from a technician's fingers can create these hot spots; never touch the tube with bare hands. Typically, clean gloves are worn during installation of the quartz tube; once the tube is installed, the lamp assembly can be handled without gloves.

Instrument Lights

Instrument lights are installed behind the face of the instrument panel. The lights illuminate the instruments but do not shine directly toward the pilot or copilot. All instrument lights must be shielded in this manner. Instrument lights are provided with a dimming arrangement so the intensity can be adjusted to suit the needs of the pilot. A transistorized dimming circuit is illustrated in Fig. 13-7. On the left side of the diagram near the top it can be seen that the dimmer circuit contains a variable resistor (potentiometer) which is controlled for light dimming by the pilot. The potentiometer controls the signal to the base of the transistor through a 20-Ω resistor. The transistor then controls the current to the lamps according to the pilot's selections. It should also be noted that each instrument light circuit contains a separate on/off switch.

Warning Lights

Warning lights are provided to alert the pilot and crew to operating conditions within the aircraft systems. Red lights are used to indicate danger, amber lights to indicate caution, and green lights to indicate safe conditions. Indicator lights that are intended only for the purpose of providing information can be white.

Many modern aircraft incorporate flat panel digital displays that provide a variety of system operational information to the flight crew. Many of the warning and indicator lights found on traditional aircraft have been replaced with these integrated information and indication systems. Today, light single-engine as well as transport-category aircraft use flat panel displays for warning, caution, and status information. Figure 13-10 shows a typical warning indication found on a modern aircraft liquid crystal display. On transport-category aircraft, cautions and warnings are often shown on one or more displays dedicated to systems information. Boeing uses a system known as the **engine indicating and**

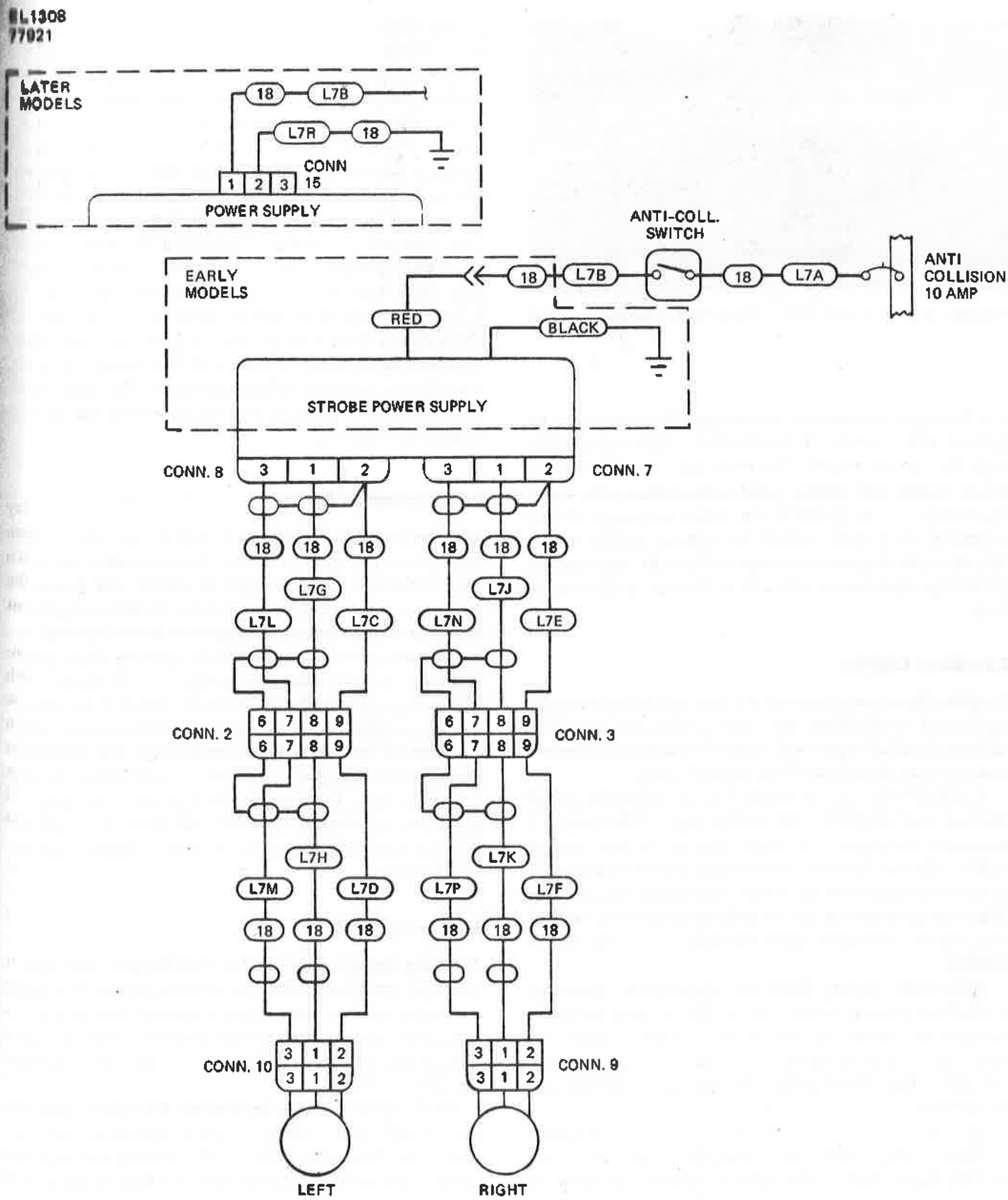


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FIGURE 13-9 Strobelight circuit schematic. (*Piper Aircraft Corporation.*)

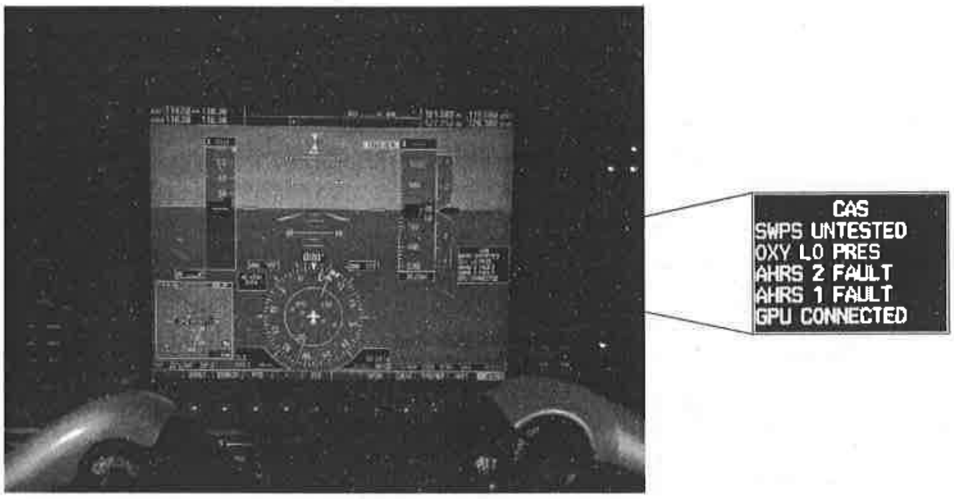

FIGURE 13-10 Caution data shown on a modern flat panel display. See also color insert.

crew alerting system (EICAS); a similar system found on Airbus aircraft is called the **electronic centralized monitoring system (ECAM)**. Both these systems monitor analyses and display information on hundreds of airframe and engine systems.

Landing-Gear Circuits

Circuits involved in the operation of electrically powered landing gear are shown in Figs. 13-11 and 13-12. This landing-gear electrical system is divided into two separate subcategories: the **actuator** and the **indicator** system. There is a separate electrical schematic used for each subsystem. It is typical for aircraft manufacturers to show details of complex electrical systems divided into logical subcategories and displayed in more than one schematic or diagram. Figure 13-11 shows the circuitry associated with the reversible electric motor that raises and lowers the landing gear. This diagram shows all the components of the landing-gear actuator circuit. The actuator circuit can further be divided into the control circuit and the motor circuit. The control portion is a low-amperage circuit that turns on/off (controls) the high-amperage motor circuit. The high-amperage motor circuit will require a relatively heavy 10-gauge wire while the control circuit uses a lighter 20-gauge wire. The control circuit is protected by a 5-A circuit breaker in the circuit-breaker panel assembly. This circuit incorporates the two **landing-gear safety switches ("squat" switches)**, which prevent the operation of the landing gear as long as the airplane is on the ground. The landing-gear safety switches are identified as S36 and S37 in the circuit. The power circuit is connected to a 30-A circuit breaker. This circuit supplies power to the UP and DOWN power relays, which are controlled through the control circuit. When the landing-gear switch, S38, is placed in the UP position with the airplane in flight, electric power flows from ground, through the UP relay, through the landing-gear UP limit switch (S39), through both safety switches, and to circuit breaker CB18. This causes the relay to close and direct power to the landing-gear motor. When the landing gear reaches the UP position, the UP limit switch opens and cuts off power to the UP relay, thus stopping the motor. The reverse action takes place when the landing gear is lowered.

Figure 13-12 is a circuit diagram of a landing-gear position-indicating system. This circuit operates in conjunction with the landing-gear control circuit shown in Fig. 13-11. The switches shown in the circuit represent the condition when the landing gear is in the down and locked position and the aircraft is on the ground. At this time, if electric power is turned on, the three green lights will be on to indicate that all three units of the landing gear are down and locked. The red gear-in-transit light will be out.

Another landing-gear circuit is shown in Fig. 13-13. The switches in the circuit are shown in the position for the gear down and the weight of the airplane resting on the landing gear. A careful study of this circuit reveals a number of safety features. For example, it is not possible to raise the gear when the airplane is on the ground, even if the landing-gear switch is placed in the UP position. Notice that the gear-relay control coil is fed through the left-gear safety (squat) switch. When the airplane is on the ground, this switch is open; hence no current can be supplied to the relay coil. Furthermore, if the gear switch is in the UP position when the airplane is on the ground, a warning horn will sound.

When the airplane is in flight and the gear switch is placed in the UP position, the gear will rise, and when it is completely up, the UP limit switch will open and break the circuit to the control coil of the gear relay (183). When the limit switch opens, it also closes the circuit through the gear-up indicator light.

When the landing gear is up, the DOWN limit switch will be closed, thus making it possible to direct current to the DOWN side of the gear motor if the gear selector handle is placed in the DOWN position. The gear lowers, but before the gear-down

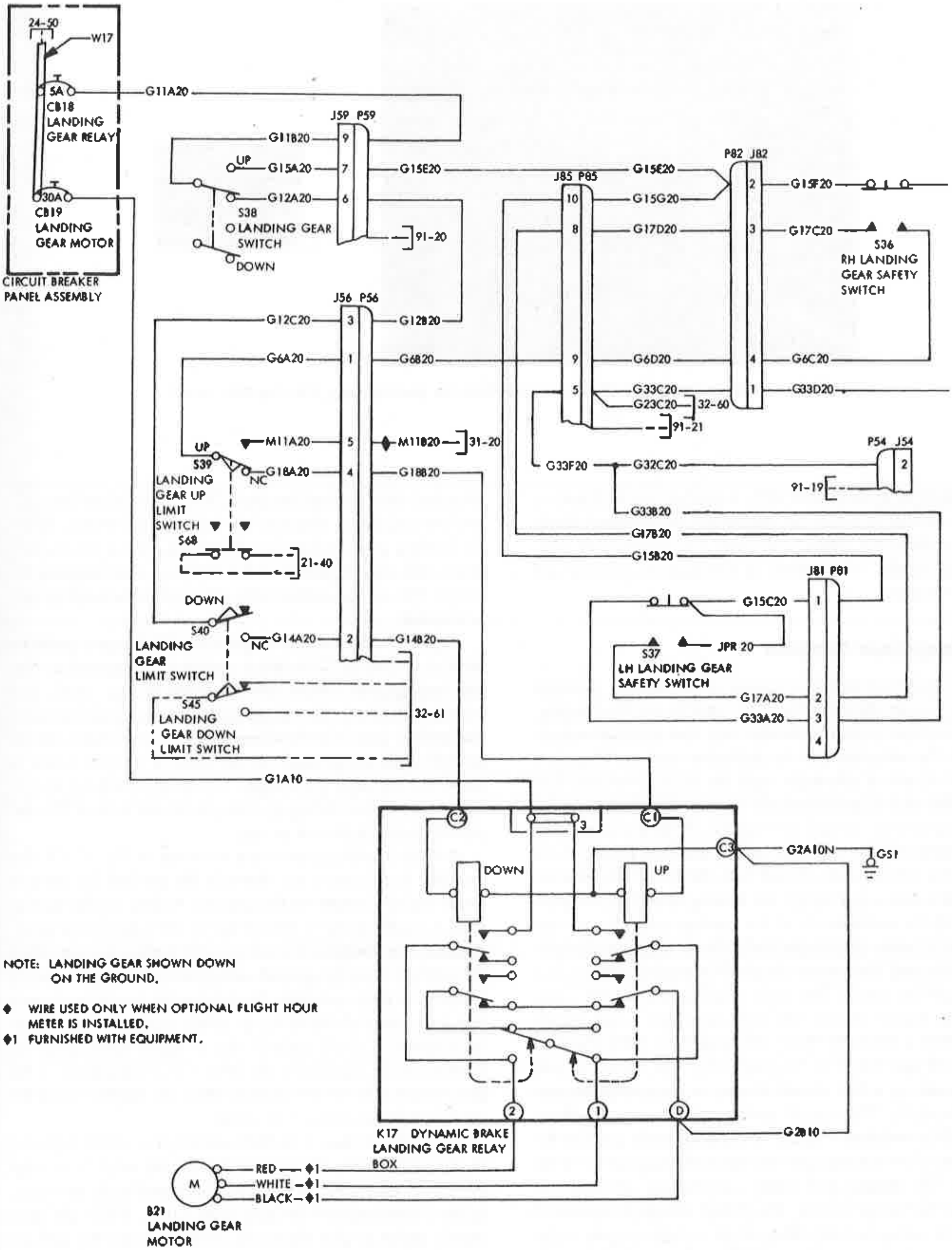

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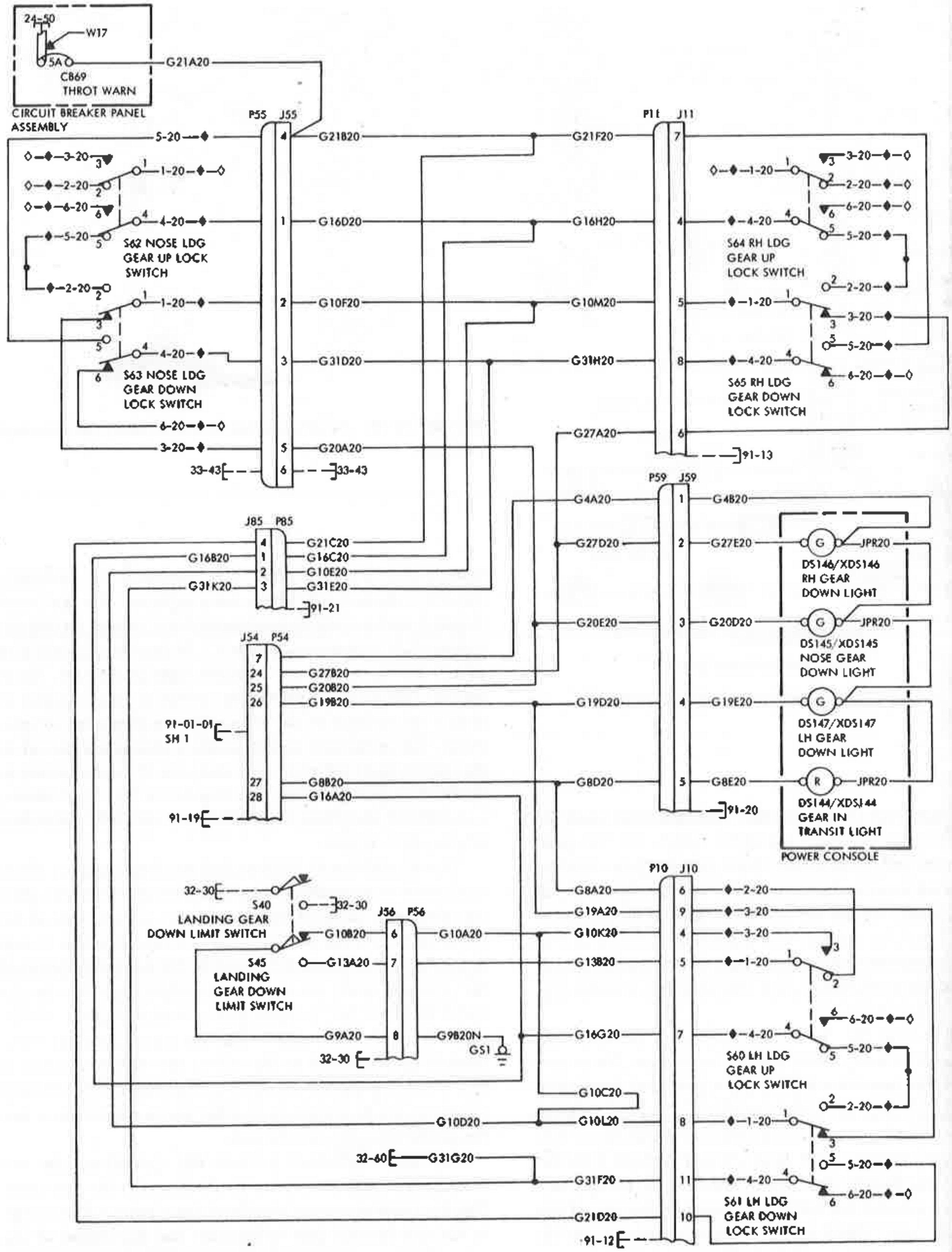
FIGURE 13-11 Landing-gear activating-circuit schematic. (*Beech Aircraft Corporation.*)



NOTE: GEAR SHOWN IN DOWN POSITION ON GROUND.
♦ STAMP REF DES OF APPLICABLE SWITCH ON HEAT SHRINKABLE TUBING & INSTALL ON WIRE FURNISHED WITH EQUIPMENT.
◊ TIE UNUSED WIRES INTO HARNESS. CUT OFF AT SPLICE LOCATION.

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FIGURE 13-12 Landing-gear position-indicating system. (*Beech Aircraft Corporation.*)

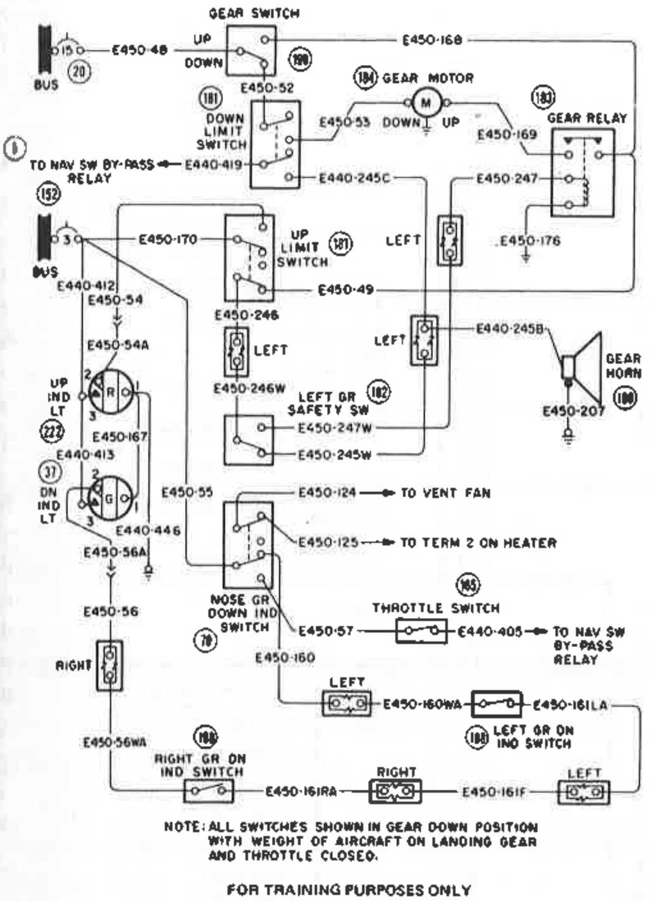


FIGURE 13-13 Landing-gear circuit. (*Cessna Aircraft Corporation.*)

indicator light can come on, three microswitches must be closed. These are the right gear-down switch, the left gear-down switch, and the nose gear-down switch. These switches are connected in series; hence no current can flow in the circuit unless all three switches are closed. In flight, if the throttle is partially closed, the warning horn will sound unless the gear is down. Note that the warning horn must obtain power through one side of the DOWN limit switch. This switch is closed except when the gear is down.

The circuit in Fig. 13-13 incorporates a **press-to-test** light in order to verify correct system operation. The power during normal operation travels from ground to terminal 1 of the light, through the bulb to terminal 2, and through the UP or DOWN limit switch to the positive bus. During the test function the current travels from ground through terminal 1, through the bulb to terminal 3, and directly to the positive bus. To activate the light's test function, the lens of the bulb is depressed, which moves a switch contact inside the light socket from terminal 2 to 3. The pilot would depress this switch during flight operations if he or she suspected a landing-gear retract or extend system failure.

The landing-gear systems found on modern electronic aircraft employ many of the hi-tech components previously discussed in various sections of this text. For example,

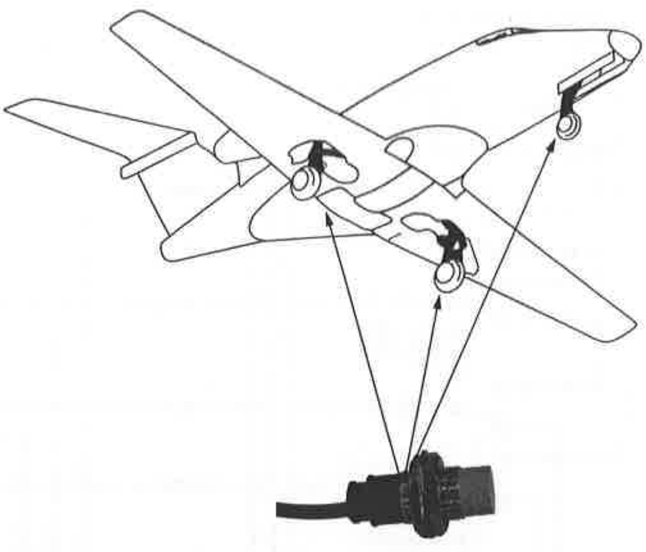


FIGURE 13-14 Proximity sensors used to detect landing-gear position.

landing-gear switches have been replaced by proximity sensors, indicator lights have been replaced with flat panel displays, and a computerized control unit is used for coordination of all components. Figure 13-14 shows the installation of a proximity sensor on a modern light jet aircraft. These sensors, often called **proximity switches**, are installed to detect the position of the retractable landing-gear components. The proximity sensor sends a low-power signal to the control unit; which in turn analyzes all inputs related to the landing-gear position. The diagram in Fig. 13-15 shows a simplified electrical schematic for a digitally controlled landing-gear system.

This aircraft has six landing-gear proximity sensors which send position information to both processors. When the pilot chooses a gear position, the appropriate signal is sent to the processors from the landing-gear selector switches. Using digital logic, the processors analyze the current position of the gear and sends the appropriate output signal to the flat panel displays, the landing-gear actuator circuit, and the warning system as needed. The flat panel displays show landing-gear position to the pilots, the actuator circuit is responsible for movement, gear up or down, and the warning circuit is used to sound a horn if the gear is not extended and the engine throttles are retarded.

The major difference between this system and the two landing-gear systems previously discussed is the processor. This is a microprocessor-based unit that employs digital logic to activate landing-gear indications and movement of the gear. All inputs and outputs of the processor are low-power circuits which allows for smaller wire and reduced weight. All aircraft employ more than one processor to allow for system backups and improved reliability. Although this is a simplified example, most modern aircraft employ a similar type of system.

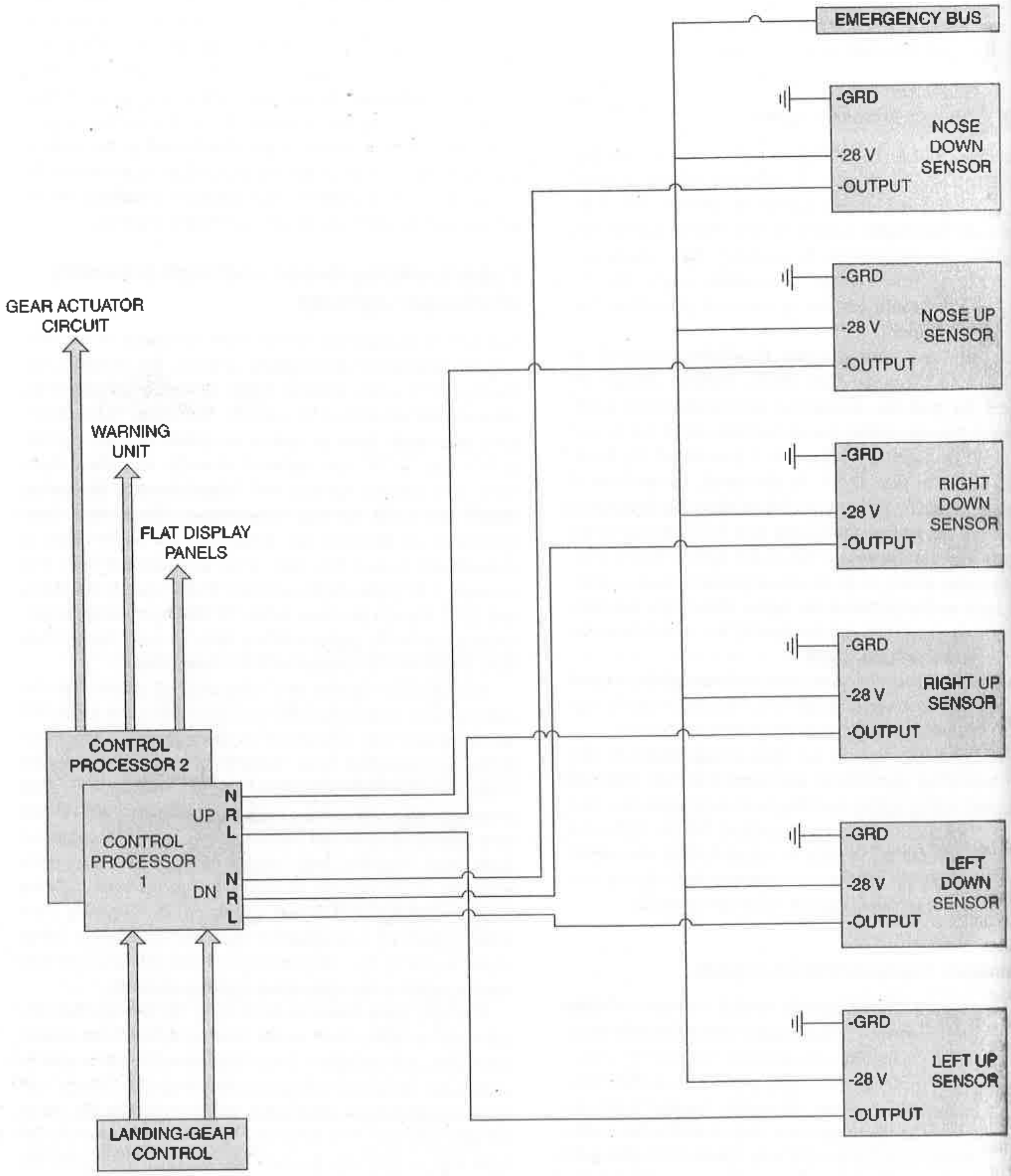


FIGURE 13-15 Digital landing-gear control circuit with six proximity sensors to measure landing-gear position.

LARGE-AIRCRAFT ELECTRICAL SYSTEMS

Lighting Circuits

Like other commercial aircraft systems, lighting circuits are classified into two basic categories, **essential** and **nonessential.** In order to facilitate safety, certain flight deck and cabin lights must be powered by the essential power bus(es), or they must contain their own battery packs. These essential lights, including exit signs and escape slide lights, will remain lit even in the event of a catastrophic electrical failure. Typically, a dedicated battery pack is used to power the emergency lights. The lights can be turned on manually or set to come on in the event of a primary lighting system failure.

Primary (nonessential) lighting systems incorporate several varieties of lights. Generally speaking, there are flight compartment lights, passenger compartment lights, service lights, and exterior lights. There are literally hundreds of lights that operate from either dc or ac electric power.

Flight Compartment Lights

There are four categories of flight compartment lights found on a Boeing 757. The Boeing 757 contains lighting systems typical of those found on all commercial airliners. The flight compartment floodlights consist of two sets of **fluorescent floodlights**, one mounted in the captain's glare shield and one in the first officer's shield. The captain's lights may be connected to the standby ac bus in the event of a primary ac power system failure.

There are also **incandescent floodlights** mounted in the ceiling and under the glare shield. Dimmer circuits are employed for both the fluorescent and incandescent floodlights. Each dimmer system has an override circuit that is used in the event of a dimmer failure. A schematic of the floodlights is shown in Fig. 13-16. As illustrated, the position of the captain's standby relay (upper left of diagram) determines the light's power source. Each light may be connected to the right ac bus or the standby ac bus. If the right ac bus is energized, the relay moves to its abnormal position, thus connecting the right ac bus power to the lights. If the right bus fails, the relay is de-energized, and the standby bus is automatically connected to the lighting circuit.

The flight compartment also contains **dome lights** mounted in the ceiling and powered by 28 V dc. The power can be supplied by either the battery bus or the ground service bus.

Panel lights are used in the flight compartment to illuminate individual instruments and panel lettering. Map and chart lights, utility lights, and threshold step lights may also be located within the flight compartment. All the lights that are in view of both pilots may be controlled by one master dim and test system. The test function is used during preflight inspection to verify that all lights are operable.

Passenger Compartment Lights

Most commercial aircraft contain several varieties of **cabin lights**. Cabin fluorescent ceiling lights with a variable intensity; sign lights, including NO SMOKING, FASTEN SEATBELT, and LAVATORY; and sidewall lights are all controlled from the flight attendants' stations. Passenger reading lights are located above each passenger seat and controlled individually by a switch adjacent to each seat. Entryway lights must also be included in all cabin compartments, along with lights in the galley and flight attendants' stations. Emergency cabin lights include exit sign lights, main aisle area lights, and emergency exit slide lights. Emergency lights typically contain their own power pack.

The fluorescent lights used in the cabin area are located in the sidewall panels or overhead panels of the aircraft. Fluorescent lights are more efficient than the incandescent lights; therefore, they are typically the system of choice. Fluorescent lights require a **ballast transformer** to increase system voltage. The high voltage is used to ionize the gas inside the fluorescent tube, thus producing light. A typical fluorescent lighting system schematic is shown in Fig. 13-17. From this schematic it can be seen that either the ground service bus or the utility bus may supply power for the lights. A bright/dim switch activates the sidewall light control relay, which in turn directs voltage to the ballast. In the dim position, 208 V ac is sent from the sidewall light transformer to the ballast, and the lights are dim. In the bright position, an additional ac voltage is sent to the ballast. This produces a stronger ballast output, and therefore the fluorescent lights brighten.

Light-Emitting Diode and High-Intensity Discharge Lighting

The newest commercial aircraft take advantage of the efficiencies offered by LED lighting systems. For example, the Boeing 787's cabin features LEDs as standard equipment, allowing the aircraft to be entirely "bulb-less." LED lights have previously been an option on Airbus aircraft and the B-777. The B-787 has replaced virtually all cabin, flight deck, and exterior lighting with **high-intensity discharge (HID)** and **LED** lighting technologies. Since these light types have no filament, the operational life of the lights is dramatically longer than that of an incandescent bulb. For example, LED cabin lights will last 50 000 operational hours and LED aircraft position lights 20 000 operational hours. Overall, the B-787 lights will last 10 to 20 times longer than their traditional incandescent bulb counterparts.

As with most circuits on a computerized aircraft, the circuitry used to control the LED and HID lighting on the B-787 are integrated with centralized computer controls. The cabin lights are controlled from multiple locations including the flight deck, the flight attendants' stations, and the individual passenger seats. Of course, each passenger can only control their individual lights and cabin lights are left to the control of flight crew. With this large number of possible control combinations, it has become necessary to operate cabin lighting through a multiplexed digital system. When a lighting command is made by a passenger or flight crew member, a digital signal is sent to the computerized control unit which in turn sends a signal to the appropriate lighting assembly.

The HID lights found on the Boeing 787 are used for various exterior lights, such as the landing lights, wing inspection lights, and taxi lights. These high-intensity lights operate using a gas-filled tube containing two electrodes. A high voltage is supplied to the electrodes, which causes the gas within the tube to ionize. This ionization creates an extremely bright light that is typically focused into a beam by a parabolic reflector mounted near the tube. This type of light requires a high-voltage power supply to produce the current flow.

Other Lights

Other lighting circuits common to large aircraft include service lights, cargo lights, and exterior lights. **Service lights** are located in the main and nose gear wheel wells, in electric equipment compartments, and in some engine compartments. The power for service lights is typically supplied by the ground power equipment through a ground service bus.

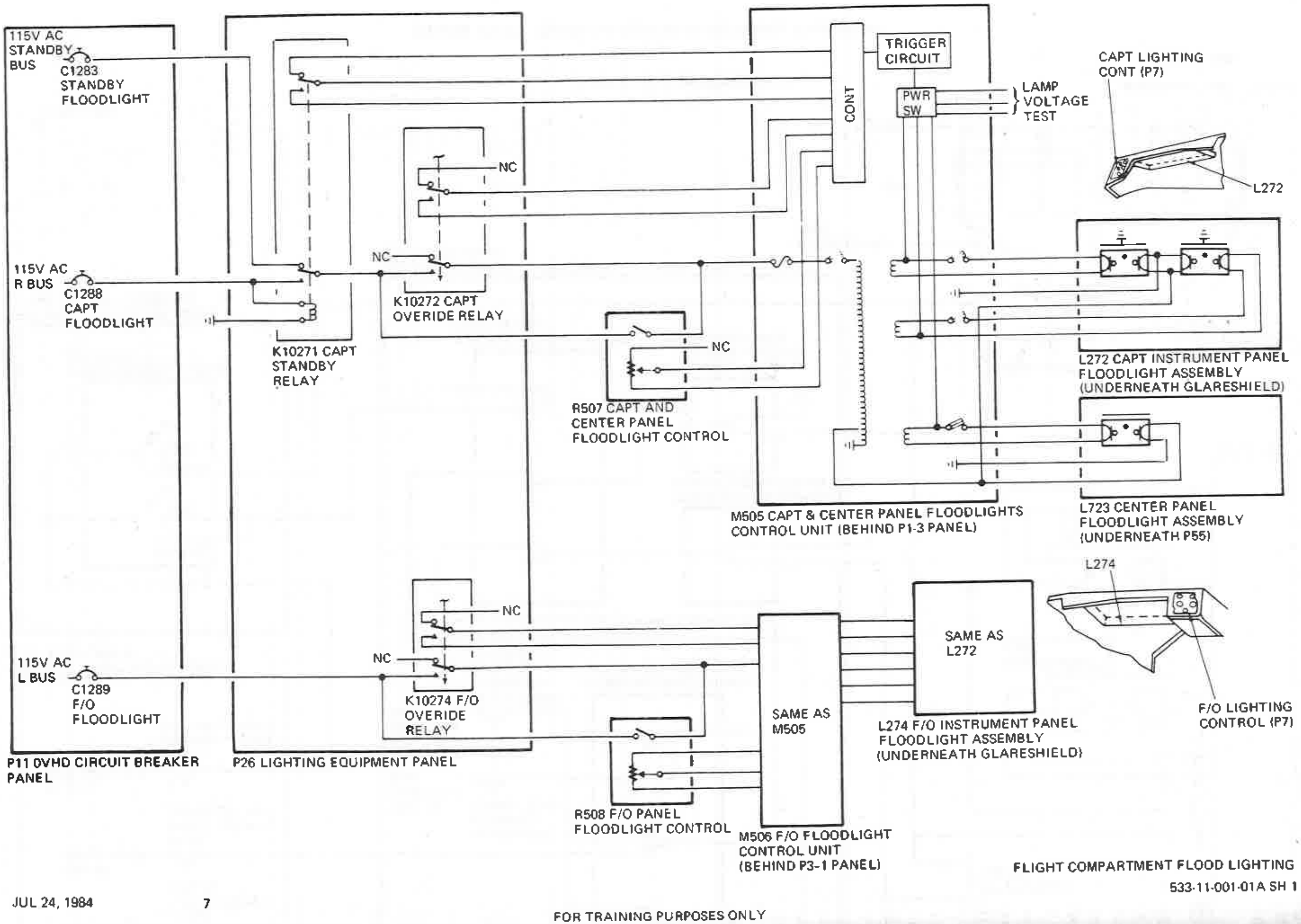


FIGURE 13-16 Floodlight circuit. (Boeing Corporation.)

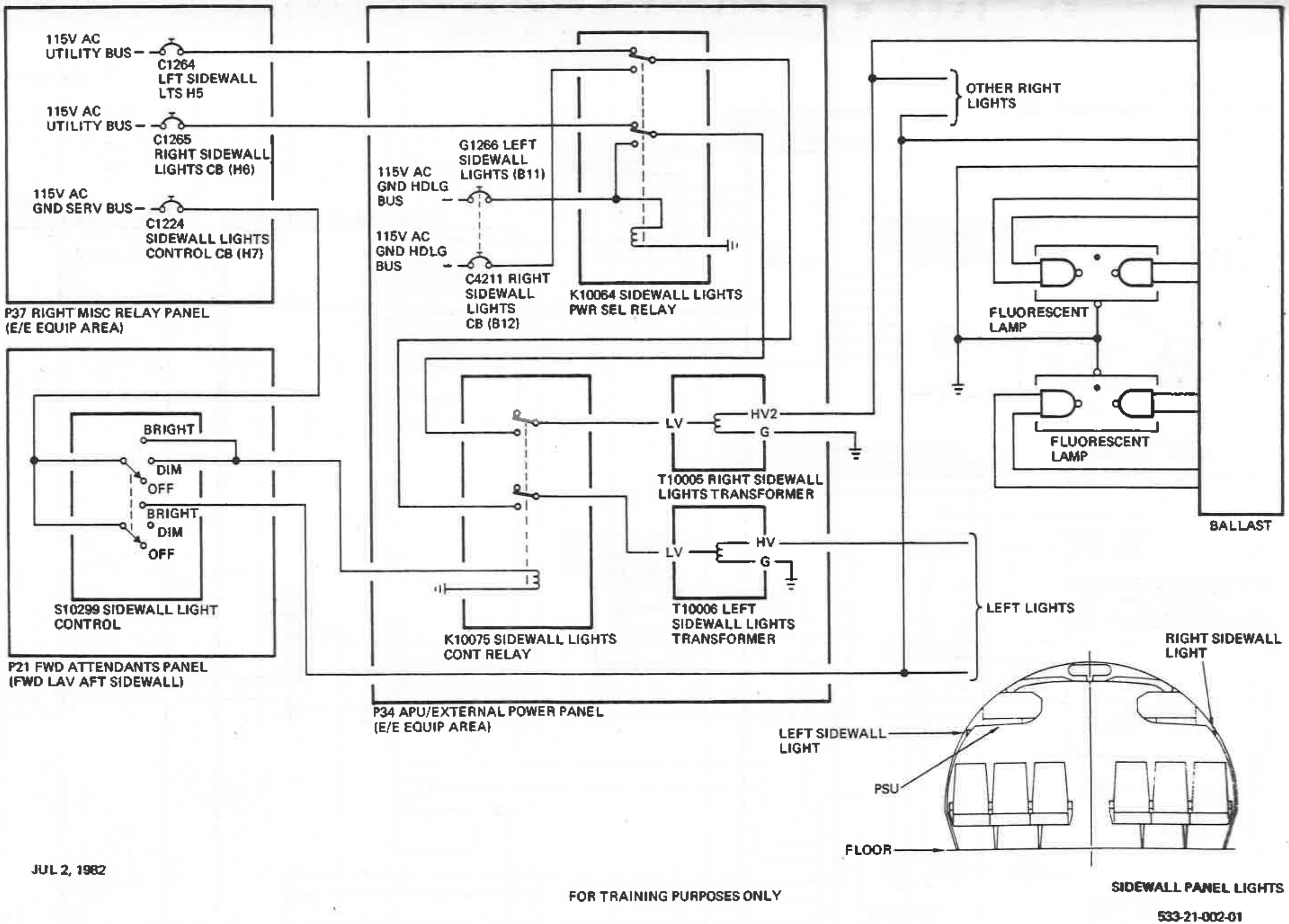


FIGURE 13-17 Fluorescent lighting circuit. (*Boeing Corporation.*)

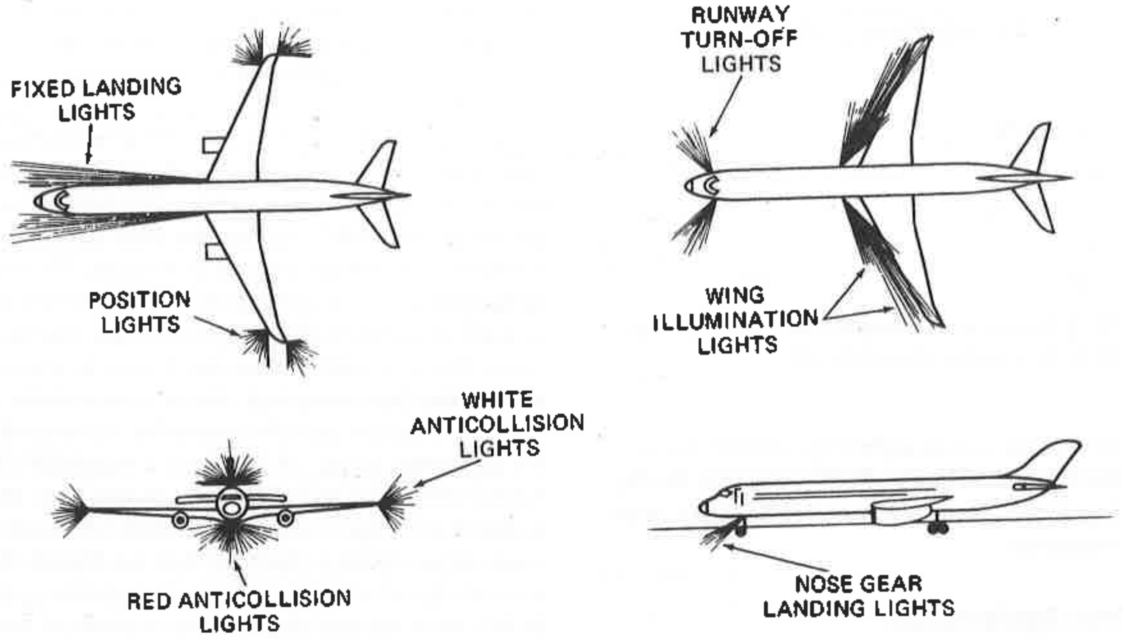


FIGURE 13-18 Typical exterior lighting locations and illumination path.

Cargo compartment lights are used on most commercial aircraft to aid in the handling and storage of cargo. Typically, an ac ground power source is used to provide power for cargo compartment lights. Several lights are used in each compartment in order to supply adequate illumination.

Exterior lighting circuits often include wing illumination lights, landing lights, runway turnoff lights, anticollision lights, and position lights. Figure 13-18 illustrates these lights and their respective illumination paths. Wing illumination lights are designed to illuminate the leading edges of the wings for inspection by ground service personnel or flight crew members. The leading edge of a wing is very susceptible to ice formation and is often visually inspected to ensure that ice has not accumulated.

Large aircraft often contain three or more landing lights. Figure 13-18 shows two wing-mounted lights and one nose gear landing light. On some aircraft these lights are automatically dimmed if the landing gear are retracted.

Runway turnoff lights are used to provide illumination of the area to the immediate right and left of the aircraft. These lights are used during taxiing operations to improve ground visibility.

Anticollision lights are mounted on each wingtip and on the top and bottom of the cabin. Red rotating beacons or flashing lights are typically located on the cabin. White flashing, or strobe, lights are located on the wingtips.

As noted earlier, position lights are designed to indicate an aircraft's position and direction. A white light must shine toward the rear of the aircraft, a red light must shine left, and a green light must shine right. On the aircraft shown in Fig. 13-18, the wingtip contains both the white and colored position lights. The red (or green) light shines forward and to the side of the aircraft. The white light illuminates an area toward the rear of the aircraft wing.

A variety of lighting circuits are found on large aircraft. Many of these have been discussed in this chapter; however, it is impossible to cover all types and combinations of lights.

Always refer to the current manufacturer's data when servicing any lighting equipment.

Landing-Gear Control Circuits

On large aircraft, landing-gear actuators are hydraulically operated. The electronic circuitry of the system is used to provide an indication of gear position and in some cases to control the hydraulic system components. On some aircraft microswitches are tripped when the landing gear reaches its limit. These switches turn off the hydraulic pump motor and turn on the correct gear indicator in the flight compartment. These systems are very similar to those found on light aircraft.

Another means of controlling landing-gear actuator and indicator systems employs **proximity sensors**. The simplest proximity sensors are inductance coils that operate in conjunction with metal targets. The inductance of a coil changes with the proximity of the target. As discussed earlier, the inductance of any coil is a function of the core material. If the steel target acts as the core for the proximity coil, the inductance of the coil changes as the target moves farther from or closer to the coil. A diagram of a proximity sensor is shown in Fig. 13-19. The advantage of these sensors is that there are no moving switch contacts to fail; therefore, the reliability of the system is improved as compared with the performance of systems that employ limit switches.

The inductance of a proximity sensor is measured by an electronic control unit. This unit interprets the input data (some from the proximity sensors) and sends out control signals to the landing-gear actuator and indicator systems.

The Boeing 757 aircraft contains a **proximity switch electronic unit** (PSEU), which provides position sensing for landing gear, cabin doors, and thrust reversers. The system

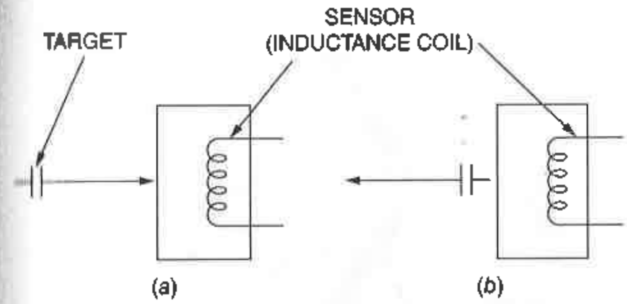


FIGURE 13-19 Proximity sensor diagram. (a) Target moving toward coil; (b) target moving away from coil.

contains 70 sensors located throughout the aircraft that provide input data for the PSEU. The PSEU processes the discrete input signals and controls relays, lights, and/or other electronic components.

Built-In Test Equipment

Large aircraft often incorporate **built-in test equipment** (BITE) systems to monitor and detect faults in a variety of aircraft systems. The use of BITE systems reduces troubleshooting costs by eliminating the time required to connect carry-on test equipment, perform tests, and analyze the fault. The built-in test equipment continuously tests the various systems and stores all fault information so it can be recalled later by line technicians. Once the appropriate repair has been made, the BITE system can be used to retest the system for proper operation. Most BITE systems are capable of isolating system faults with at least a 95 percent probability of success on the first attempt.

The introduction of digital systems on aircraft has made BITE systems possible. Discrete digital signals are used as the code language for BITE systems. Built-in test equipment interprets the various combinations of digital signals to determine a system's status. If an incorrect input value is detected, the BITE system records the fault and displays the information upon request. As shown on this version of a BITE system illustrated in Fig. 13-20, the fault information is displayed by light-emitting diodes on the face of the BITE unit when the appropriate button is depressed.

Another built-in troubleshooting system common on modern aircraft is known as the central maintenance computer system (CMCS). Virtually all complex digitally controlled aircraft now employ an integrated built-in test system; this means all BITE functions that were previously located throughout the aircraft are now centralized. The exact name of the centralized test system may be different between manufacturers or even aircraft; however, the basic functions are the same. That is, a computer system is used to monitor faults, analyze the data, store fault data in a nonvolatile memory, and allow access to this information for system troubleshooting and repair. Figure 13-21 shows a simplified CMS for a typical transport-category aircraft. As seen here, the central maintenance computer monitors a variety of aircraft systems, sends output signals to the flight deck for display of standard and warning information, and can send reports to the ground facility or an onboard printer. Most centralized systems can be accessed from several different locations often called central control display units; wireless access is also available on most modern aircraft like the B-787. Also, fault data can be transmitted to a ground facility during flight through the use of a satellite or other radio systems. This allows for faster repairs, less aircraft downtime, and greater productivity for the airline. It should be noted that Fig. 13-21 is intended to present concepts only; the actual aircraft would contain several additional computers and control systems for operation of a complete CMS. More complete details on design, functions, and use of computerized systems will be presented in the remaining chapters of this text.

Intercom and Interphone Systems

The **intercom** system is used for communication between flight crew personnel and passengers. This system typically contains a control panel and microphone at one or more flight attendants' stations and in the flight compartment.

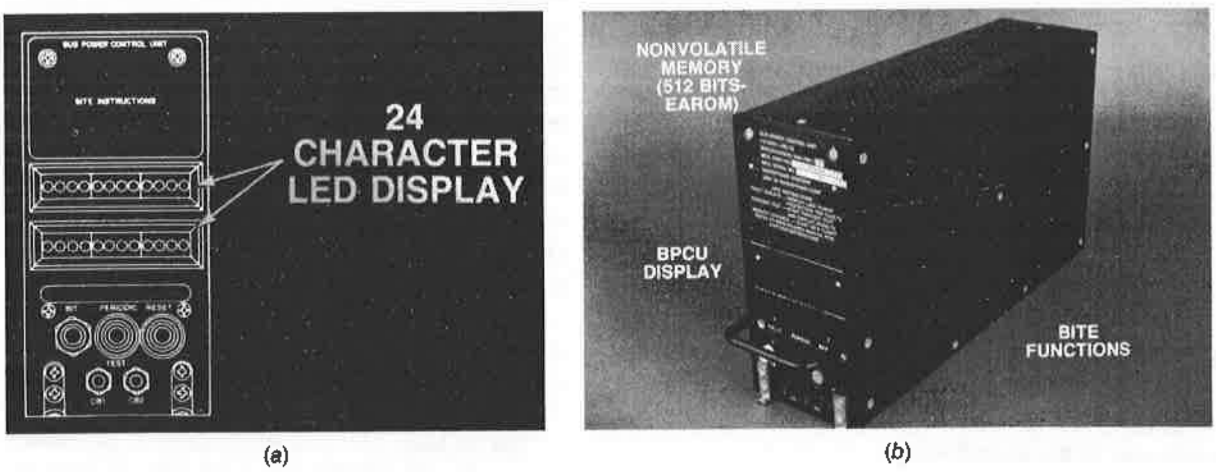


FIGURE 13-20 Built-in test equipment. (a) LED display (b) bus power control unit with BITE display.

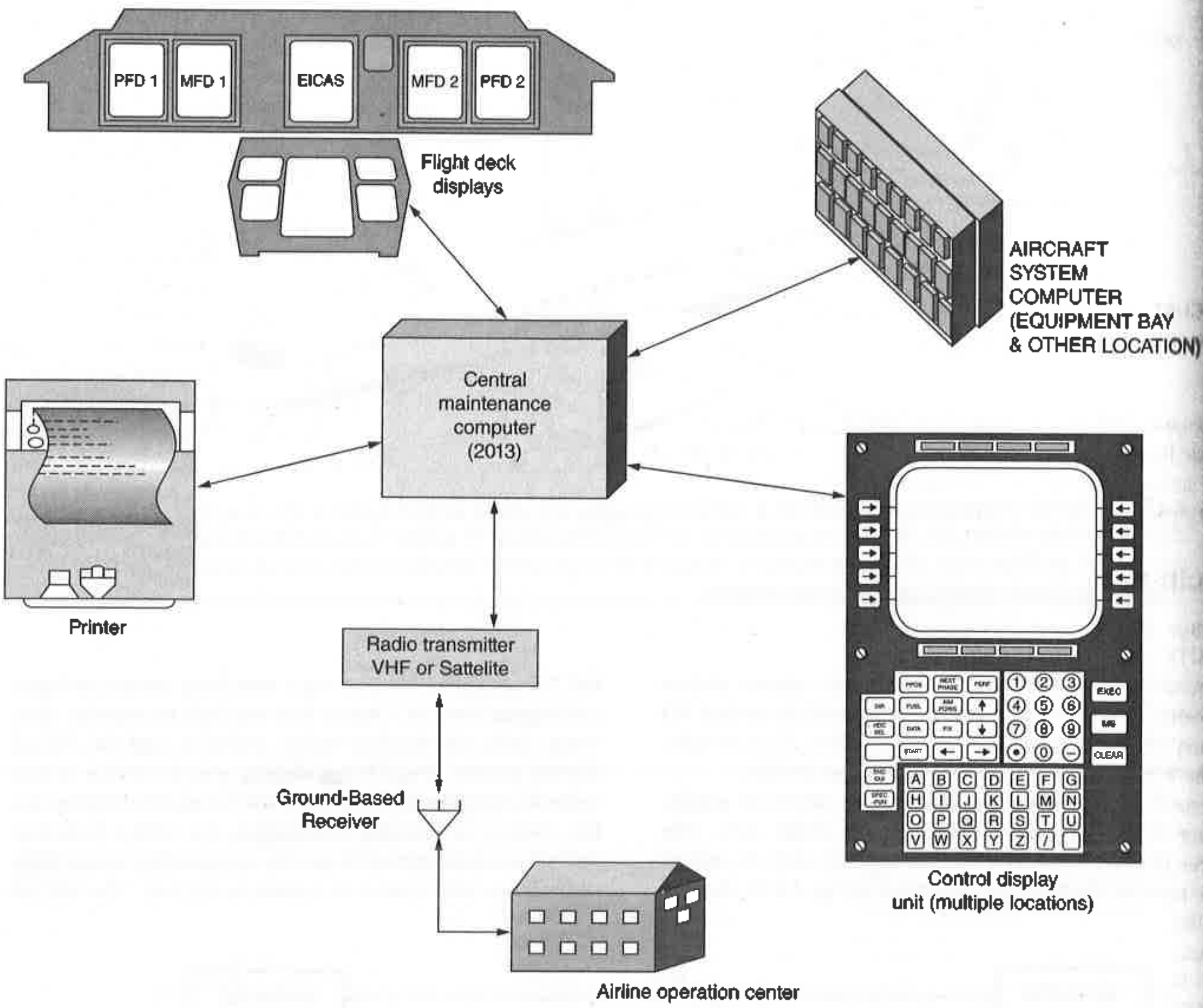


FIGURE 13-21 Major elements of a central maintenance system.

The intercom is used to inform passengers of flight details and communicate any instructions necessary to ensure a safe and comfortable flight. On most aircraft there is one central intercom amplifier, which connects to several speakers throughout the aircraft. The amplifier's volume level is automatically adjusted to compensate for varying cabin noise.

An **interphone** system provides a means of communication between flight crew members and ground service personnel. Communication during fueling, ground handling, and baggage storage is essential. On a large aircraft it is virtually impossible to communicate from the cockpit to areas outside the aircraft without some form of assistance. The interphone system contains an amplifier and several stations where a headset, containing a microphone and speaker, can be connected to the system.

The interphone system can also be used during aircraft maintenance. Figure 13-22 shows the interphone configuration for a typical Boeing 737. If communication is needed between maintenance personnel inside and outside the aircraft, the interphone system is typically used. The system receives power from the ground service bus; thus it can be operated without use of the aircraft's generators.

Electronic Control Units

On modern large aircraft there are several types of control units used to monitor, test, and regulate various electrical systems. These control units, commonly known as LRUs, are miniature computers designed for a specific function. Typically, LRUs are designed for quick removal and installation. Employing the LRU concept has helped to reduce maintenance times and improve airline productivity. Several of these control units are found on modern commercial aircraft. The **control maintenance computer (CMC)**, **generator control unit** (GCU), and **ground power control unit** (GPCU) have already been discussed.

Other common control systems include the **thrust management computer** (TMC), which is used to analyze engine parameters and power requests in order to control engine thrust, and the **flight management computer** (FMC), which monitors flight parameters and performs autopilot functions.

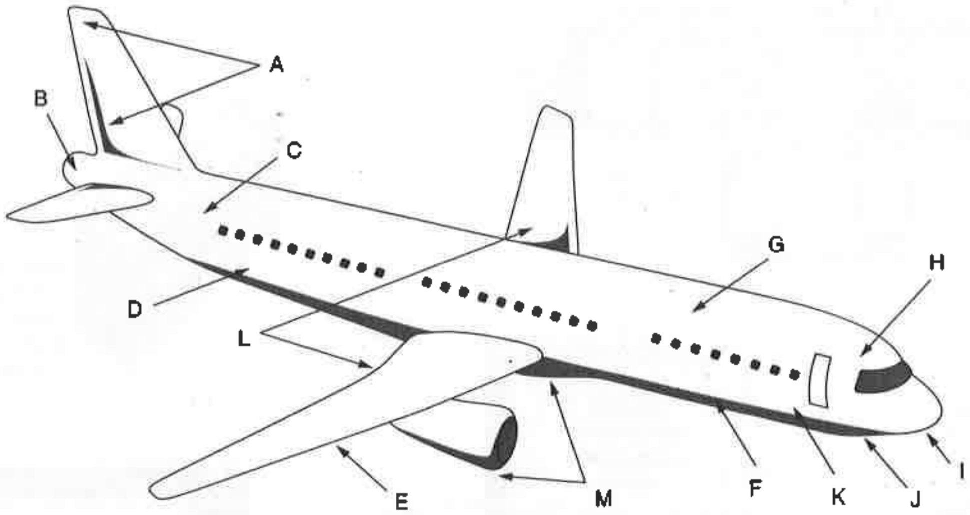


FIGURE 13-22 Typical interphone connections on a transport-category aircraft: (*a*) vertical stabilizer; (*b*) aft accessory compartment; (*c*) aft flight attendants station; (*d*) aft cargo compartment; (*e*) Fuel control panel; (*f*) forward cargo compartment; (*g*) forward flight attendants station; (*h*) flight deck; (*i*) forward accessory compartment; (*j*) ground handling access panel at nose landing gear; (*k*) electronics bay; (*l*) main landing gear; (*m*) main engines.

The FMC regulates the movement of the control surface actuators. These actuator mechanisms provide control for most primary and secondary control surfaces, such as stabilizers, elevators, rudders, speed brakes, and spoilers.

EICAS control units monitor various electrical parameters and display system status to the flight crew. The EICAS is also responsible for alerting the crew in case of an emergency situation. As illustrated in Fig. 13-23, the two EICAS computers receive input data from various airframe and engine sensors. Output data are sent to warning electronic units, the standby engine indicator, and the EICAS display panels. The EICAS display panels consist of two cathode-ray tubes (CRTs). Each CRT is used to display status, caution, or warning information. On Airbus Industries aircraft a similar system is used to monitor engine and flight parameters. This system is known as ECAM. The EICAS

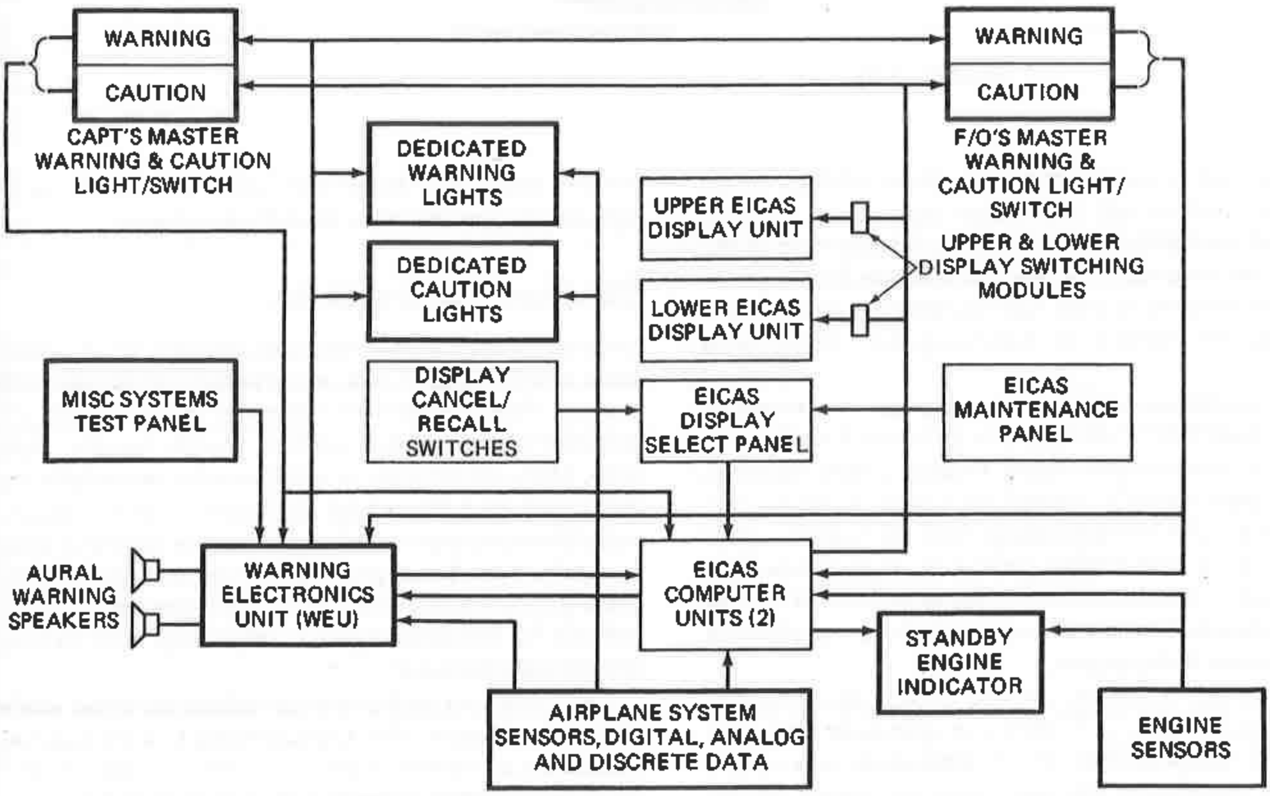


FIGURE 13-23 Block diagram of engine indicating and crew alerting system. (*Boeing Corporation*.)

and the ECAM system will be discussed in greater detail in Chap. 17.

Equipment Cooling

Heat is an electronic unit's biggest enemy; therefore, most aircraft contain some means of electronic-equipment cooling. Since large aircraft contain numerous electronic LRUs, they are, for the most part, centrally located. Typically, this equipment compartment is behind and/or below the aircraft's flight deck. Some large transport-category aircraft use multiple equipment bays. For example, the Airbus A-380 contains two main equipment bays; one on the upper deck and one on the lower deck. The use of a centralized equipment center enables cooling with a minimum of air ducts.

Cooling fans and air ducts are commonly employed to force air over the warm equipment and dispense the heat overboard. In some cases heat exchangers are used to cool the warm air and recirculate it back over the equipment. On some aircraft separate air-conditioner units are used to ensure proper equipment cooling. In this case the warm air is circulated through the air conditioner, and the cool air is returned to the equipment compartment.

Most equipment-cooling systems also employ overheat and smoke detector sensors. These sensors monitor the system and provide an appropriate indication for the flight crew. The flight crew may then take the appropriate actions to ensure proper system operations.

Pressurized air can also be used to cool electronic instruments. Cooling air is forced into a plenum chamber created by an inner and outer instrument panel. As illustrated in Fig. 13-24, holes in the inner panel direct air over each instrument. This process improves instrument cooling and enhances the reliability of the instruments.

Static Dischargers

During flight, aircraft produce **precipitation static** through contact with rain, dust, snow, and other particles. Precipitation static **(P-static)** can also be created by the movement of jet exhaust over the aircraft's surface. P-static may occur in either large or small aircraft; however, it is only prevalent on relatively high-speed vehicles. At high speeds the friction between the air and the aircraft's surface increases. It is this friction that produces a static electrical charge on the aircraft's surface.

The static charge itself poses little threat to flight safety; however, the discharge of the P-static back into the air creates problems. As the P-static "jumps" from the aircraft to the air, a low-frequency magnetic wave is produced. This magnetic wave creates radio interference identical with that produced by a lightning bolt discharge, except that P-static discharge creates a weaker interference signal.

Radio interference can also be created as a static charge moves from one portion of the airplane to another. As discussed in Chap. 12, electrical bonding techniques are used to eliminate static discharge between aircraft components.

The correct use of static dischargers is vital to proper P-static control. Static dischargers reduce the threshold at which the P-static leaves the aircraft. In other words, a lesser amount of static charge must accumulate before it discharges back into the air. This lower level of discharge current produces a lower level of radio interference. If the discharge is controlled to a low enough value, the radio interference becomes negligible.

Static dischargers are located at numerous places on an aircraft, as illustrated in Fig. 13-25. P-static tends to accumulate on the tips and trailing edges of wings, on control surfaces, and on horizontal and vertical stabilizers. Dischargers located in these areas have the greatest potential to reduce radio interference. As shown in Fig. 13-26, dischargers are typically mounted to a retainer. The retainer is permanently mounted to the aircraft's surface. This facilitates discharger replacement in the event the discharge pins become damaged or pitted from use. Always inspect the static dischargers at the appropriate time intervals and in accordance with

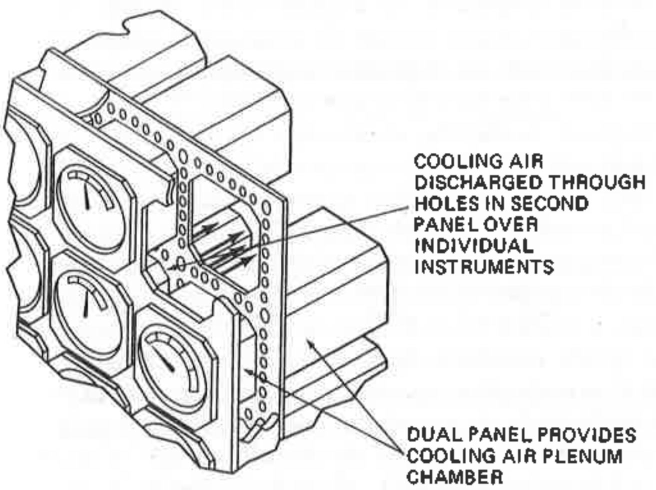


FIGURE 13-24 Instrument cooling system. *(Boeing Corporation.)*

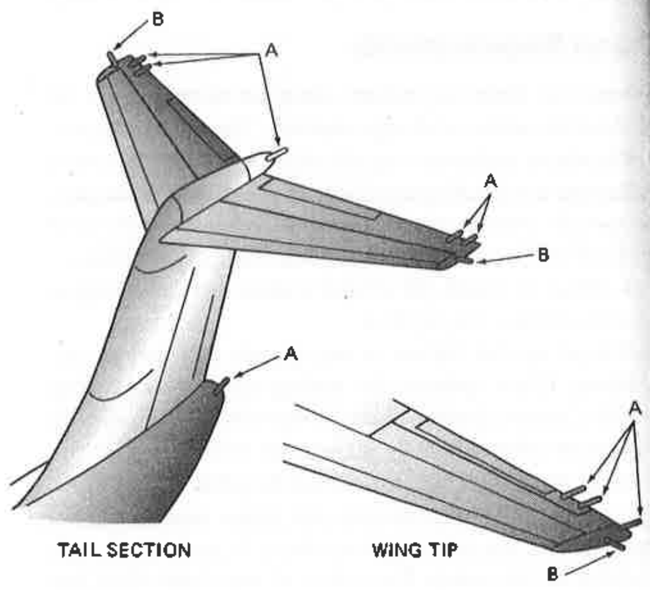


FIGURE 13-25 Typical location of static dischargers. (*a*) Trailing type and (*b*) tip type.

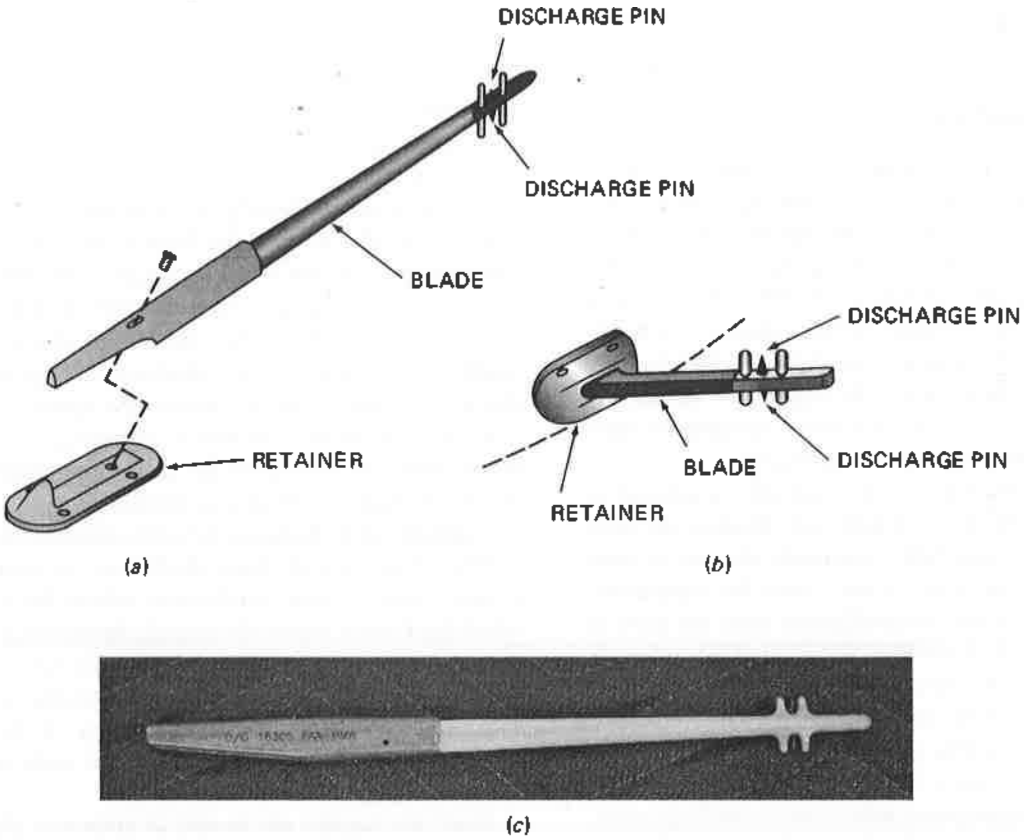


FIGURE 13-26 Typical installation of static discharger: (*a*) Trailing type; (*b*) tip type; (*c*) photograph of complete assembly. (*Dayton Aircraft Products.*)

the manufacturer's recommendations. Figure 13-26*c* is a photograph of a typical static discharger.

MAINTENANCE AND TROUBLESHOOTING OF ELECTRICAL SYSTEMS

General Requirements

To ensure safe flight operations, electrical systems must be maintained in perfect working condition. The routine inspection procedures performed on all aircraft are used to detect any potential electrical system failures. During these inspections, specific electric components are inspected and tested as directed by the current technical documents. If a malfunction or defect is found, the proper maintenance procedures are used to correct the problem.

Electrical system failure is not always detected during inspections. Often systems fail during operation and must be repaired prior to further flight. Maintenance of this type is usually more critical; that is, the aircraft downtime must be as short as possible. Unexpected maintenance causes flight delays, passenger inconvenience, and lower profit margins. Maintenance of electrical systems must be performed with both speed and accuracy. The safety of any flight often lies in the hands of the aircraft technician. Be sure to perform all maintenance procedures and electrical system inspections in accordance with the manufacturer's recommendations and to the best of your ability.

Modern aircraft are built with a fail-safe design to help ensure the safety of all passengers. This design concept typically means that for all critical systems the aircraft will contain multiple components that perform the same task. In the event of a system or element failure, another backup component is automatically, or manually, set to take over. On transport-category aircraft, the most critical systems typically contain a primary and two backup systems. One major advantage of multiple systems is the ability to dispatch an aircraft even if one or more components are inoperative. For example, on most transport-category aircraft, the plane can be safely and legally flown with one inoperative engine-driven ac generator; the APU generator will be used as backup.

Whenever performing maintenance on any aircraft, it becomes very important to repair critical systems; however, on many aircraft one or more system failures may not be critical. In order to determine airworthiness status of an aircraft with a defective system, the technician must consult the **minimum equipment list (MEL)** for that aircraft. The MEL contains a detailed list of all necessary equipment and under what specific conditions the aircraft can be dispatched. In short if an inoperative system is not listed as a "NO-GO" item by the MEL, the aircraft can safely fly. During a quick turnaround between flights if the aircraft can still be dispatched according to the MEL, the repair of noncritical systems will be deferred until the next maintenance opportunity.

Inspection Schedules

By mandate of the FAA flight regulations, all civilian aircraft must be inspected in accordance with a schedule set forth by an approved inspection program. The **100-hour**, the **annual**, or the **periodic inspection program** can be used for light-aircraft inspections. Each of these programs is designed to instruct the aircraft technician as to which systems and components require routine maintenance and/or inspection.

Large aircraft are typically maintained according to one of the inspection programs approved by the FAA. These programs, known as **continuous airworthiness inspection programs**, include various routine service inspections and more complete maintenance procedures. Traditionally **A-check**, **B-check**, **C-check**, and **D-check** have been designed to meet the specific needs of a given aircraft and operator. The A-check was the simplest and conducted most often, every 200 to 500 flight hours. The D-check was often referred to as "heavy maintenance" because many of the large and heavy systems were removed and/or inspected during this phase. A traditional D-check often required 7 to 10 days for completion. Many inspection schedules still follow this scenario, especially on older aircraft; however, this is beginning to change. With the help of new technologies, improved aircraft designs, better system monitoring capabilities, and more LRUs, there is less need for scheduled inspections. Today the concepts of **reliability centered maintenance** and **advanced component monitoring** allow aircraft to fly more hours and received less maintenance while at the same time improving safety. Better system analysis using improved sensor technologies, CMCSs, and instant wireless downloads permit airlines to conduct most maintenance as needed; not according to a certain schedule. And, since most aircraft are now designed for ease of maintenance, extended inspection and repair time is unnecessary. Today, it is estimated that aircraft like the B-787 will fly close to 10 to 12 years before requiring a classic heavy maintenance hangar visit.

On large aircraft the use of built-in test equipment and central maintenance computer systems often facilitates an inspection. The technician can quickly and easily inspect an electrical system by examining the fault data stored by the test equipment. If a fault is stored within the system's memory, the technician can make necessary repairs during the inspection. The current trend in the aircraft industry is to employ more BITE systems wherever possible. This is being done in an effort to reduce maintenance costs and aircraft downtime. Many of these systems allow for downloads of maintenance data using a secure wireless connection and a laptop computer. If the aircraft and airport facilities are so equipped, the most modern systems allow the aircraft to download data automatically or upon request before the aircraft even parks at the gate.

Light aircraft are often maintained on an annual or 100-hour inspection basis. During an inspection of this type, the entire aircraft is inspected, including the electrical systems. All electrical systems, their components, and related wiring should be checked in accordance with the inspection schedule. Typically, an operational check of all electrical systems is conducted. Any defects are repaired, routine maintenance is performed, and all life-limited parts are replaced.

Life-limited parts are those that deteriorate beyond use in a given length of time. For example, emergency lighting system batteries are often considered life-limited parts; that is, they must be replaced on or before specific dates. Routine maintenance of electric components may include servicing batteries, lubricating bearings, and replacing generator brushes. Inspections of electrical systems include an operational check and a visual inspection. While performing a visual inspection, the technician should look for loose connectors chafed wires, poor electrical bonding, loose bundle supports, nicked or damaged wire insulation, and any other obvious defects.

Multimeter Troubleshooting

As discussed in Chap. 8, a multimeter is a combination of three basic instruments: an ohmmeter, a voltmeter, and an ammeter. This combination instrument has made it possible for the technician to reduce his or her inventory of test instruments. Each of the three instruments contained within a multimeter performs a specific function. A common **digital multimeter (DMM)** is shown in Fig. 13-27; meters were previously discussed in Chap. 8. Of the three instruments contained within a typical DMM, the voltmeter is by far the most useful tool to detect an open circuit. **Open circuits** (opens) are the most common wiring defect. Open circuits are created by broken wires, defective connectors, loose terminals, and any other

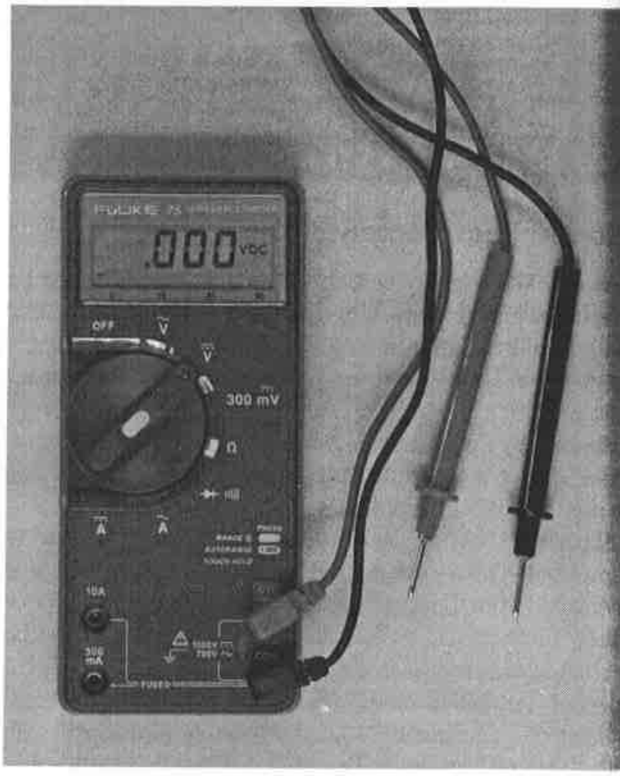


FIGURE 13-27 A common digital multimeter (DMM) and test probes.

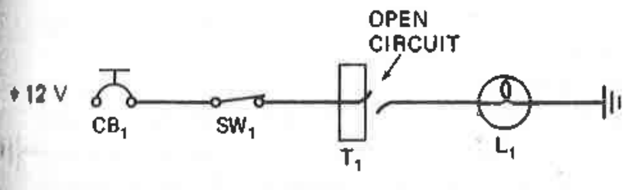


FIGURE 13-28 Diagram to illustrate an open circuit.

condition that creates a circuit disconnection (see Fig. 13-28). Opens can also occur within components such as switches, fuses, circuit breakers, lamps, or motors. An open circuit will always cause a circuit or portion of that circuit to be inoperative. An open circuit is basically an infinite resistance caused by the fault. Although opens can technically occur anywhere along a wire or within a component, they commonly happen adjacent to a connector plug or wire termination point. That is, the wire comes loose from the crimped or soldered connection. Whenever troubleshooting an open circuit, consider the wire termination points to be the most likely location to find the defect. Connector pins and sockets should also be considered a likely spot for an open circuit.

Short circuits (shorts) are also common problems for aircraft electrical systems. There are two types of short circuits, a short to ground and a cross short. A **short to ground** from a positive wire creates an infinite current flow because of the extremely low resistance from the voltage positive to negative (see Fig. 13-29). In Fig. 13-29*a*, the wire broke, forming an open circuit; the conductor exposed by the break then shorted to ground by touching the nearby metal airframe. In Fig. 13-29*b*, the wire's insulation failed and exposed the conductor; the exposed conductor shorted to ground on a nearby metal component. The high current flow opens the circuit protector (the fuse or circuit breaker). If the circuit is not protected, the wiring will overheat and most likely melt into a disconnection. A **cross short** takes place when two or more circuits are accidentally connected together (see Fig. 13-30). In this situation, when one circuit is switched on, more than one circuit operates, or the entire circuit may become inoperative. A cross short connects power to an "extra" circuit. Short circuits are most likely created by the friction between two wires or between a wire and the airframe. The friction wears through the insulation, and the conductor is exposed,

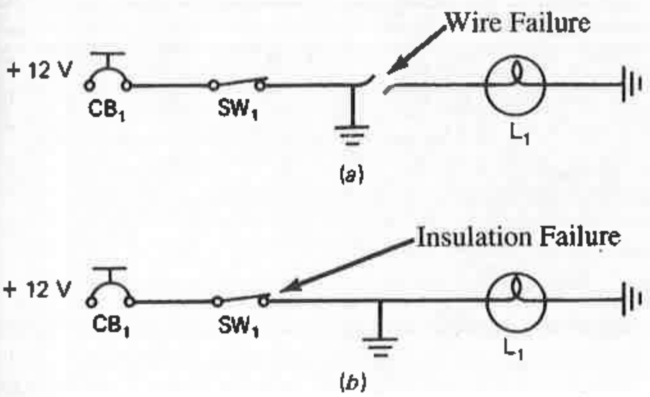


FIGURE 13-29 An illustration of a short to ground (a) created by a broken wire and (b) created by defective insulation.

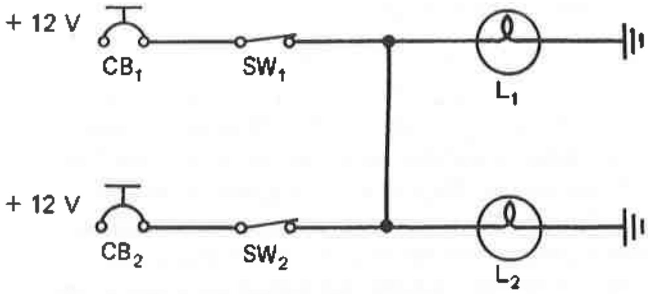


FIGURE 13-30 An illustration of a cross short. Both L_1 and L_2 illuminate when SW_1 or SW_2 is closed.

thus creating the potential for a short circuit. An ohmmeter is usually used to troubleshoot both types of short circuits.

When a short circuit occurs between a positive wire and a ground (most likely the airframe), the circuit will always blow a fuse, or open (pop) the circuit breaker. When a short circuit occurs between two different circuits, a fuse or circuit breaker may open; or the two circuits may operate simultaneously. Remember when troubleshooting, if the fuse or circuit breaker is open or if two circuits operate abnormally, the fault is most likely a short. If the system does not operate and the fuse or circuit breaker is OK the fault is most likely an open circuit.

Voltmeter Troubleshooting

Voltmeters are always connected in a circuit in parallel with respect to that portion of the circuit to be measured. If one probe of a voltmeter is connected to a positive voltage and the other probe to a negative voltage, the meter will indicate the voltage difference between those two points. Voltage, as you may recall, is the difference in electrical pressure between two points.

It one desires to measure the voltage available to the lamp represented in Fig. 13-31*a*, the voltmeter should be placed

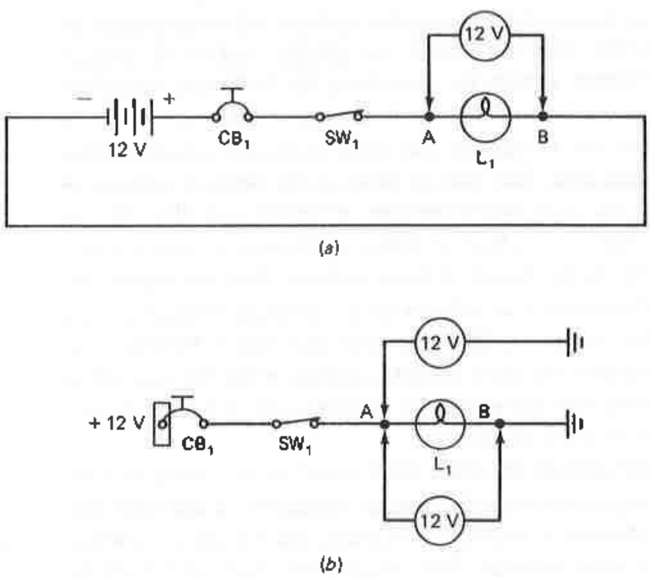


FIGURE 13-31 Measuring the voltage available to a light (a) in a two-wire system and (b) in a single-wire system.

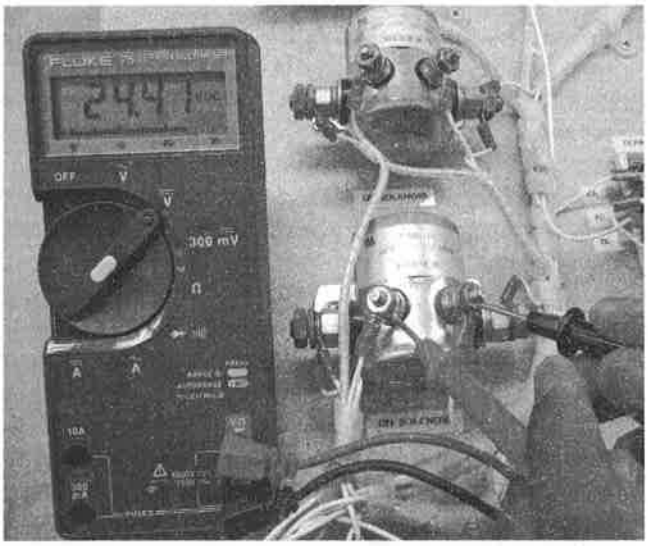


FIGURE 13-32 Digital multimeter connected to the terminals of a solenoid circuit to measure voltage. See also color insert.

between points *A* and *B*. Point *A* is connected to the positive of the battery, and point *B* is connected to the negative of the battery. In this case the voltmeter would indicate 12 V.

The simplified circuits shown in this section of the text are for explanation of DMM connections; a typical aircraft circuit would likely be more complex. The actual placement of all DMM connections must take place at a connector or terminal strip within the circuit. The technician must never strip wire insulation in order to connect a meter. Connector plugs and other types of wire termination points are excellent places to install a meter for troubleshooting purposes. Figure 13-32 shows a DMM connected to the terminals of a solenoid circuit; the DMM probes are connected at wire termination points.

In an aircraft most circuits are connected from the positive bus through a load to the aircraft's ground, as shown in Fig. 13-31*b*. Since the negative connection of the battery is connected to the aircraft's ground, a voltmeter connected between points *A* and *B* will indicate 12 V, and a voltmeter connected between point *A* and the aircraft's ground will indicate 12 V. The fact that the entire metal structure of the aircraft is connected to the battery negative makes the voltmeter a very versatile tool. As illustrated in Fig. 13-33, a voltmeter can be connected to any convenient ground in order to find the positive voltage present in a circuit. Voltmeter V_1 indicates 12 V, V_2 indicates 12 V, and V_3 indicates 12 V. Voltmeter V_4

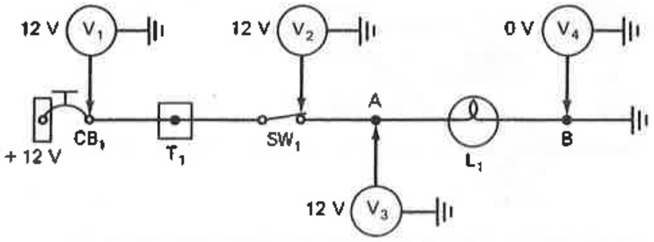


FIGURE 13-33 Voltmeters used to test voltage in a circuit.

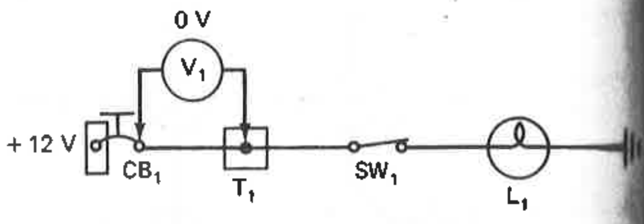


FIGURE 13-34 A voltmeter connected between two points of positive voltage.

indicates zero volts because its probes are connected between two negative voltage points (ground to ground).

When using a voltmeter, it is important to consider voltage as consisting of two parts, a positive voltage and a negative voltage. As long as a voltmeter is connected to one positive voltage and one negative voltage, it will indicate system voltage. As illustrated in Fig. 13-34, if the voltmeter is connected to two equal positive voltage values or two equal negative voltage values, it will indicate zero.

When troubleshooting a circuit with an open (disconnected) wire, the technician should place the voltmeter in various convenient places along the suspect wire. Since the positive voltage signal initiates at the aircraft bus, it is logical to first test for a positive voltage near the bus and move systematically toward the load. This concept is illustrated in Fig. 13-35. The first test is performed as represented by voltmeter V_1; the second test, voltmeter V_2; the third test, voltmeter V_3; each measures 12 V. This indicates that the circuit's positive wire is continuous (not open) from the bus through terminal 1 and the switch. Voltmeter V_4, being connected to what should be the positive side of the lamp, should read 12 V. Since V_4 indicates zero volts, the circuit must be open between the switch and the light.

When you are dealing with complex circuitry, the troubleshooting process becomes more difficult. When deciding where to connect the voltmeter, always consider the following: (1) A wire's insulation should never be removed to install a meter's test probe; therefore, take all measurements at open terminals, plug connectors, switches, fuses, or any other areas where the conductor is exposed. (2) Since an open in a wire can occur virtually anywhere, always connect the test meter to an easily accessible connection. If there is no positive voltage at that point (while you are referencing ground with the other meter probe), you can conclude that the open is between that test point and the positive bus. To further pinpoint the defective wire or connector, move the positive voltmeter probe to the next exposed terminal nearer the aircraft bus. If the voltmeter indicates zero volts, the open is between that test point and the positive bus. If the meter indicates system voltage, the open circuit is between the first and second test points, as shown in Fig. 13-36. The first test was performed at the switch because it was easily accessible. From this test it was easy to determine which portion of the circuit (before or after the switch) should be tested next.

In many situations it is easiest to check voltage at the load of a circuit. In this case, if there is no voltage available to the load, the circuit is defective. If voltage is present to the input connections of the load, the load itself is defective. Be cautious

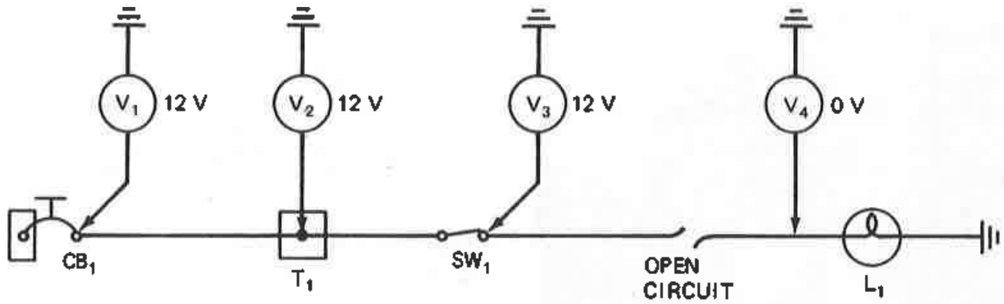


FIGURE 13-35 Placement of a voltmeter to troubleshoot an open circuit.

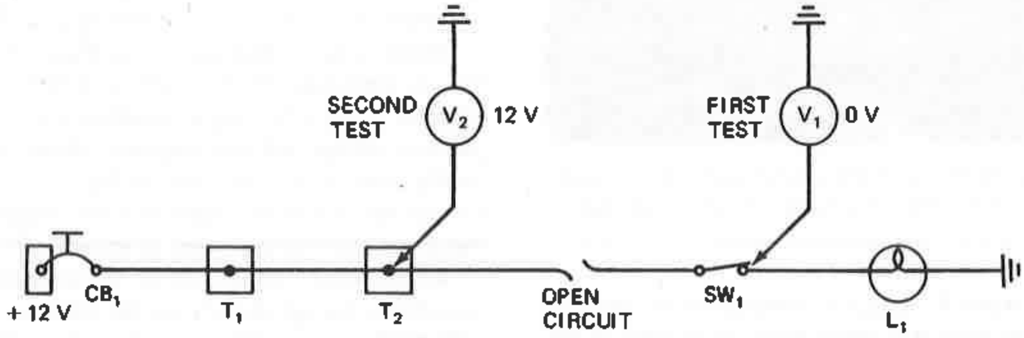


FIGURE 13-36 Voltage tests of an open circuit. Since the first test indicated 0 V, the second test is made closer to the bus.

voltage consists of two parts, positive and negative, and both must be available to the load in order for it to operate.

A voltmeter may be used to determine if the negative voltage of a circuit is available to the load. As illustrated in Fig. 13-37, the voltmeter should be referenced to a positive voltage source when testing for a negative signal. That is, the meter's red test probe should be connected to a point that is known to be a positive voltage. The aircraft's bus, or any other positive connection, may be used for this purpose. In this configuration, if the meter's negative probe is connected to a negative voltage, the meter will indicate system voltage. If no negative signal is present at the meter's black test probe, the meter will indicate zero volts.

Voltmeters and Composite Aircraft

It should be noted that the new breed of composite aircraft require some special procedures when voltage is checked. As with systems on metal aircraft, both the negative and positive voltage signals must be present to all electric power users. However, on composite aircraft the negative voltage cannot be transmitted through a metal structure. Some composite aircraft use a separate wire to carry the negative (ground) voltage from a *ground bus* to each electrical load. When checking for a positive voltage on this type of system, be sure to verify that you are connected to an uninterrupted ground source, as seen in Fig. 13-38. To verify an uninterrupted ground circuit, place your voltmeter probes between a known voltage positive source and the ground wire in question. Never draw conclusions about voltage measured between two unverified points.

Some composite aircraft incorporate a *ground plane* on the inside skin of the aircraft. This ground plane is used as the negative-side voltage source. When an electric component is not working because of a lack of voltage, be sure to check the ground plane. To check for a negative voltage signal on the

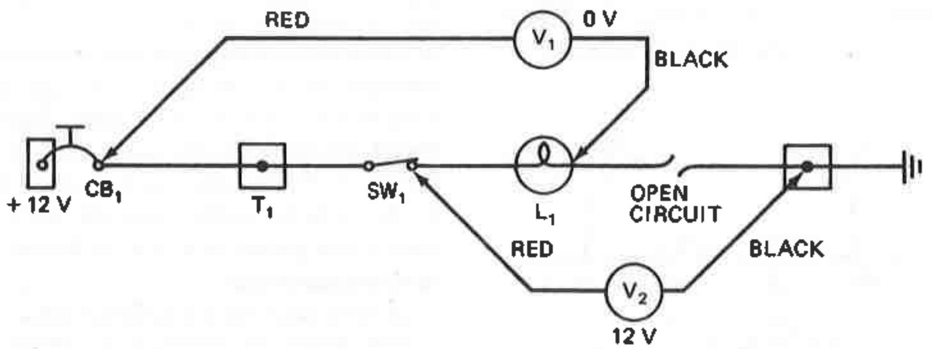


FIGURE 13-37 Using a voltmeter to test for a negative voltage. If V_1 measures 0 V, there is no negative voltage present at the meter's black probe. If V_2 measures 12 V, negative voltage is present at the black probe.

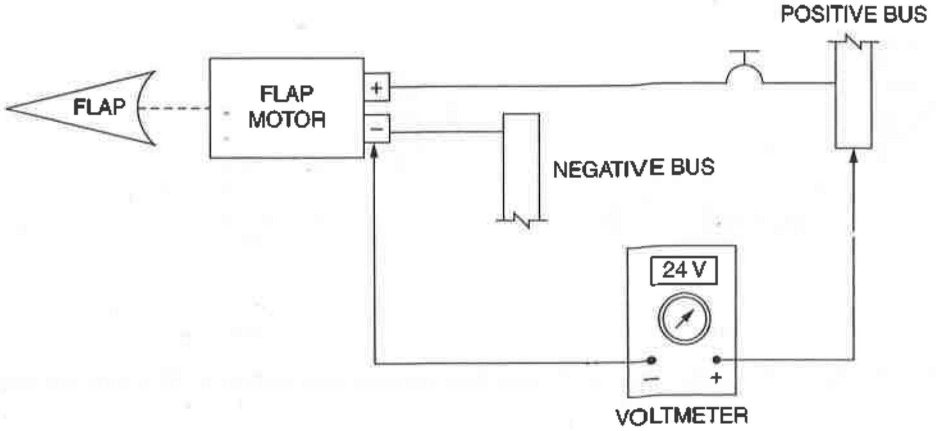


FIGURE 13-38 Testing for an uninterrupted ground circuit on a composite aircraft.

ground plane, use a voltmeter and reference a known positive voltage. On some aircraft special low-resistance ohmmeters are used to verify continuity of the ground plane.

Ohmmeter Troubleshooting

Ohmmeters are best suited for two types of tests: (1) continuity checks of components removed from a circuit and (2) continuity checks of short circuits. Components such as switches, relays, lightbulbs, and transformers may all be tested with an ohmmeter. However, these components must be removed or disconnected from the circuit prior to testing.

Figure 13-39 illustrates the use of an ohmmeter for testing components. A component such as a switch, circuit breaker, or fuse must have zero resistance (when closed) to operate properly. If the ohmmeter measures infinite resistance, the component is defective.

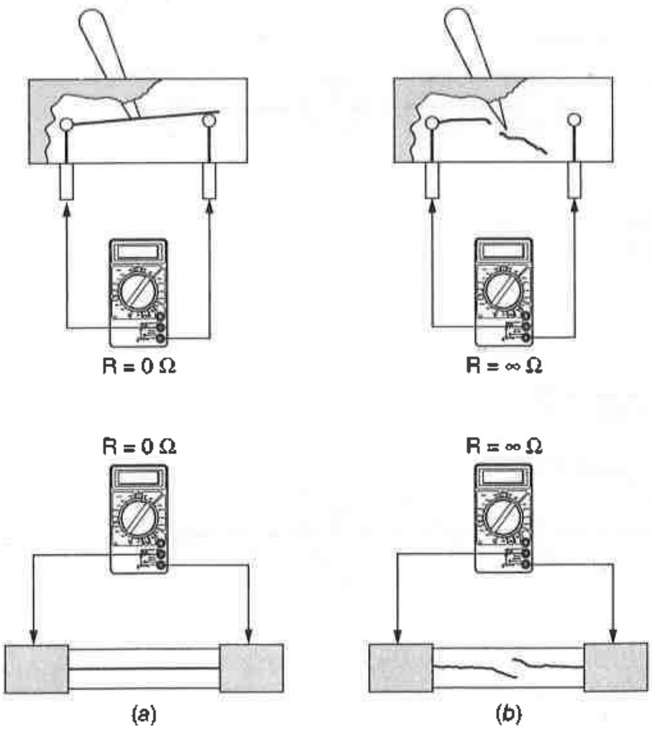


FIGURE 13-39 Testing components with an ohmmeter. (*a*) Zero resistance measured across operable components; (*b*) infinite resistance measured across defective components.

An ohmmeter test is also valid for most power users as shown in Fig. 13-40. The light tested should show relatively low resistance if it is functional. If it is defective (open), the light will show infinite resistance. In general, any power user should have a resistance equal to its rated voltage divided by its rated amperage ($R = E/I$). Any load that has infinite resistance is defective.

Ohmmeters are often used to troubleshoot shorted circuits. For this type of troubleshooting, the circuit power must be turned off and the circuit isolated from the rest of the electrical system. In most cases this can be achieved by turning off the aircraft's battery master switch and opening the appropriate circuit breaker. Figure 13-41 shows the ohmmeter configuration for testing a wire shorted to ground. In Fig. 13-41*a* the short to ground seems to appear at T_2; however, this is incorrect. The short is in wire segment C; but since wire segment C is connected to T_2, the meter indicates zero resistance from T_2 to ground. To pinpoint the location of the shorted circuit, isolate the various segments of wire. In Fig. 13-41*b*, segment C is isolated from T_2. The ohmmeter now reads infinite resistance; the short no longer appears to be at T_2.

If the meter probe is moved to the end of wire segment C, it will once again measure zero resistance to ground. Figure 13-41*c* illustrates the final test needed to find the defective wire. In this case wire segment C is completely isolated; the switch is open, and wire segment C is removed from T_2. Since the ohmmeter indicates zero resistance, wire segment C (a positive wire) must be shorted to ground.

Ohmmeters can be used to test for open circuits; however, it is typically easier to use a voltmeter. The physical length of a meter's test leads may inhibit the use of an ohmmeter for a continuity check of open circuits. If you want to test a wire that is routed from the flight deck to the tail of the aircraft, your ohmmeter must be connected on both ends of the wire. With even a relatively small aircraft, this is impossible without extending the length of the meter's test leads. Using a voltmeter, one could simply test voltage at the tail end of the wire (compared to ground) to determine the wire's condition.

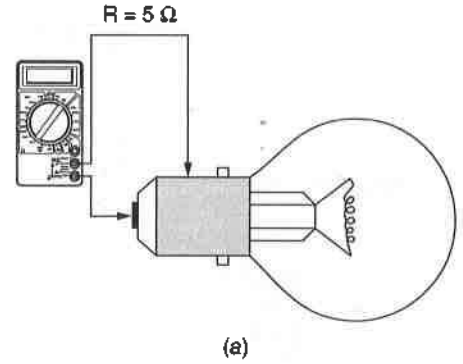


FIGURE 13-40 Testing load units with an ohmmeter. (*a*) A good bulb indicates low resistance; (*b*) a defective bulb indicates infinite resistance.

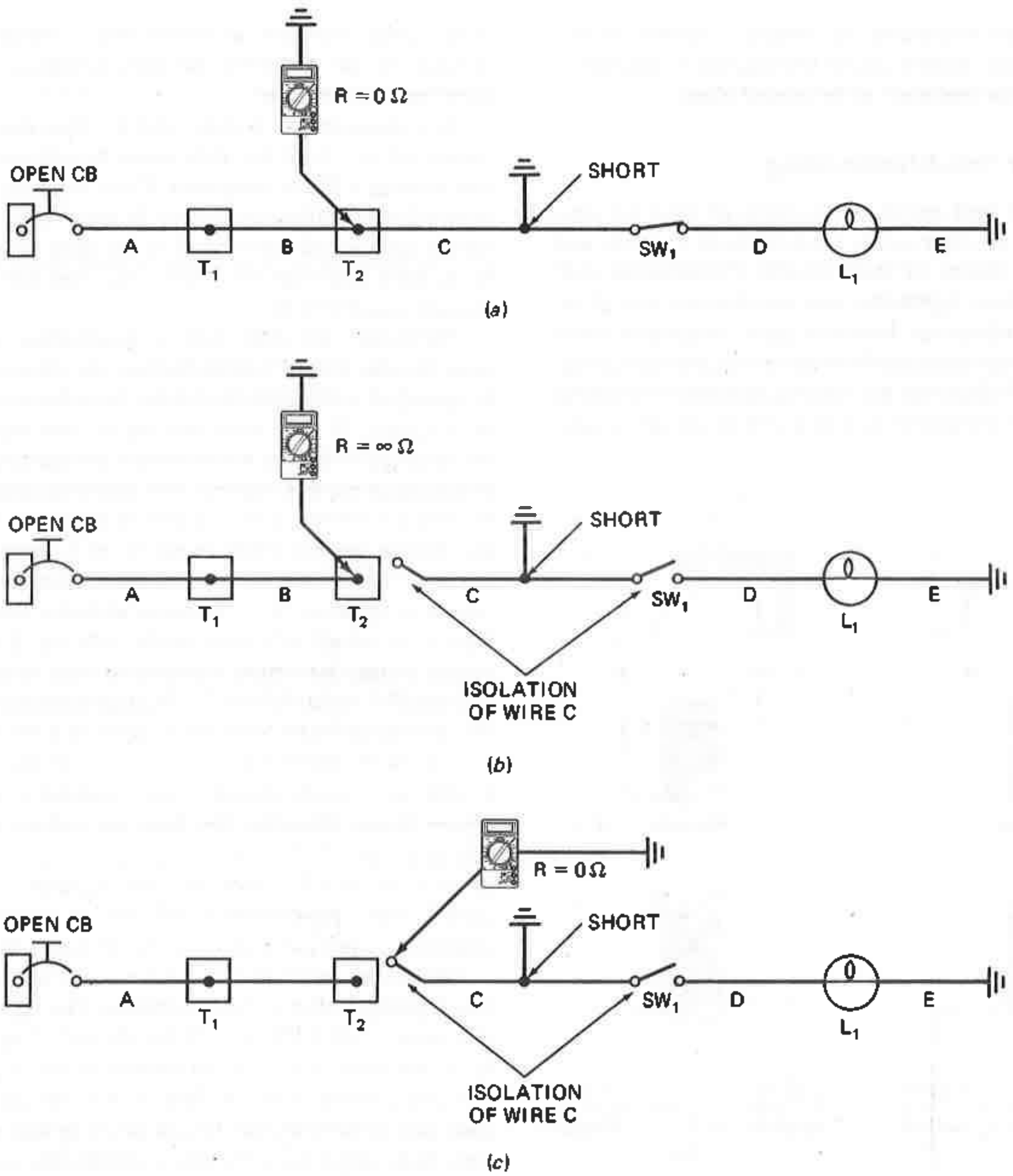


FIGURE 13-41 Using an ohmmeter to find a short to ground. (*a*) T_2 has zero resistance to ground when wire *C* is not isolated. (*b*) T_2 has infinite resistance to ground with wire *C* isolated. (*c*) Wire *C* has zero resistance to ground.

Ammeter Troubleshooting

Ammeters are the least common troubleshooting element of any multimeter. Most troubleshooting is performed using a voltmeter, the ohmmeter is less common, and the ammeter is seldom used. Since ammeters are placed in series with the circuit to be measured, this dictates that wires be disconnected for every test and a "quick measurement" is not possible. Also most ammeters on a common multimeter are designed for low amperage readings only and often not suitable for most circuits.

Ammeters are typically used to test aircraft charging systems. In such cases it is often important to measure the total output amperage of an alternator or generator. Although multimeters normally incorporate an ammeter, they are not typically of high enough capacity to measure charging system current. If it becomes necessary to measure a relatively high amperage, be sure to utilize an ammeter that is capable of measuring the anticipated current. The installation of charging system ammeters is discussed in Chap. 10.

A Typical Troubleshooting Sequence

Before the technician opens any aircraft panels, prepares any tools, or connects any meter, it is important to have a thorough understanding of the system. Troubleshooting a fault typically begins with a review of the pilot's **defect and malfunction report**; the technician should then study the maintenance documents. Next confirm the aircraft is in a safe condition to operate any needed systems, and if practical verify the fault reported by the pilot through system operation. This sequence of events can be called **troubleshooting from the flight deck**; only after this process is complete should further tests be made.

A typical sequence for troubleshooting a defective position-light circuit is as follows. First examine the schematic diagram, and operate the defective system. While operating the system, make note of exactly what operates correctly and what operates incorrectly. Examine the circuit protector of the system, and determine its condition. If the fuse or circuit breaker has opened, the circuit is most likely shorted to ground. If the fuse is continuous or the circuit breaker is closed, the defect is most likely an open. Study the circuit's schematic diagram, and determine which component or wire is a likely suspect.

If the defect is a short circuit, as illustrated in Fig. 13-42, an ohmmeter should be used to find the defective wire segment. Before the ohmmeter is installed to troubleshoot the short, a portion of the circuit could be tested from the flight deck. For example, if switch 1 is turned off and the fuse (or circuit breaker) opens when the circuit is tried again, wire segments *C* through *J* are not the cause of the defect. This must be true, since these wire segments are disconnected from the bus when switch 1 is opened. If switch 1 is turned off and the fuse remains closed (operable), the circuit defect must be located between the switch and the position lamps (wires *C* through *J*). This must be true since the circuit protector did not open while the wire segments *C* through *J* were disconnected from the circuit.

Troubleshooting from the flight deck is an important part of the repair process. As illustrated in the last paragraph, this is done by operating the flight deck controls and drawing accurate conclusions from the results. If done properly, considerable time can be saved by studying the system's schematic and operating related electrical systems. Often this process can significantly reduce the possible defect locations, therefore improving the troubleshooting process.

If the defect in the position-light circuit is an open, as in Fig. 13-43, a voltmeter should be used to locate the fault. In this case opening switch 1 would not allow the technician to draw any significant conclusions. A voltmeter must be installed systematically throughout the circuit to determine which wire segment is defective.

Troubleshooting with Built-In Test Equipment

Built-in test equipment (BITE) systems found on modern commercial aircraft are designed to troubleshoot the electrical problems typically encountered during maintenance. System faults that occur during normal aircraft operations must be repaired swiftly and accurately. A typical aircraft may use several BITE units to monitor the major systems, such as electric power, environmental control systems, and

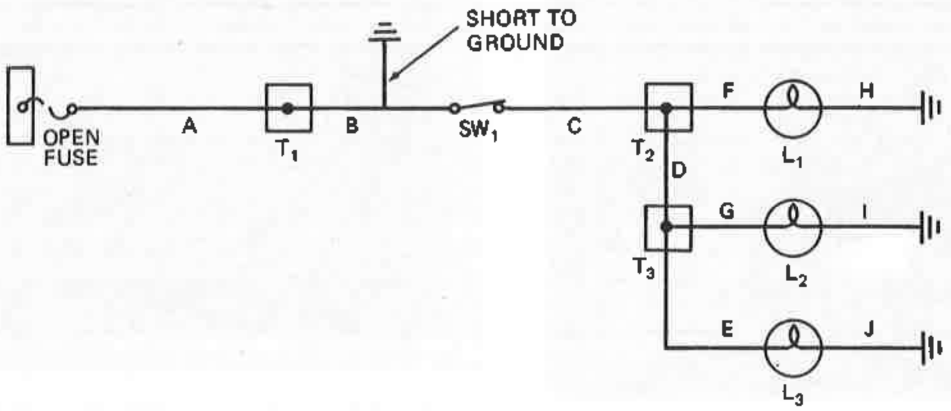


FIGURE 13-42 A typical short circuit.

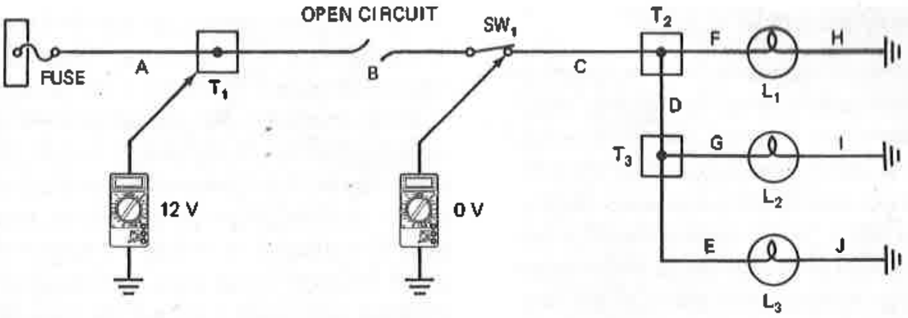


FIGURE 13-43 A typical open circuit.

flight control systems. BITE systems perform fault detection, fault isolation, and operational verification after system repair.

BITE systems provide fault detection continuously during aircraft operation. If a fault is detected, the BITE system stores the necessary defect information in a nonvolatile memory and sends the appropriate display signal (if any) to the flight deck. If the fault requires immediate attention, the flight crew or central maintenance system will notify the aircraft operations center via a wireless transmission or upon landing. The technician must access the appropriate BITE system to perform the fault isolation test. Through correct operation, many BITE systems will display failure data and repair code information. Stand-alone BITE circuits are usually found on aircraft designed prior to 1990; aircraft constructed after this date typically employ a centralized maintenance system.

Several versions of built-in test equipment are in use today. Simple systems typically incorporate a **go/no go** red or green LED on the equipment LRU. More complex systems use a multicharacter display and monitor more than one LRU and the associated wiring. The system in Fig. 13-44 is accessed from the equipment center of the aircraft. More advanced BITE systems incorporate displays that are activated from the flight deck and have paper printouts. In addition, advanced systems may have a means to transmit data from the aircraft to the maintenance facility during flight.

The BITE system shown in Fig. 13-44 is incorporated with the bus power control unit (BPCU). The BPCU is an LRU located in the back of a typical large aircraft equipment bay. This system monitors the entire electric power generation system, including the left, right, and APU generators; the constant-speed drives; and their related control units. The BIT button is depressed on this system to activate the 24-character LED fault display. Typically, a BITE system will display fault information in a coded message, as illustrated in Fig. 13-45. The message is then decoded by the technician through the use of the aircraft's maintenance manual. The appropriate manual will inform the technician of any LRU to be replaced or circuit to be repaired and its location within the aircraft. The fault information on this

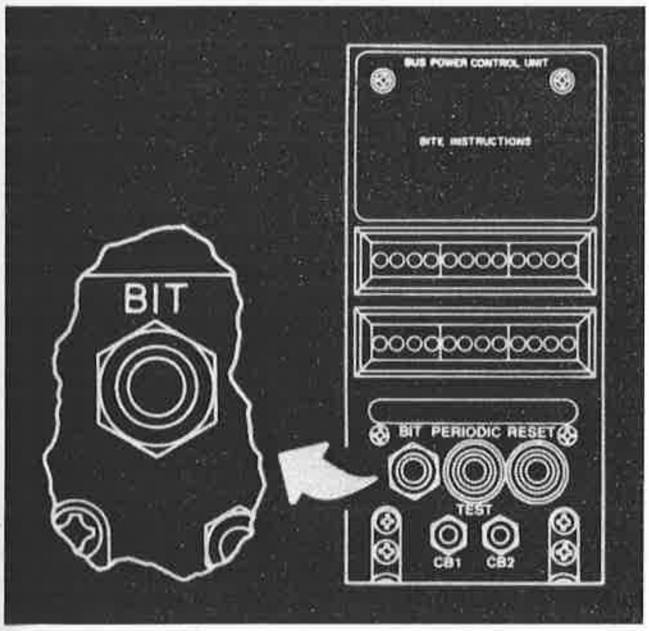


FIGURE 13-44 BITE system display. (*Sundstrand Corporation.*)

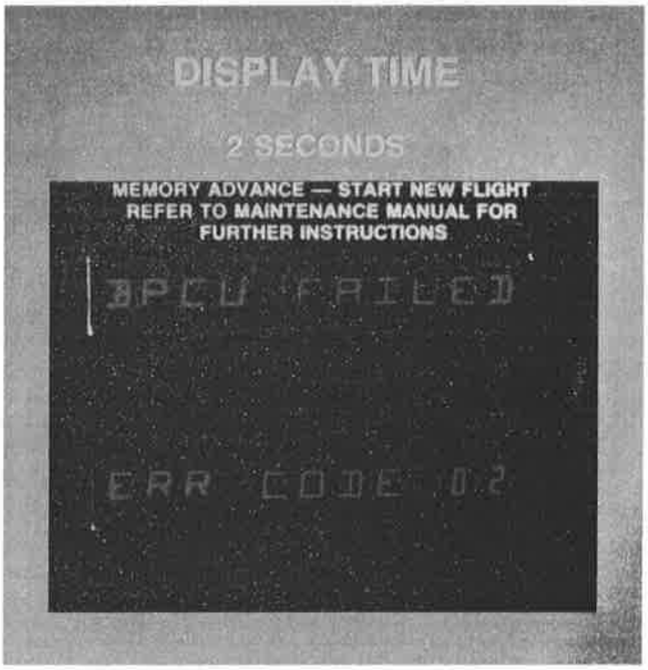


FIGURE 13-45 Typical BITE display: BPCU FAILED ERROR CODE 02. (*Sundstrand Corporation.*)

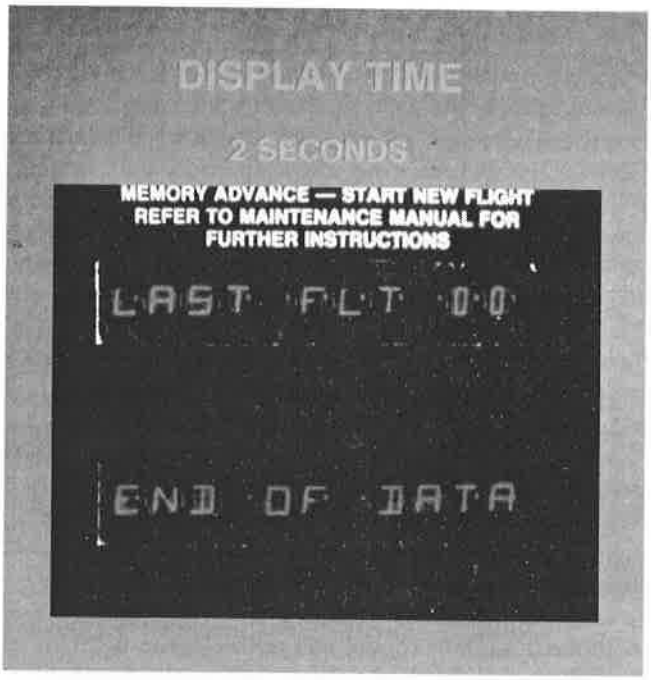


FIGURE 13-46 BITE display of LAST FLT 00 END OF DATA. (*Sundstrand Corporation.*)

system is displayed for 2 s, and then the display automatically advances to the next fault. This BITE system will make an appropriate indication when all fault data have been displayed, as in Fig. 13-46.

After the system fault has been repaired, the BITE box should be reset and an operational check performed. The repaired system should be run through a complete cycle of operation. In the case of the electric power generation system, the appropriate engine and ac generator should be subjected to a variety of operating parameters. The flight deck instruments and failure indicators are monitored during the test to detect any further problems.

After the repaired system has been run, the BITE system fault display should be reactivated. This will initiate the readout of the nonvolatile memories, and remaining operational faults will be displayed. If the system is found to be without fault, the BITE display will respond accordingly, as in Fig. 13-47.

Multipurpose Control Display Unit

A multipurpose control display unit (MCDU) is used to access a slightly more advanced **BITE** system. Some aircraft require that the MCDU be accessed from the equipment bay, while other aircraft require a carry-on MCDU controller, which is connected to the system on the flight deck. Many aircraft use a controller located on the instrument panel and display information on the EICAS display unit. The operation of the MCDU is similar to the operation of the previously described BITE system. The MCDU is typical of the system found on the Boeing 757 and 767 aircraft. The MCDU receives digital data in an ARINC 429 format from the thrust management, flight control, and flight management computers, along with EICAS inputs. The MCDU both monitors inflight faults and performs ground test functions. In-flight faults are directly correlated to the various flight deck effects associated with in-flight problems. A **flight deck effect** is any EICAS display or discrete annunciator used to inform the flight crew of an in-flight fault.

When the aircraft lands, the MCDU automatically records any in-flight faults (from the last flight) in a nonvolatile memory. To access this memory, the technician must first cycle the MCDU off and on again. This will result in an internal test of the MCDU. After the internal test has been completed and OK'd by the display, the technician should select the in-flight mode of operation. The unit will respond accordingly with faults listed in order of occurrence. At the end of the fault data, the unit will ask if it should display faults from previous flights. The MCDU will store faults from a maximum of 10 flights.

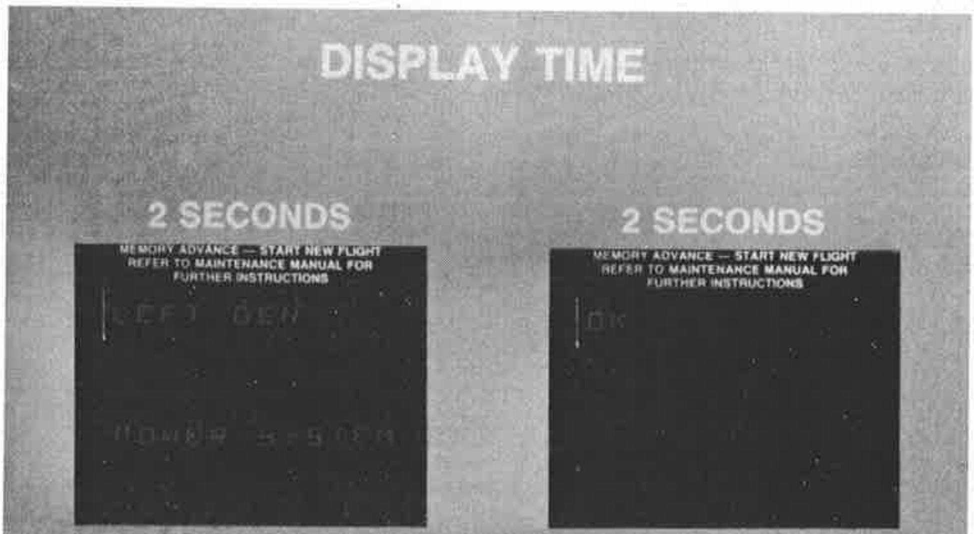


FIGURE 13-47 BITE display of a system with no recorded fault data: LEFT GEN POWER SYSTEM, OK. (*Sundstrand Corporation.*)

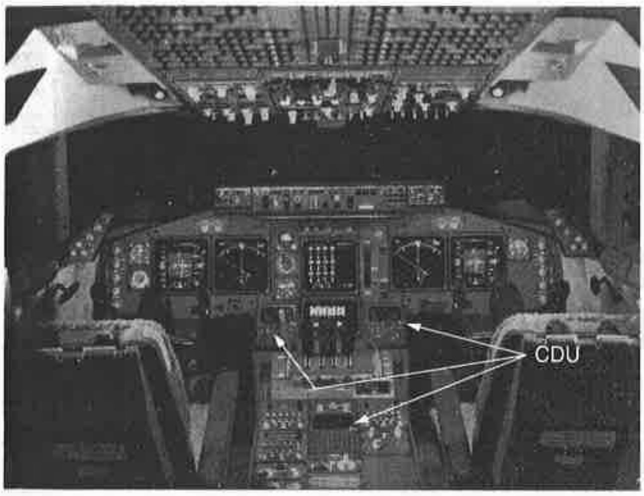


FIGURE 13-48 A central display unit (CDU) on a Boeing 747-400 aircraft. (*Boeing Corporation.*)

In the case of an MCDU located in the equipment bay, fault data appear on an LED display similar to that shown in Fig. 13-45. On this type of MCDU, the top line displays the flight on which the fault occurred and the related flight deck effect; the bottom line displays the faulty LRU to be replaced. If the MCDU is accessed from the flight deck, the EICAS is used to display the message.

Central Maintenance Computer System

Many transport-category aircraft employ an integrated system to detect and store fault data. This system is often called the CMCS. This system is designed to perform in-flight and ground tests of virtually every aircraft system, each one accessed from a central location. The **control display unit** (CDU), used to access and display faults, is located in the center console of the flight deck. This type of system is found on the Boeing 747-400 a four-engine transport-category aircraft. Most aircraft contain multiple CDUs on the flight deck and in the equipment bay. As shown in Fig. 13-48, the CDU uses a CRT or flat panel display. This type of display allows for a more descriptive message of system faults than the simple stand-alone BITE. The B-747-400 employs three CDUs located on the pedestal between the pilots. A CMCS printer is incorporated to provide a written report of the fault data, and a software data loader is used to store faults on a computer disk or digital flash drive (Fig. 13-49). Aircraft equipped with ACARS are capable of transmitting fault data from the aircraft to a ground facility. ACARS will also answer all maintenance data requests from the ground facility. **Aircraft communication addressing and reporting system** (ACARS) is an automated digital communications system found on many modern aircraft. The system is used to send digital messages to/from the aircraft similar to an e-mail or text message. ACARS will be discussed in greater detail in Chap. 15.

There are two central maintenance computers (CMCs) located in the aircraft's equipment bay. The CMCs receive up to 50 digital ARINC 429 data inputs and various discrete inputs. Each CMC has 10 ARINC 429 outputs; one is a crosstalk bus to the other CMC. The outputs are sent to the aircraft systems through the left CMC; therefore, if only one CMC is available, it must be installed in the left slot. If the left CMC detects internal faults, output data are automatically passed from the right CMC directly through the left CMC. Figure 13-50 is a block diagram of the CMC data inputs and outputs.

During flight the CMCs receive fault data from the aircraft's electronic interface units (EIUs) and other digital and discrete systems to record in-flight failures. The EIUs monitor system parameters and control the displays of the EICAS and EFIS (electronic flight instrument system). Once the aircraft is on the ground, the CMC can be interrogated for any history of in-flight faults stored in a nonvolatile memory. Up to 500 faults can be stored in the nonvolatile memory.

A technician would use the CDU to retrieve the menu pages used to initiate interrogation of the CMC. The first page is used primarily for line maintenance and operations; the second page is used for in-depth troubleshooting.

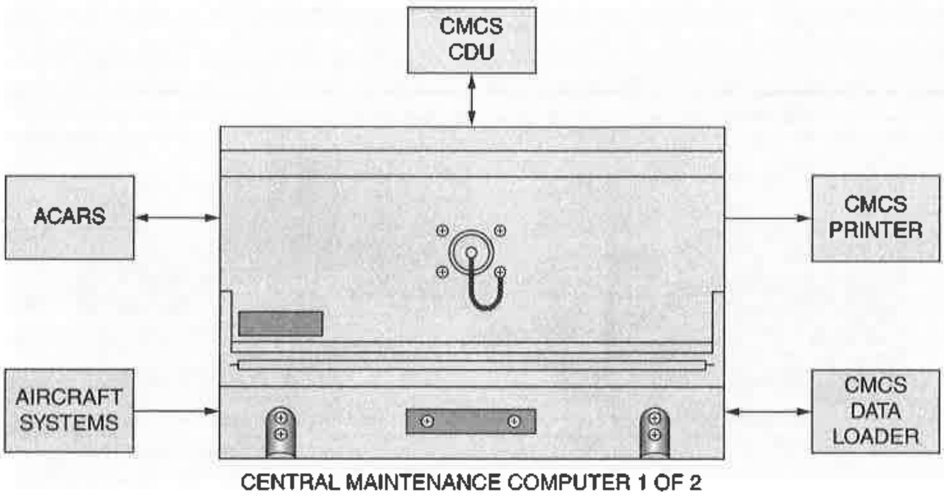


FIGURE 13-49 Centeral maintenance computer and data links to CDU, printer, data loader, aircraft systems, and ACARS.

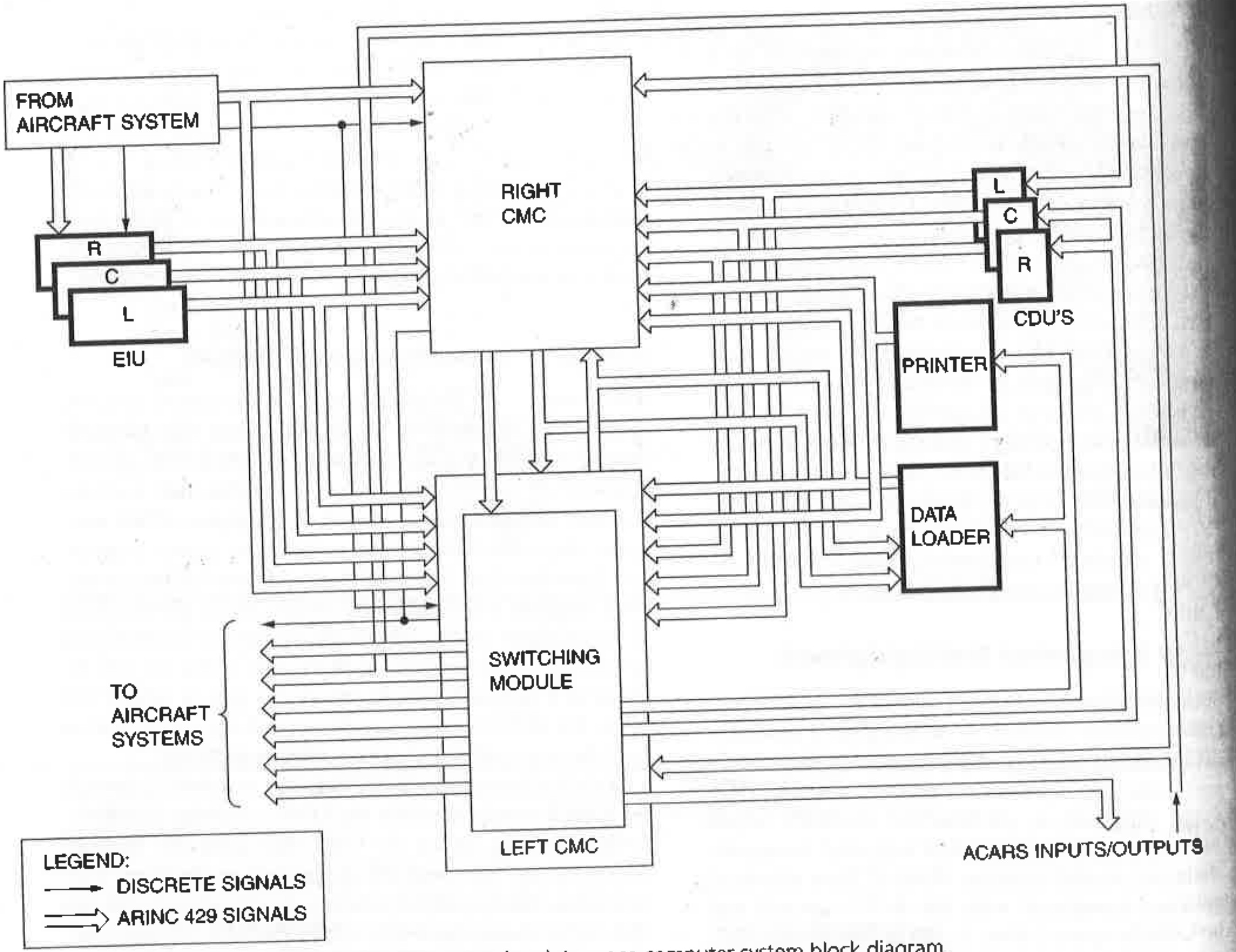


FIGURE 13-50 Central maintenance computer system block diagram.

Figure 13-51 shows the two CMC menu pages; these would be presented on the CDU display screen. A specific function is selected from the menu by pressing the button adjacent to that function. There are three basic types of faults: (1) **existing faults** (those faults active at the time of inquiry), (2) **present leg faults** (those faults recorded during the last flight), and (3) **fault history** (those faults that were recorded during present leg or previous flights).

Depressing the button for the **ground tests** function tells the CMC to test LRUs and various systems. The **EICAS maintenance pages** function will activate the real-time display of various systems, such as electric power. This function will also allow for access of maintenance pages recorded in memory at an earlier time, called *snapshots*. The **confidence tests** function allows the technician to perform tests that are typically performed before a flight. These preflight tests are used to determine if the aircraft is ready for dispatch.

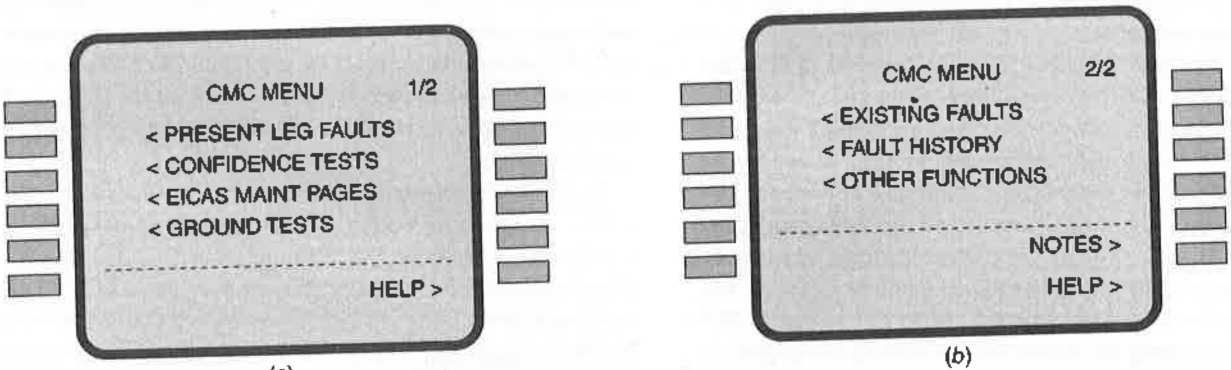


FIGURE 13-51 Central maintanance computer menu display. (*a*) Page 1 of 2, for line maintenance; (*b*) page 2 of 2, for extended maintenance troubleshooting.

Centralized Fault Display System

The Airbus A-320 employs a similar central maintenance system called the **central fault display system** (CFDS). This system classifies faults into three categories: **Class 1, Class 2**, and **Class 3** failures. Class 1 failures have an operational consequence on the flight. The crew is notified by a red warning or amber caution on the electronic centralized aircraft monitoring (ECAM) system or by discrete instrument flags. The pilot must report Class 1 failures in the logbook, since they require maintenance action before the next flight. Class 2 failures are displayed to the pilot by means of the ECAM system only after landing and engine shutdown. Class 2 failures must be reported by the pilot in the log because they cannot be left uncorrected until the next scheduled maintenance. Class 2 failures are categorized by **the minimum equipment list** (MEL) to determine the number of flights allowable prior to initiating repair. Class 3 failures are not reported to the pilot and can be left unattended until the next scheduled maintenance. Class 3 failures are displayed only during access of CFDS data.

Advanced Integrated Test Equipment

With the introduction of advanced computerized systems, a concept commonly referred to as **integrated modular avionics (IMA)** has allowed improvements in fault monitoring and recording systems on modern aircraft. IMA systems are designed in modularized elements which allows for enhanced integration and improved communications between aircraft systems. Many of these advanced concepts were introduced with the B-777 aircraft and enhanced with the newer Airbus A-380 and the Boeing 787. Advanced centralized maintenance systems as well as wireless communications are now offered on many corporate aircraft and even some light piston engine aircraft like the Cirrus SR20. Most modern centralized maintenance systems allow for real-time downloads of system status and condition monitoring. This ability to continually monitor systems, even during flight, is a major advantage found on advanced CMSs. The ability to collect continuous data allows for trend monitoring of critical systems; which in turn allow a maintenance facility to predict system faults before they occur. For example, if the maintenance facility notices an abnormally high-bearing temperature in a jet engine that turbine can be inspected/repaired prior to a critical flight situation.

The B-787 and A-380 also employ **electronic flight bags (EFBs)**, which create an integral part of the aircraft's CMS. EFBs found on transport-category aircraft employ flat panel display units which can access and process a variety of aircraft information such as the minimum equipment list (MEL). The MEL is used to determine the minimum number of operational systems (maximum failures) needed to dispatch the aircraft. Since the pilots can now easily access the MEL prior to flight, dispatch times are reduced. The EFB data can easily be updated while parked at the gate or in the maintenance hangar using a secure wireless Internet connection.

The use of electronic flight bags linked to wireless technologies has made it possible to offer flight deck management applications to airlines and corporate operators. Many of these services are offered by a third-party provider, such as Rockwell International, Inc. or Jeppesen Sanderson, Inc. The service provider can perform trend monitoring as well as routine updates of charts and flight manuals all completely seamlessly for the airline or corporate user. Web-based systems can also offer real-time airport weather that can be used to determine takeoff performance and improve safety.

Boeing 777 Central Maintenance System

The Boeing 777 aircraft employs an integrated systems architecture designed by Honeywell called the **Airplane Information Management System (AIMS)**. AIMS employs concepts of systems integration, line replaceable modules (LRMs), and advanced computer technologies. AIMS integrates data collection, computing functions, power supplies, and fault detection. The B-777, as with other advanced aircraft, employs a fault tolerance design, which allows AIMS to detect a fault and reconfigure the system for uninterrupted operations. In many cases, the flight crew would not even be aware of a system failure. In theory this type of design will allow the B-777 to continue flying with the failed system until the next convenient maintenance opportunity.

Troubleshooting the B-777 avionics is achieved through the CMCS contained within the AIMS computing functions. Technicians can access the CMS data using the **Maintenance Access Terminal (MAT)** located on the flight deck just behind the first officer's station. A local area network can also supply maintenance data using a **Portable Maintenance Access Terminal (PMAT)**. There are five different functions that can be accessed through MAT or PMAT; **line maintenance, extended maintenance, other functions, help**, and **reports**. For selection of the various functions, the terminals contain a keyboard and cursor control device (similar to a track pad on a laptop computer).

The A-380 Integrated Test Equipment

Diagnostics and maintenance of the Airbus A-380 is performed with the help of the integrated CMS called the **Onboard Maintenance System (OMS)**. The OMS provides support for maintenance, aircraft servicing, aircraft condition monitoring, and configuration of system software. The OMS access points are the permanently mounted on the **Onboard Maintenance Terminal (OMT)** located in the aft portion of the flight deck and wireless device similar to a common laptop computer called the **PMAT**.

Figure 13-52 shows the OMS three major subsystems; the CMSs, the Aircraft Condition Monitoring Systems (ACMS), and the Data Loading and Configuration System (DLCS). Diagnostics data for virtually all aircraft systems is collected and stored through a CMS and can be easily accessed by technicians using onboard equipment or a secure wireless signal.

The ACMS is used to provide support for preventative maintenance and in-depth analysis of maintenance data.

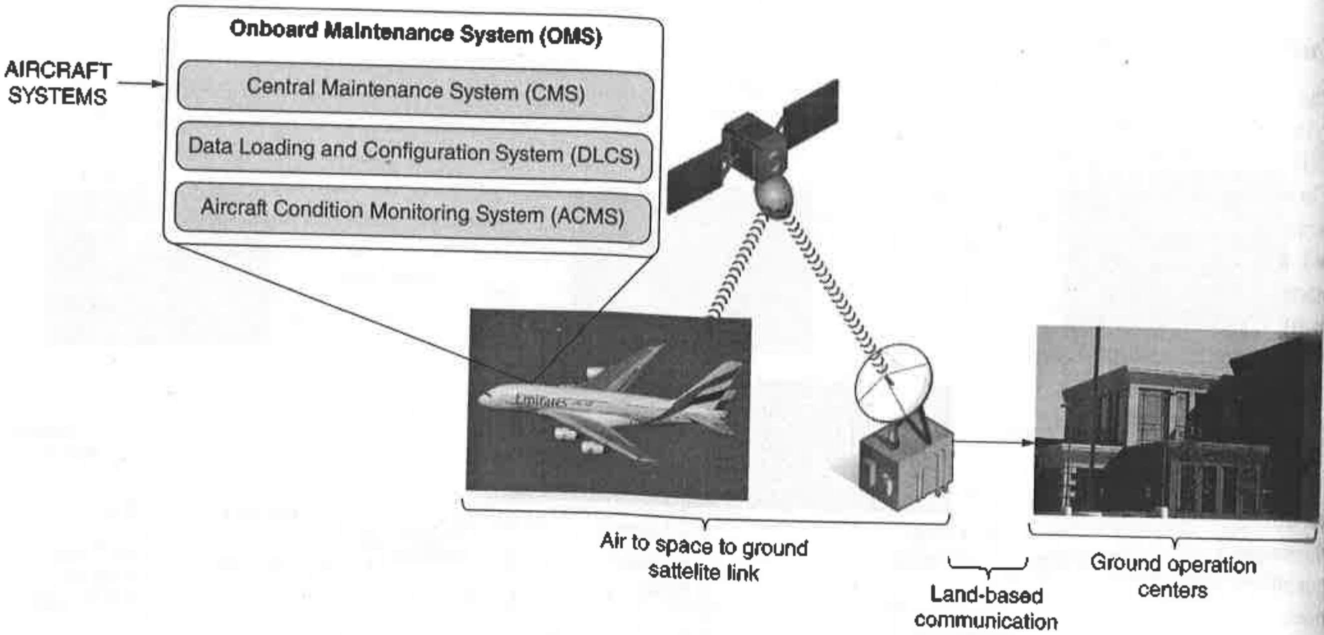


FIGURE 13-52 Major elements of the A-380 onboard maintenance system.

The ACMS can be used to transmit trend data to ground facilities for real-time analysis during flight; or the data can be downloaded after landing. The DLCS is designed to manage all data related to system configuration including all data uploads/downloads. The DLCS controls the download of all CMS fault reports. When the CMS detects a serious fault, a report is sent to the flight deck where it can be evaluated by the crew and transmitted to the airline ground centers via satellite. After landing, the CMS data **servicing reports** can be accessed by the technician; electronic links to other maintenance documents are also available as needed. Once the repair is complete the CMS can be used for system verification.

The Boeing-787 Central Maintenance System

The B-787 uses a CMS similar to the B-777 and the A-380, that is, there are several access points for data; portable wireless terminals can be used by technicians, and air-to-ground communications are available using satellite technologies. The software for the central maintenance computing (CMC) functions will be hosted in the common core network and uses the ARINC 664 data bus standard for all communications. As with most modern aircraft, the B-787 is highly reliant on software for systems operation; therefore, the configuration management function of the CMC tracks the current versions of software and hardware installed in the 787. This helps to ensure compatibility of all hardware and software on the aircraft. Software updates can be conducted through the onboard data loader or through a secure wireless connection.

Built-In Test Equipment for Light Aircraft

Today commuter, corporate, and even single-engine aircraft contain elements of built-in test equipment. State-of-the-art light aircraft such as the Cirrus SR20 and the Embraer Phenom light business jet operate with an integrated electronics package made by Garmin International. The systems found on these aircraft are designed to offer a variety of diagnostic and maintenance information presented on the aircraft's flat panel displays. Software uploads are also necessary on these aircraft and provided through the installation of a **secure data** (SD) card on the integrated electronics system display. Figure 13-53 shows an **SD** card adjacent to the installation slot on the Garmin G-1000 system.

FIGURE 13-53 A secure data (SD) card used for software configuration on the G-1000 system.

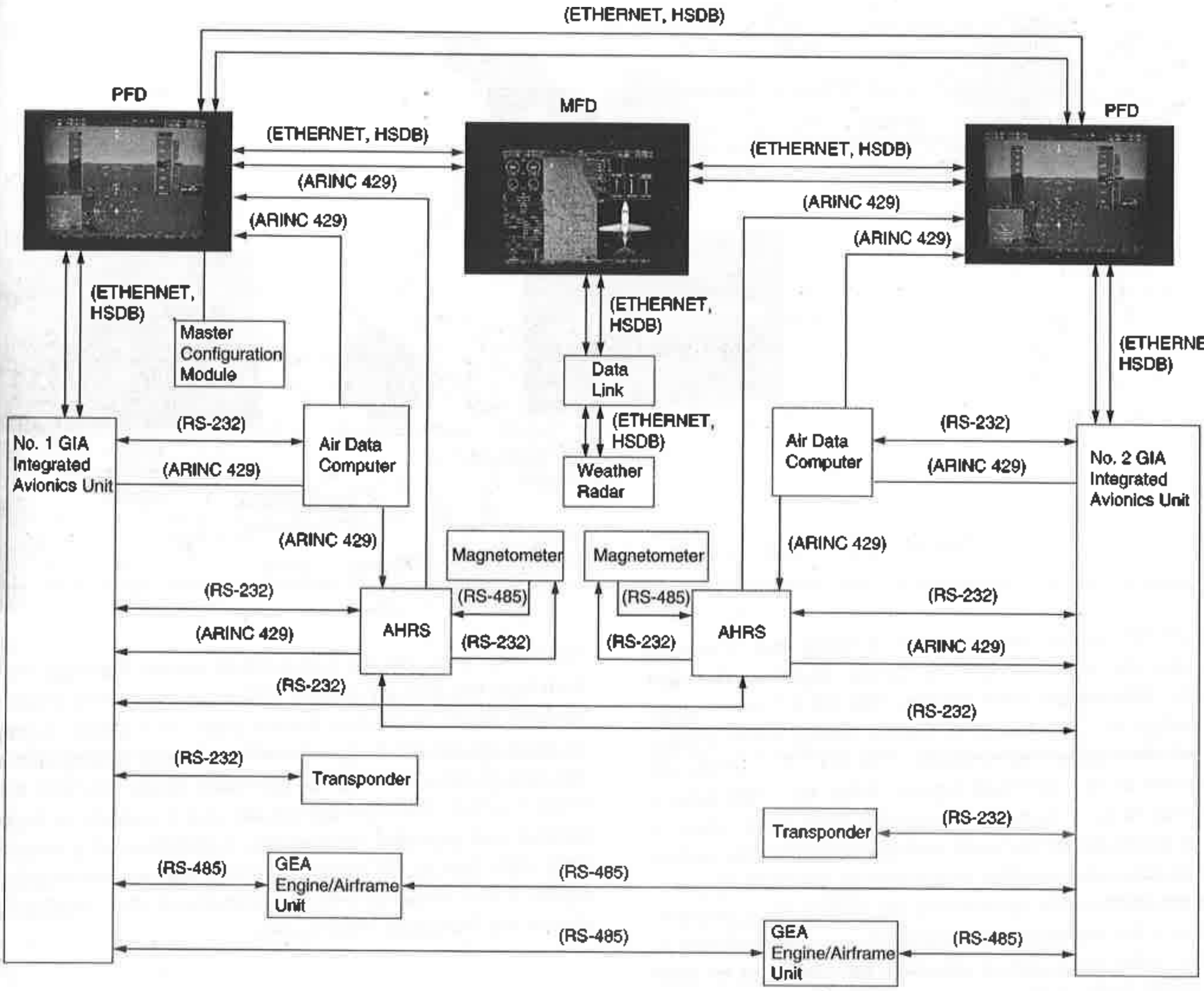


FIGURE 13-54 Phenom integrated avionics unit main interface diagram.

Figure 13-54 shows the two main processors, called the **integrated avionics units (IAUs)**, and related interconnections found on the Embraer Phenom. The IAUs contain hardware and software for the central maintenance functions, however, the actual BITE software is contained within the system's individual LRUs. As shown in the diagram there are several different data bus formats which feed the IAUs. This system has the ability to perform trend monitoring of critical systems. Trend monitoring on the Phenom is used to help predict a potential system failure; this is extremely useful on turbine engine aircraft. The system can monitor fuel flow, temperature, and vibrations related to engine components to help predict the health of the engine and improve aircraft safety.

This aircraft also has the capability to employ wireless connectivity to download/upload data. During flight the data link system employs the use of satellite communications. The wireless, Wi-Fi connection automatically enables maintenance data downloads when the aircraft is on the ground within range of the appropriate wireless hub.

There are several different types of built-in test equipment systems found on modern aircraft. The descriptions above give an overview of common equipment. Systems of the future promise to be even more accurate, cover more equipment, and be easier to use. BITE systems are here to stay and for good reason: they simplify complicated troubleshooting tasks. The operation of many BITE systems is relatively complex, so before using any particular system, the technician should become completely familiar with the operation of the central maintenance equipment.

Electrostatic-Discharge-Sensitive Equipment

Some electronic units found on modern aircraft are extremely sensitive to stray current flows. Even a static electrical discharge from a technician to a sensitive component could damage that component. These extremely delicate components are said to be **electrostatic-discharge-sensitive** (ESDS). ESDS parts are identified by one or more of the symbols found in Fig. 13-55. A part labeled as electrostatic-discharge-sensitive may be damaged by a static discharge of as little as 100 V. A technician walking on an aircraft's carpet, removing a coat, or simply rubbing his or her hair can accumulate

FIGURE 13-55 Typical symbols used to identify ESDS parts.

a static charge well over 1000 V. A static charge of this magnitude will damage ESDS parts. Most people cannot feel an electrostatic discharge below 3000 V. A visible spark from a static discharge is typically above 12 000 V. Each of these two levels is well above the tolerance of ESDS parts. A technician may become charged and damage a component without even realizing it.

A technician and all of his or her equipment must be connected to the aircraft's ground prior to servicing any ESDS components. This will neutralize any electrostatic charge that may have accumulated. The most common way to ground a technician employs the use of a grounded wrist strap. The wrist strap, as shown in Fig. 13-56, is connected around a bare wrist of the technician and connected to the aircraft's ground by means of a wire and plug. All bench technicians and equipment used to repair ESDS units that have been removed from the aircraft are also grounded to prevent component damage.

If an electronic LRU is to be removed from a modern aircraft, it is more than likely sensitive to static discharge. Be cautious and always read the appropriate documents for the maintenance being performed; also look for ESDS labels on all equipment. When a component is identified as ESDS, be sure to wear a wrist strap that is connected to ground. The aircraft should have a nearby ground connection, or the metal frame of an aircraft structure could be used. When removing the LRU, be cautious not to touch any electrical contacts on both the wire harness and LRU. Use special ESDS covers for all connectors while the LRU is removed. Once all electrical connections are protected, the LRU should be placed into a specially designed ESDS container. These containers are basically a plastic case with internal padding

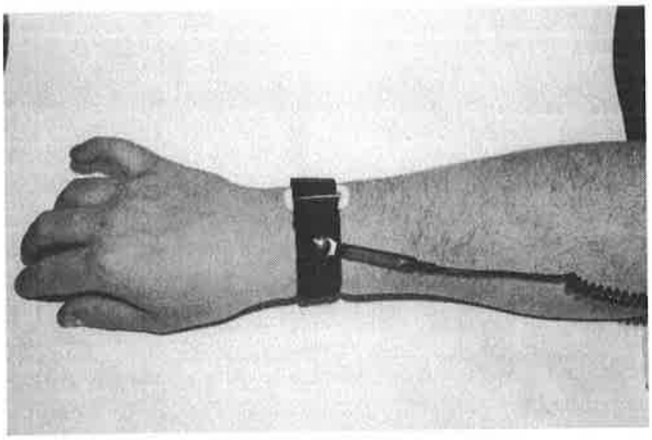


FIGURE 13-56 A typical wrist strap.

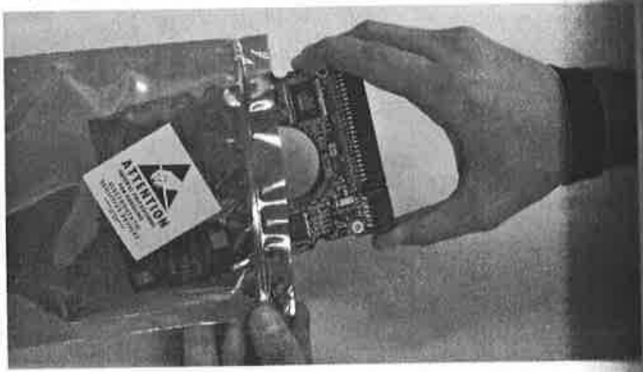


FIGURE 13-57 Storage of ESDS parts in a protective package.

designed to minimize static electricity during LRU shipping and handling. If performing work which requires removal of a printed circuit board or small electronics module, the unit should be placed into an ESDS bag (see Fig. 13-57). Once inside the bag the component can be handled without ESDS precautions. All protective containers are designed to prevent static charge from reaching the components inside. ESDS components must be handled correctly during all phases of removal, maintenance, repair, shipping, and installation; always follow appropriate procedures to protect sensitive components.

REVIEW QUESTIONS

1. Why are dependable electrical systems essential in modern aircraft?
2. How is reliability in aircraft electrical systems attained?
3. List general requirements for aircraft electrical systems.
4. What is an *essential electric circuit*?
5. Give an example of a nonessential electric circuit.
6. Where are the basic requirements found for transport-category electrical systems?
7. Describe the requirements for a circuit that is critical to flight safety.
8. Discuss the different types of electrical diagrams used for aircraft maintenance.
9. Explain the purpose of schematic diagrams.
10. What is meant by the term *LRU*?
11. List the major components of a typical position-light system.
12. Where are position lights located on an aircraft?

13. What colors for position lights are required on an aircraft?

14. What is an anticollision light?

15. Describe the operation of a typical strobelight system.

16. What is the purpose of the trigger signal in a strobelight system?

17. What are the flashing requirements for an anticollision light?

18. How many anticollision lights are typically found on modern aircraft?

19. Where are anticollision lights located?

20. Where are landing lights located?

21. Describe the difference between a landing light and a taxi light.

22. What is the purpose of landing-gear indicator lights?

23. How are landing-gear positions controlled?

24. What is a *proximity sensor* and how is it used in a landing-gear control circuit?

25. Describe an essential lighting circuit for large aircraft.

26. How are essential lights powered in a large aircraft?

27. What types of passenger compartment lights are found on large aircraft?

28. List the various types of exterior lights found on large aircraft.

29. What are the advantages of LED lighting systems?

30. What are proximity sensors?

31. What is the purpose of BITE systems?

32. Describe the functions of an interphone system.

33. Describe the functions of an intercom system.

34. What is the function of the EICAS?

35. How are electric components cooled in a large aircraft?

36. What method is used to cool panel instruments?

37. Describe the function of static dischargers.

38. Where are static dischargers located?

39. Why are static dischargers needed on high-speed aircraft?

40. What are the different types of inspection schedules for light aircraft?

41. What electrical system components are checked during an airframe inspection?

42. Describe the process used during voltmeter troubleshooting.

43. What is an *open circuit*?

44. What are the two types of short circuits?

45. Ammeters are typically used for troubleshooting which electrical system?

46. What is meant by the expression *troubleshooting from the flight deck*?

47. Describe a typical troubleshooting sequence.

48. What is the purpose of a centralized maintenance computer system?

49. What are the three basic types of faults presented by the control display unit?

50. What are the differences between the central maintenance computer system and the central fault display system?

51. What are electrostatic-discharge-sensitive components?

52. Describe the procedure used to protect ESDS components during aircraft maintenance.

53. What is the function of the minimum equipment list (MEL)?

54. Explain how ACARS is used during aircraft maintenance.

55. What is an electronic flight bag (EFB)?

56. Describe the integrated maintenance systems found on modern transport-category aircraft.

57. Describe an integrated maintenance system found on modern light aircraft.

Radio Theory 14

INTRODUCTION

The transmission and reception of radio signals involve the use of electronic equipment to develop electromagnetic and electric fields that are modulated to carry the type of intelligence desired, project these fields into the atmosphere, and then intercept these fields and convert them into usable information or data. In this section the principles of radio transmission and reception are discussed.

Radio for aircraft includes communication equipment, navigation equipment, radar, and other electronic systems. In each of these areas there are many different types of electronic circuitry and devices designed to assure the safe and efficient operation of modern aircraft under all types of weather conditions and air traffic.

Radio transmitters and receivers are particularly important in the vicinity of large commercial airports. In this area the airspace can be very congested, and the pilot must be able to communicate with air traffic control. Special radios are designed for air-to-ground communication. Each airport control tower has one or more assigned frequencies. To ensure the safe operation of an aircraft, the airborne radio-communications equipment must be capable of operating at any control-tower frequency.

Most of the material in this chapter is generic and will apply to almost any type of radio receiver or transmitter. However, there are areas that apply to analog radios and do not apply to digital systems. While reading this chapter, please consider the theory to be presented in terms of analog systems. A specific section has been included to discuss the operation of digital radio technologies and how they differ from analog radios.

RADIO WAVES

Radio signals emanate from the antenna of a transmitter partly in the form of **electromagnetic waves**. Such waves are radiated from any current-carrying conductor when the current periodically changes in magnitude and direction. The radiation of an electromagnetic wave from an antenna may be compared in some respects to a sound wave sent out by a vibrating tuning fork. The sound wave is a mechanical compression and rarefaction of the air caused by the vibration of the tuning fork (see Fig. 14-1).

It was explained in Chap. 1 that a magnetic field surrounds a current-carrying conductor. If the current flow in the conductor changes, the magnetic field will also change. The resulting movement of the field will cause the induction of a voltage in any conductor cut by the moving field; this is due to the process of electromagnetic induction.

During radio transmission, an electric field is generated by the antenna in addition to the electromagnetic field produced. The two fields radiate from the antenna at the speed of light, which is approximately 186 300 mi/s [300 000 000 m/s].

Since a radio wave travels at the speed of light, it can readily be understood that when a transmitter starts operation, the signal from that transmitter may be detected "instantly" hundreds or thousands of miles from the transmitter. The actual transmission distance depends on the power of the transmission and the nature of the wave being transmitted.

The **electromagnetic** and **electric fields** produced by a radio transmitter antenna are at right angles to each other, as shown in Fig. 14-2. The polarization of the fields with respect to vertical or horizontal positioning depends on the design and position of the antenna from which they are being emitted. The polarity of the fields reverses rapidly, with the rate of reversal established by the frequency of the wave.

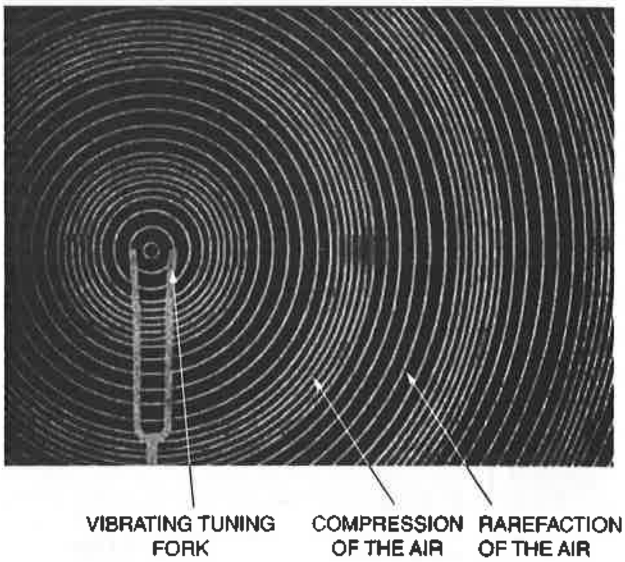


FIGURE 14-1 Sound wave emanating from a tuning fork.

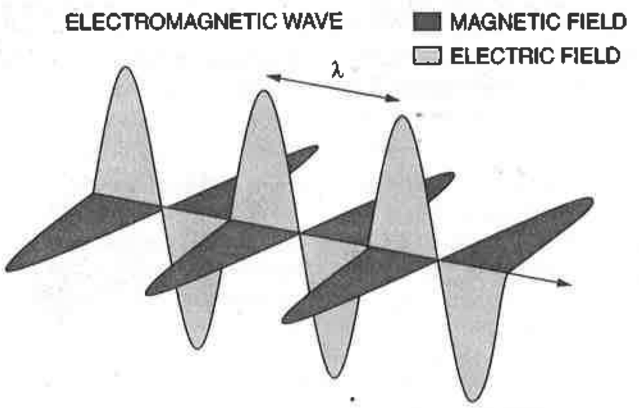


FIGURE 14-2 Electric and electromagnetic waves as radiated from a radio transmission antenna.

The electromagnetic field radiated by an antenna accounts for the majority of the energy being transmitted. As illustrated in Fig. 14-3, the electromagnetic wave travels from the transmitter's antenna to the receiver's antenna. The transmitter typically radiates an electromagnetic signal in a 360° pattern from the antenna. The electromagnetic wave travels through the air and passes the receiver's antenna. Acting as an inductor placed in a moving magnetic field, the receiver's antenna produces an induced voltage and sends current into the radio receiver circuitry. The current produced in the receiver's antenna has proportionately the same characteristics (frequency and amplitude) as the current of the transmitter's antenna. The induced-current flow is very weak and therefore must be amplified in order to produce a usable signal.

Wavelength and Frequency

The length of a radio wave depends on its **frequency**. Like an ac sine wave, the wave emanating from an antenna increases to a maximum in one direction, drops to zero, and then increases to a maximum in the opposite direction, as indicated by the curve in Fig. 14-4. The **wavelength**, indicated by the Greek letter lambda (λ), is the distance from the crest of one wave to the crest of the next. Since the wave travels at the rate of 300000000 m/s, the wavelength in meters is equal to 300000000 divided by the number of cycles per second (hertz). If a wave is produced at the rate of 1 Hz, the length of the wave will be 300000000 m. If 300 cycles are produced per second, the wavelength will be 1000000 m [328000000 ft]. The equation for wavelength is

$$\lambda = \frac{300000000}{f}$$

If the wavelength is known, the frequency may be found by the equation

$$f = \frac{300000000}{\lambda}$$

For example, if an aircraft's VHF communication radio is operating at 30 MHz, the wavelength is determined as follows:

$$\lambda = \frac{300000000}{f}$$

$$f = 30\text{ MHz, or } 300000000\text{ Hz}$$

$$\lambda = \frac{300000000}{30000000}$$

$$= 10\text{ m}$$

The distance between crests of the 30-MHz wave is 10 m; λ = 10 m.

Frequency Bands

Frequencies utilized in various types of radio systems range from 3 kHz to as high as 300 gigahertz (GHz). The frequencies are divided into eight bands, and these bands are assigned to certain types of operations. The table on the next page shows the utilization of the various bands.

Above this radio frequency spectrum lie the various light, x-ray, and gamma ray frequencies. Infrared and white light are currently being used for some information transmission

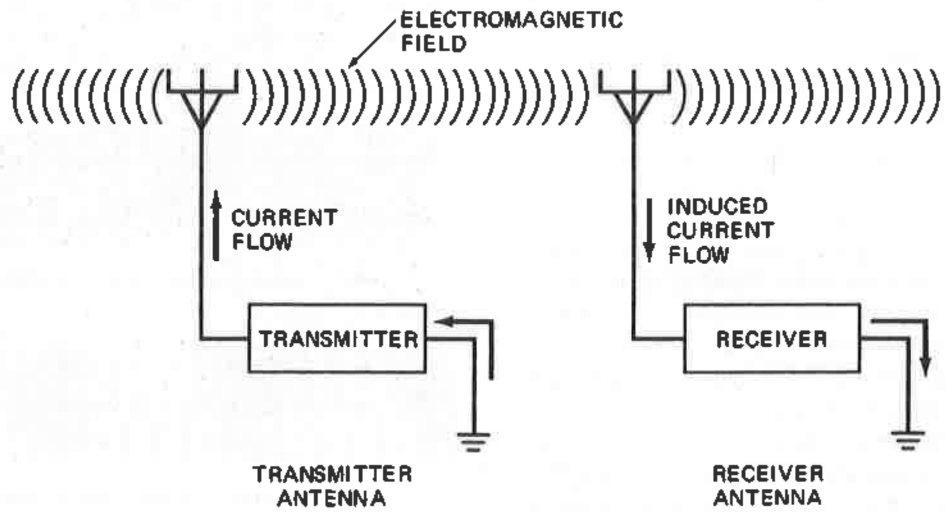


FIGURE 14-3 Radiation of an electromagnetic wave from a transmitter to a receiver.

Designation	Frequency range	Wavelength	Utilization
Very low frequency (VLF)	3–30 kHZ	100 000–10 000 m	Navigation, time signals (currently unused)
Low frequency (LF)	30–300 kHz	10 000–1000 m	Navigation, broadcasting, maritime mobile, fixed
Medium frequency (MF)	300–3000 kHz	1000–100 m	Broadcasting, maritime mobile, aeronautical navigation
High frequency (HF)	3–30 MHz	100–10 m	Broadcasting, amateur, maritime and aeronautical, citizens' band (CB)
Very high frequency (VHF)	30–300 MHz	10–1 m	FM and TV broadcasting, aeronautical navigation and communication, amateur, maritime mobile
Ultrahigh frequency (UHF)	300–3000 MHz	1 m–10 cm	TV broadcasting, radar, aeronautical and maritime mobile, navigation, radio location, space communication, meteorological
Superhigh frequency (SHF)	3–30 GHz	10 cm–1 cm	Space and satellite communication, radio location and navigation, radar
Extremely high frequencies	30–300 GHz	1 cm–1 mm	Space and satellite communication

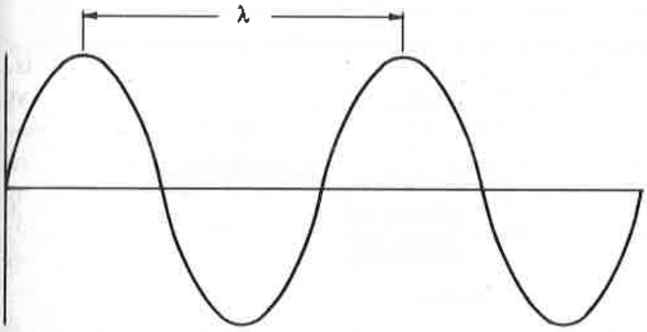


FIGURE 14-4 Wavelength of a sine wave.

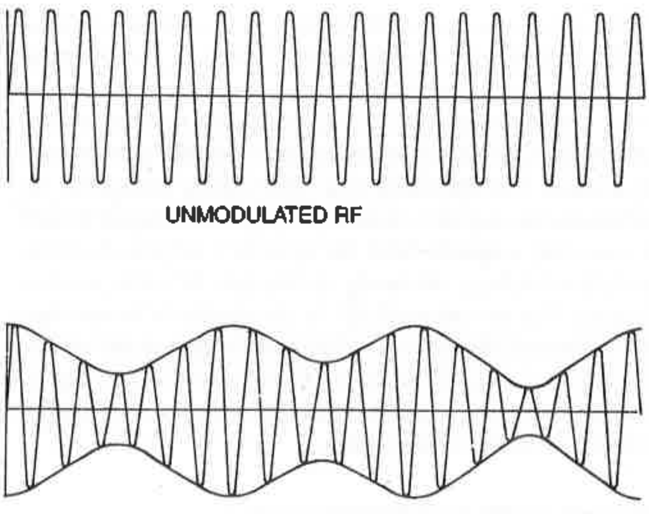


FIGURE 14-5 Carrier waves: unmodulated and modulated.

at frequencies between 10^9 and 10^{11} kHz. Below the radio frequency spectrum are the audible sound waves, ranging from 20 Hz to 15 kHz. Long-distance transmission of data at these frequency levels is virtually impossible, because any information transmitted would simply be heard by anyone receiving the sound wave.

The Carrier Wave

The field of electric and electromagnetic energy that carries the intelligence of a radio signal is called a **carrier wave**. The frequency of this carrier wave may be only a few hundred kilohertz or several thousand megahertz. Carrier waves are usually in the **radio frequency** (RF) range, which is in excess of 20000 Hz. Frequencies below 20000 Hz are in the **audio frequency** (AF) range.

In order to carry intelligence, an RF carrier wave must be modulated. This means that its form and characteristics are changed by means of some type of signal impressed upon it. Figure 14-5 shows an unmodulated carrier wave and a wave that has been modulated in amplitude by an AF signal. An RF carrier wave that has been modulated in amplitude is called an **amplitude-modulated (AM)** signal. If a voice signal is impressed upon a carrier, the modulation curve will follow the pattern of the voice frequencies.

Frequency modulation can be used in the VHF range and above. This type of modulation, commonly called **FM**, provides a signal that is much less affected by interference than an AM signal. As indicated by the name, frequency modulation is accomplished by varying the frequency of the carrier wave in accordance with the audio signal desired. Figure 14-6 shows how frequency modulation affects a carrier wave.

The carrier waves emitted by a radio transmission antenna may be broken into three different categories: ground waves, sky waves, and space waves. Low-frequency waves (up to

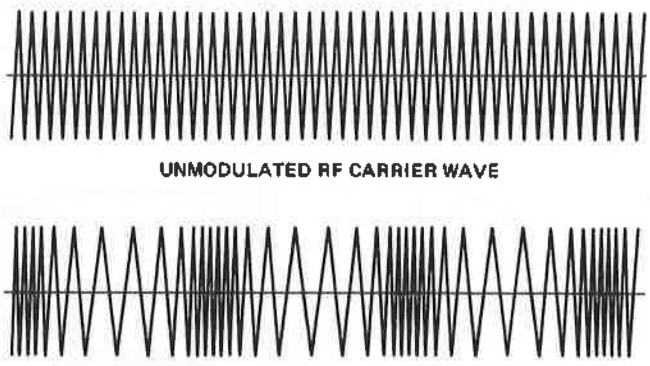


FIGURE 14-6 Frequency modulation.

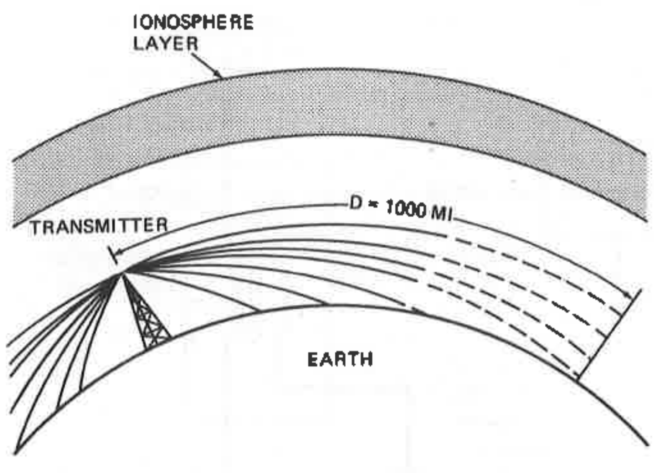


FIGURE 14-7 Ground-wave transmission pattern.

about 2 MHz) are considered ground waves. As illustrated in Fig. 14-7, **ground waves** tend to be held near the earth's surface and "bend" with the curvature of the earth. Ground waves will travel a distance limited by the transmitter's output power, antenna design, local terrain, and current weather conditions. Typically, a relatively powerful transmitter is capable of sending ground waves a maximum of 1000 mi.

Sky waves, which are produced in frequencies from 20 to 30 MHz, tend to travel in straight lines. As illustrated in Fig. 14-8, sky waves may be transmitted in a straight path or reflect off the ionosphere layer in order to reach the receiving antenna. Because of this means of travel, sky waves may produce a skip zone, where no reception is possible. Neither the line-of-sight wave nor the reflected wave can be received in the skip zone. The ionosphere density and distance from the earth determine the skip-zone range and the exact frequencies that are reflected. The ionosphere is a layer of ionized gases that surrounds the earth at an altitude of about 60 to 250 mi [96.6 to 402.6 km], varying with the time of day, the season, and the location. The density of this layer is affected mainly by the sun's solar flare activities. All these factors will determine the exact frequencies that are reflected and their angle of reflection off the ionosphere.

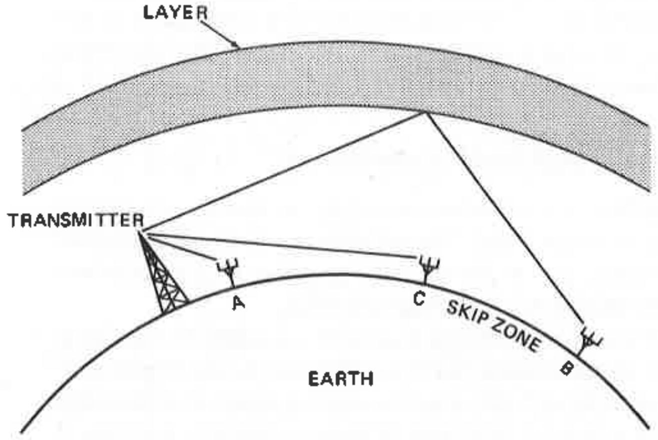


FIGURE 14-8 Sky-wave transmission pattern.

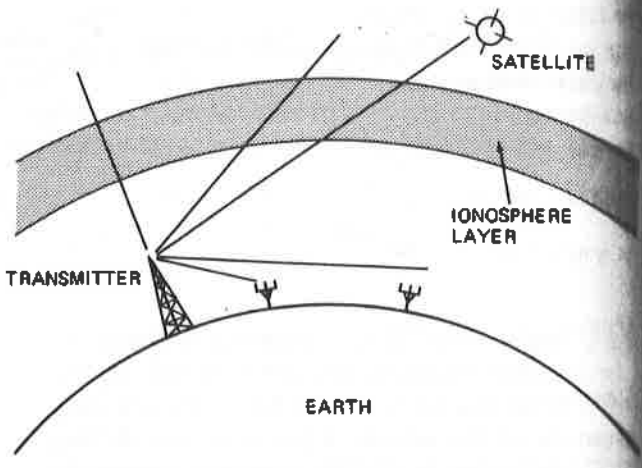


FIGURE 14-9 Space-wave transmission pattern.

Space waves are found in frequencies above 30 MHz. Because of their high frequencies, space waves have a short wavelength, which allows them to travel through the ionosphere layer. As illustrated in Fig. 14-9, space waves are limited to line-of-sight reception. The properties of high-frequency space waves make satellite and space communications possible. Most aircraft communication and navigation radio frequencies are those for space waves; therefore, transmission is limited to line of sight. This means that there should be no mountains, buildings, or other objects between the transmitter and the receiver if good reception is to be expected.

Antennas

An **antenna** is a specially designed conductor that accepts energy from a transmitter and radiates it into the atmosphere. During reception, an antenna acts as a device that receives an induced current from passing electromagnetic waves. This induced current is then sent to the radio receiver circuitry. Where transmitters and receivers are built into one unit, often called a **transceiver**, the same antenna may serve for both transmitting and receiving.

The size and design of antennas vary in accordance with the frequency or frequencies of the radio signals for that radio. As frequencies increase, the length of the antenna must decrease. This is because wavelengths decrease as frequencies increase, and the length of an antenna must be matched as closely as possible to the wavelengths of the carrier waves. Typical antenna lengths are full-wave (the same length as the carrier wave), half-wave, quarter-wave, and some other fraction of the wavelength. It should be noted that antennas of these lengths will produce the strongest current flow for a given RF signal; however, shorter antennas are often used with modern amplifier systems that compensate for antenna inefficiencies. Smaller, less efficient antennas produce less drag on the aircraft, and they can be placed behind nonconductive panels to produce a **flush mounted antenna** system.

The simplest form of receiving antenna is merely a length of wire insulated from the ground and connected to the antenna coil of the receiver. The wire is cut by radio waves, and these waves induce very small voltages of many frequencies in the wire. The signal for which the receiver is tuned will pass through the receiver and to the loudspeaker in a form suitable for sound reproduction.

The correct antenna length (half-wave) for either a transmitter or a receiver is determined by using the following equation:

$$l = \frac{468}{f}$$

where l = length, in feet, and f = frequency, in megahertz. This equation gives the length for a half-wave antenna. The figure 468 in the equation is a factor derived by converting meters per second into millions of feet per second, dividing by 2, and multiplying by 0.95 the correction constant for antennas.

The equation for the length of a half-wave antenna is also expressed as

$$l = \frac{300000000 \times 3.28}{2 \times f}$$

In this equation the correction constant 0.95 is ignored. The principal objective in constructing an antenna and antenna-coupling system is to match the output impedance of the transmitter with the input impedance of the antenna system.

Remember, as discussed in Chap. 5 ("Alternating Current"), impedance is the total opposition to current flow in an ac circuit. Impedance is a function of the resistance, capacitive reactance, and inductive reactance. Since all RF waves are ac waves, their total opposition to current flow is impedance Z.

The simplest types of antennas are the **Hertz** antenna and the **Marconi**, or vertical, antenna. The Hertz antenna consists of two lengths of wire extended in opposite directions, as shown in Fig. 14-10. Each length of wire is $\frac{1}{4}$ wavelength ($\frac{\lambda}{4}$) long. (A study of a sine wave shows that $\frac{1}{4}$ wavelength permits voltage or current to increase from zero to maximum in one direction.) The two lengths of wire are fed by the transmitter at the center; hence one length will become negative as the other becomes positive.

Coupling from a transmitter to an antenna is normally accomplished by means of an ***LC* circuit**. A typical coupling circuit for a coaxial transmission line and a dipole antenna is shown in Fig. 14-11, but this is only one of the many possible arrangements.

The proper coupling of an antenna to a transmitter is essential for the maximum radiation of energy. The input impedance of the antenna must be matched as closely as possible to the internal impedance of the transmitter, and the effective length of the antenna must be adjusted to the wavelength of the signal being broadcast. The coupling circuit in the transmitter accomplishes these requirements. When a transmitter is being prepared for operation, it is necessary to determine that a signal of the maximum strength will be radiated from the antenna. The antenna output is checked by means of a standing-wave ratio (SWR) meter. If the meter indicates poor signal radiation, the coupling circuit can be adjusted.

FIGURE 14-10 The Hertz dipole antenna.

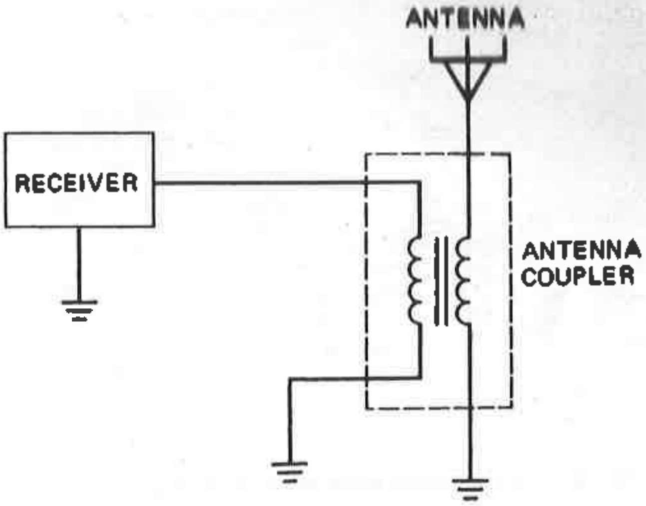


FIGURE 14-11 A simple antenna coupler.

Since antennas are inductors, their effective length may be changed by adding an inductance coil in series or parallel with the antenna element. Inductors in parallel will decrease the antenna's total inductance. Inductors in series will increase the antenna's total inductance. The fine tuning of an antenna may be performed by adjusting a variable inductor in the antenna coupler circuit. This is known as "peaking" the antenna.

AMPLIFIERS

Definition

An **amplifier** is a circuit that receives a signal of a certain amplitude and produces a signal of greater amplitude. The amplification may affect voltage or power or both, but its principal purpose is to increase the value of a weak signal so that it may be used to operate a speaker or some other electronic device.

Classification of Amplifiers

Amplifiers are classified according to function, operating level, or circuit design. The function may be to amplify power or voltage, and in this case the amplifier is described as a **power amplifier** or a **voltage amplifier**.

When an amplifier is classified according to operating level, the classification refers to the point on the characteristic curve through which the transistor operates as established by the emitter-to-base bias. A **class A** amplifier operates at a level such that the emitter-collector current flows at all

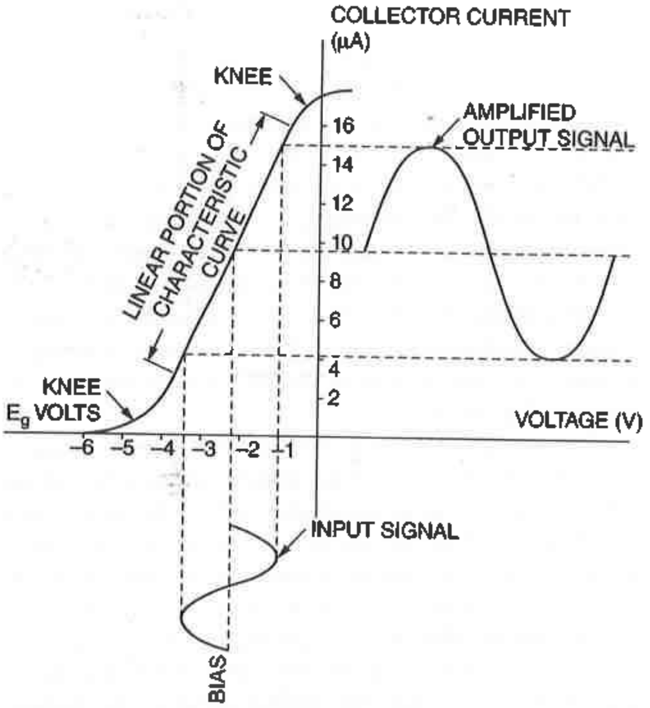


FIGURE 14-12 Operation curves for a class A amplifier.

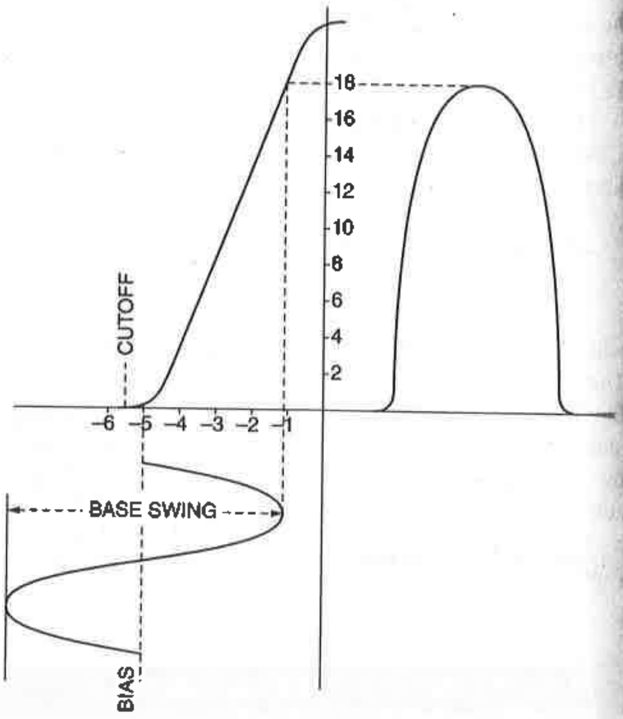


FIGURE 14-13 Operation curves for a class B amplifier.

times because the voltage never reaches a sufficiently negative value to cut off the electron flow. The operation of this type of amplifier is shown by the curves in Fig. 14-12. It will be seen that the transistor is biased near the center of the linear portion of the operating curve. The class A amplifier provides for a minimum of distortion of the signal; hence it is used where maximum fidelity is desired.

A **class B** amplifier is biased at approximately the cutoff point. With this arrangement only one half of the signal will be amplified, but the amplification can be carried to a much higher level than it can be by a class A amplifier because a much greater bias range is possible. Class B amplification is often used in **push-pull** amplifiers, in which two transistors are employed, one amplifying one half of the signal and the other amplifying the other half. The two amplified halves of the signal are recombined in the output circuit to produce a signal of low distortion and high power. The curves in Fig. 14-13 illustrate the operating level of a class B amplifier and the curves in Fig. 14-14 show how class B amplification performs in a push-pull circuit. Note that one half of the signal is amplified by transistor 1 and the other half by transistor 2. The circuit for a push-pull amplifier is shown in Fig. 14-15.

In **class C** amplification the emitter-base circuit of the transistor is biased well beyond the cutoff point so that only a small portion of the positive peaks of the signal is amplified. Current flows only during approximately 120° of the cycle. The use of class C amplifiers is limited to RF circuits because only a part of the signal curve is reproduced. In an RF circuit, when the output of the class C amplifier is fed into an *LC* system, the flywheel effect of the tank supplies the missing parts of the signal curves. The E_b-I_c curves for a class C amplifier are shown in Fig. 14-16.

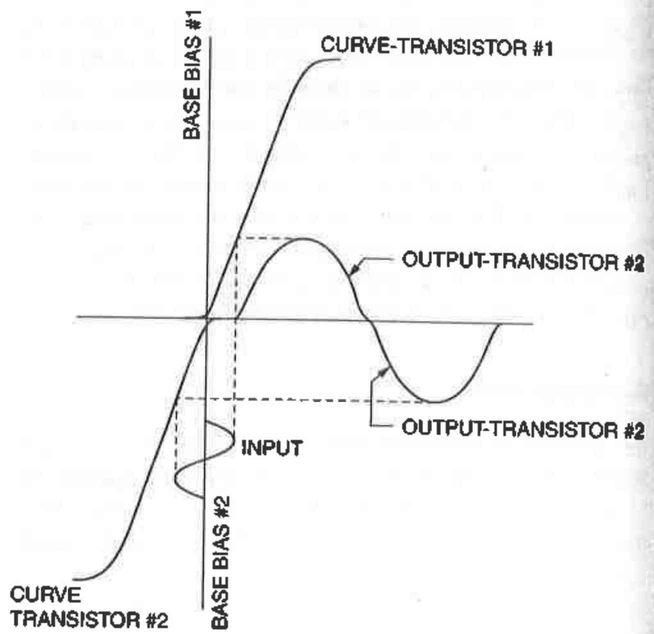


FIGURE 14-14 Class B amplification in a push-pull circuit.

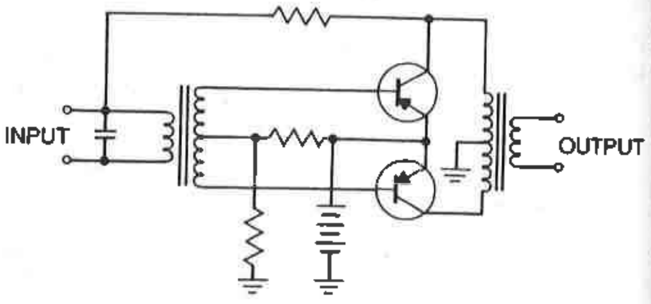


FIGURE 14-15 Circuit for a push-pull amplifier.

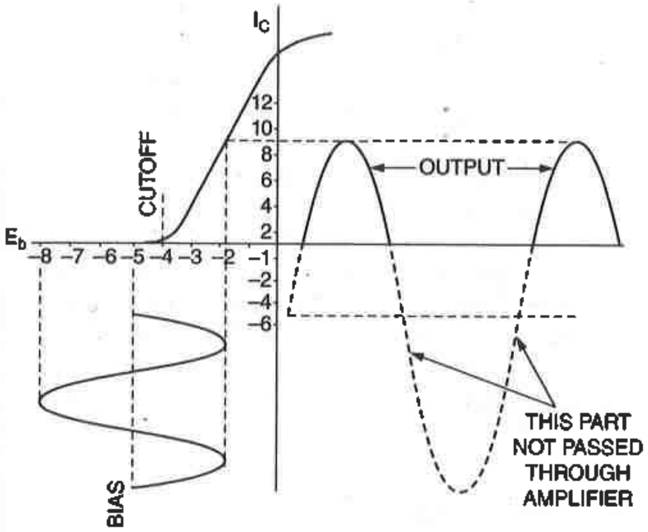


FIGURE 14-16 Operation curves for a class C amplifier.

FUNCTIONS OF A TRANSMITTER

A radio transmitter has several functions and one final objective. Briefly, the functions are (1) to generate an RF carrier wave; (2) to amplify the carrier wave; (3) to modulate the carrier wave with a sound wave, digital signal, or some other form of information; (4) to amplify the modulated signal, (5) to couple the modulated signal to an antenna; and (6) to radiate the signal into the atmosphere. All these functions except the last are performed by circuits within the transmitter system so that the final objective is accomplished. The radiation of the signal is accomplished by the antenna.

A block diagram of a typical radio transmitter is shown in Fig. 14-17. This is only one of many possible arrangements.

Microphones

The purpose of a **microphone** (MIC) is to convert sound energy into electric energy. This process is completed by using the dynamic energy of the sound wave produced by the pilot. The sound wave strikes a diaphragm, and the sound energy is converted into mechanical energy. The mechanical energy is then converted into electric energy.

There are three common aircraft microphones: **carbon**, **dynamic**, and **electret**. Each microphone is shown in Fig. 14-18, refer to this diagram during the following discussion. Each uses a different means to create the electric signal that is sent to the radio transmitter. The **carbon MIC** contains tiny carbon granules compressed in a sealed chamber. The voice diaphragm vibrates the carbon chamber, changing the resistance of the carbon granules. A current that passes through the granules changes in amplitude as the sound wave moves the diaphragm. A carbon microphone requires a power source as shown by the battery in Fig. 14-18*a*.

The **dynamic MIC** uses the process of electromagnetic induction to produce the electric signal. The diaphragm of this MIC is connected to an inductance coil. As the pilot's voice moves the voice diaphragm, the coil moves into and out of a magnet core. This movement produces a current flow. The signal is then amplified and sent to the radio transmitter.

The **electret MIC** uses two plates, similar to a capacitor, to control the electric current. This MIC's diaphragm moves one of the plates, and this motion changes the distance between the plates. This controls the current flow in the MIC circuit. An electret MIC requires a power source as shown in the diagram. The electret MIC is currently the most common type of MIC found on modern aircraft. Many modern aircraft radio systems employ **noise-canceling MIC**. This unit contains two MIC elements mounted in a single housing; one MIC is directed to receive the pilot's voice as well as cabin noise, the other MIC is directed away from the pilot to monitor only cabin ambient noise. The MIC is designed so the cabin noise entering from two different directions cancels and only the pilot's voice is sent to the amplifier circuitry. Electronic circuitry can also be used to perform the cancellation of cabin ambient noise. Today, noise-canceling technologies have become the system of choice for most pilots.

Use of Oscillators

An **oscillator** is a circuit designed to generate an alternating current that may be of a comparatively low frequency or of a very high frequency, depending on the design of the oscillator.

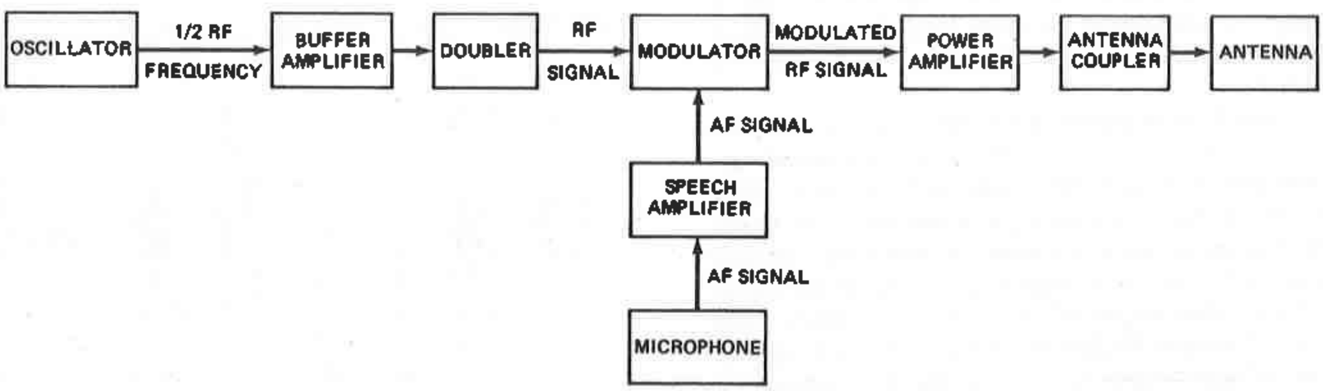


FIGURE 14-17 Block diagram of a radio transmitter.

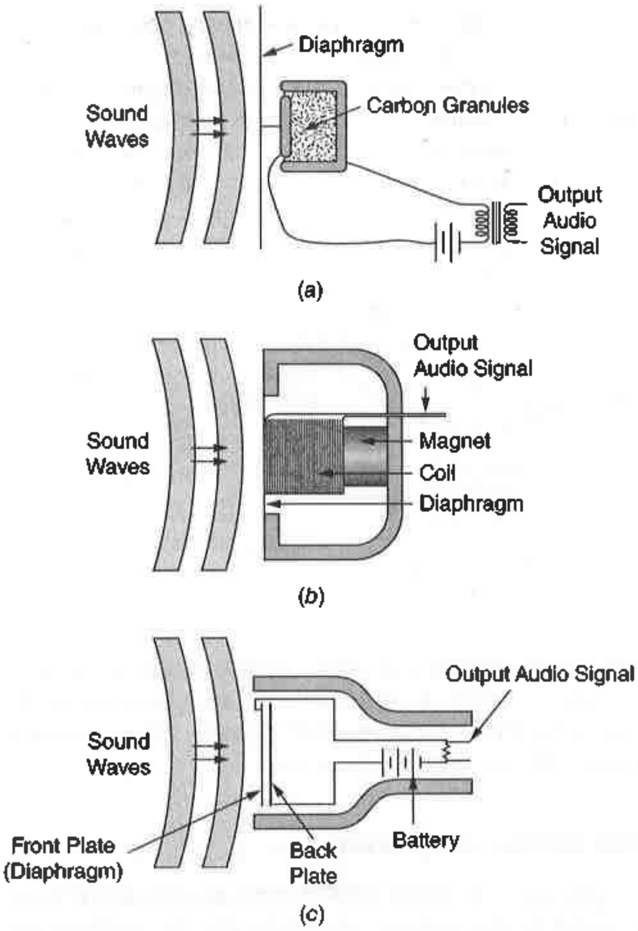


FIGURE 14-18 Three common microphone configurations: (*a*) a carbon MIC, (*b*) a dynamic MIC, and (*c*) an electret MIC.

Oscillators are used in radio transmitters to generate the RF carrier waves, in receivers to produce the intermediate frequency, and in other circuits and systems in which it is necessary to develop an alternating current with a particular frequency.

Oscillator Theory

Fundamentally, an oscillator consists of an ***LC* tank** circuit, a transistor, and a means of feedback to supply power to replace signal losses.

Examine the simple tank circuit in Fig. 14-19. A battery is connected with a double-throw switch to a capacitor *C*.

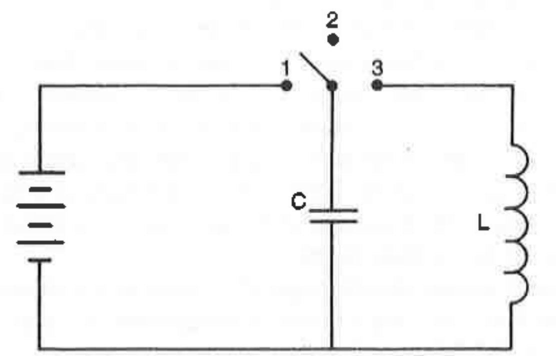


FIGURE 14-19 A simple tank circuit.

When the switch is thrown to position 1, the capacitor will charge to the voltage of the battery. If the switch is then placed to position 2, the battery will be disconnected from the capacitor, and the capacitor will retain its charge. Now when the switch is moved to position 3, the capacitor will be connected to the inductor *L* and will discharge through the inductance coil. When the capacitor first starts to discharge, the current through *L* will build a magnetic field that induces an opposing voltage in *L*. This slows the discharge of *C*. When *C* becomes almost discharged, the field around *L* will begin to collapse, and this will induce a voltage that keeps the current flowing. This induced voltage charges the capacitor in a direction opposite to that in which the battery originally charged it.

When the charge of the capacitor reaches a voltage equal to the induced voltage in *L*, the current flow will stop, and the capacitor will start to discharge back through *L*, with current flowing in the correct opposite direction. This action will be continuously repeated, with the energy stored first in the capacitor and then in the field of the inductance coil. An alternating current results that will degenerate to zero because of losses sustained in the circuit. If we could replace the small amount of energy lost during each cycle, we could prolong the generation of alternating current indefinitely. Oscillator circuits must contain some means of applying energy to the tank circuit in order to maintain a constant frequency and power output.

The operation of an oscillator may be compared to the operation of the pendulum of a clock, as illustrated in Fig. 14-20. If the pendulum is raised to the far right position and set free, it will travel in one direction to the center position, where it reaches a maximum velocity, and then swing up to the far left position. At the end of the swing, the motion of the pendulum stops and reverses direction, just as an ac current stops and reverses direction; the pendulum then swings back to the right, gaining speed to a maximum velocity and then slowing until it reaches the far right. This process then repeats. In a clock the mainspring adds power to the pendulum in order to maintain a constant frequency. The pendulum would eventually stop, owing to friction losses, if power were not added.

A **simple oscillator circuit** is illustrated in Fig. 14-21. If *SW*, is closed, the transistor is forward-biased, and current flows through L_2. At this time the transistor base is connected to positive voltage through R_B, and the emitter is connected to the battery negative. The current flow through L_2 produces a magnetic field. This magnetic field induces a current into L_1, thus charging the tank circuit. The tank circuit now produces an alternating current between L_1 and C_1. This current flow applies a negative voltage to the base of the transistor for one-half of every cycle. This negative signal to the base reverse-biases the transistor emitter-base circuit and turns off the transistor. Current flow through the emitter-collector and L_2 circuit is, therefore, pulsating. The circuit is designed to allow the correct amount of pulsating current through L_2 in order to maintain a constant frequency in the tank circuit.

The exact frequency of the oscillator will be a function of the inductance of L_1 and L_2, the capacitance of C_1, and the

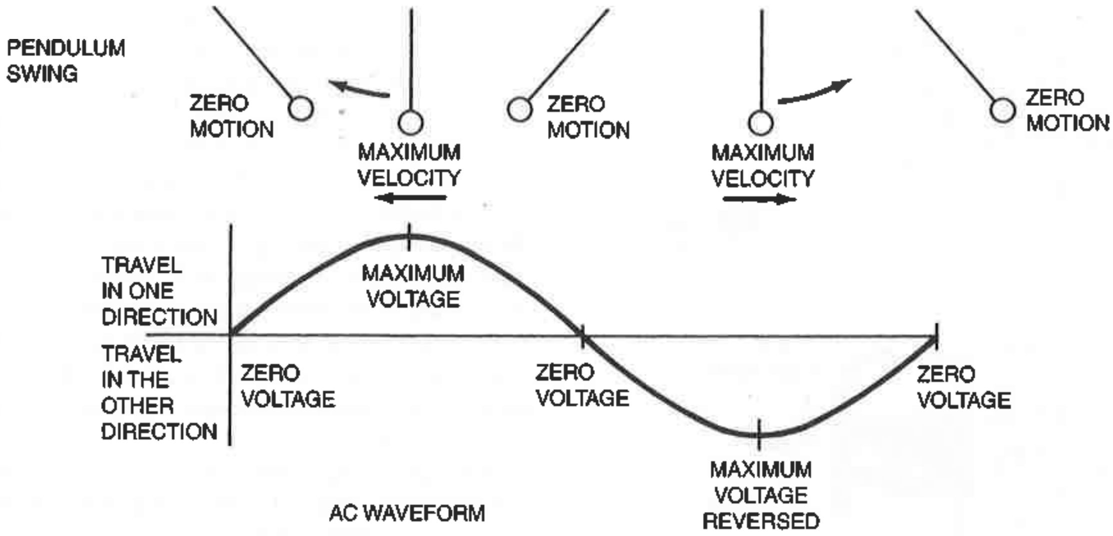


FIGURE 14-20 Pendulum representation of a tank circuit.

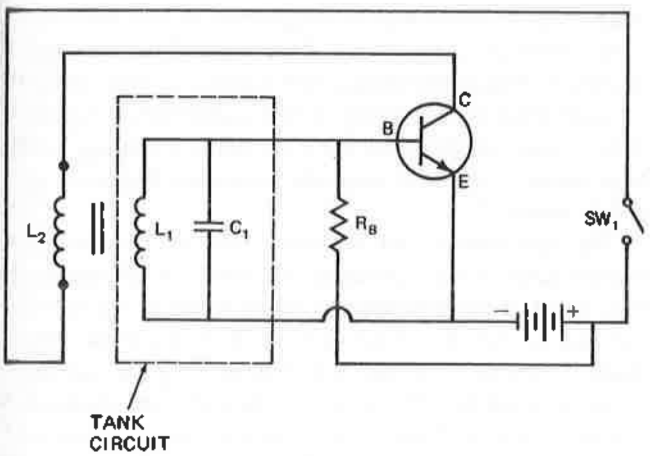


FIGURE 14-21 A simple oscillator circuit.

current flow through the transistor. There are several different types of oscillators currently in use. The Armstrong, Hartley, and Colpitts oscillators are three common types. Each of these oscillators contains a variation of the basic tank circuit previously described.

A basic **crystal-controlled oscillator** circuit is shown in Fig. 14-22. In this circuit the crystal takes the place of the tank circuit employed in other oscillators, and feedback is provided by means of capacitive coupling. Maximum amplitude of the RF signal is obtained when the output circuit is tuned to the frequency of the crystal.

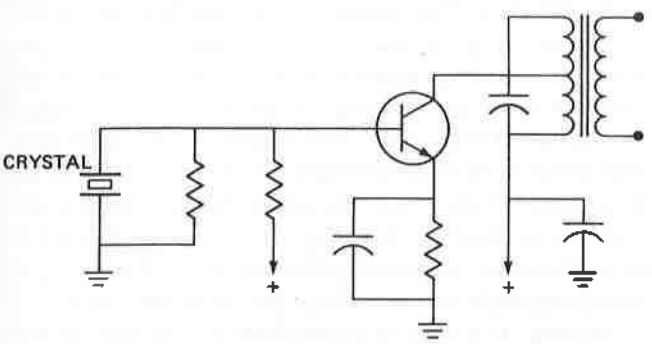


FIGURE 14-22 A crystal-controlled oscillator circuit.

The Buffer Amplifier

The purpose of the **buffer amplifier** is to amplify the RF signal produced by the oscillator without loading the oscillator circuit which could cause a change in the output frequency. This means the amplifier must not draw power from the oscillator. Because the buffer amplifier must be extremely sensitive it is usually an amplifier operated as a class A type, which has no appreciable base current flow. A field-effect transistor (FET) is ideal for this application because emitter-collector current is controlled by the strength of an electric field rather than current flow through the base circuit. The RF current is coupled to the next amplifier stage through the coupling capacitor and a tank circuit. If it is desired, the tank may be used as a frequency multiplier by having it tuned to a higher multiple of the oscillator frequency. If the tank is tuned to twice the oscillator frequency, it is called a **doubler**; if it is tuned to three times the frequency of the oscillator, it is called a **tripler**.

Frequency Multipliers

Most oscillator circuits produce a frequency that is below the actual RF required for signal transmissions. Due to the nature of the circuit design, it is difficult to produce high-frequency oscillators without distortion to the waveform.

To overcome the frequency limit, **frequency-multiplying circuits** are employed. These may be doublers or triplers, depending on the frequency of the tank circuit into which the output of the oscillator is fed.

The principal disadvantage of a frequency-multiplying circuit is that the output power is considerably less than it is from an amplifier operating straight through, that is, one in which no change in frequency takes place.

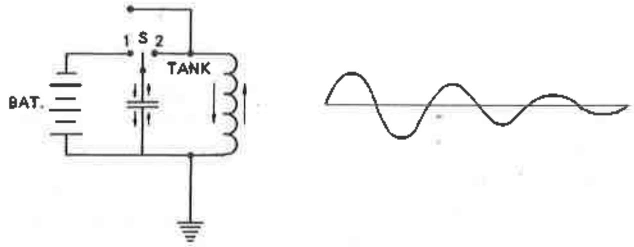


FIGURE 14-23 Operation of a tank circuit.

The principle of frequency multiplication may be understood by considering the action of a tank circuit. Any tank circuit has a resonant frequency that is determined by the values of its capacitance and inductance according to the equation

$$f = \frac{1}{2\pi\sqrt{LC}}$$

If the capacitor in Fig. 14-23 is charged by means of the battery through the switch S in position 1 and the switch is then shifted to position 2, the electrons stored on one plate of the capacitor will start to flow through the inductance coil toward the opposite side of the capacitor. Current flow through the inductance coil will create a magnetic field in which is stored electric energy. When the current flow begins to decrease, the inductance coil tends to keep it flowing, and so the capacitor becomes charged in the opposite direction. Thus the cycle continues back and forth, with the energy being stored alternately in the electrostatic field of the capacitor and in the electromagnetic field of the inductor. Because of the resistance in the circuit, the alternating current will degenerate and disappear unless additional energy, is supplied to keep it up.

In a frequency multiplier, the energy to maintain current flow is supplied by the transistor output. If the transistor is connected as a class C amplifier, the output will be in the form of widely separated pulses, as shown in Fig. 14-24.

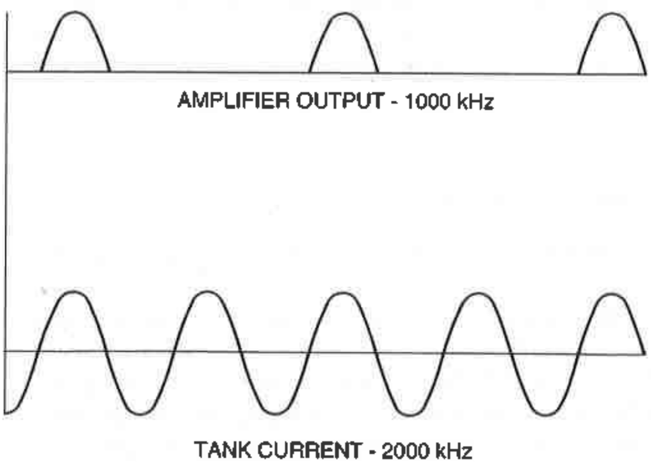


FIGURE 14-24 Voltage curves to illustrate the operation of a frequency doubler.

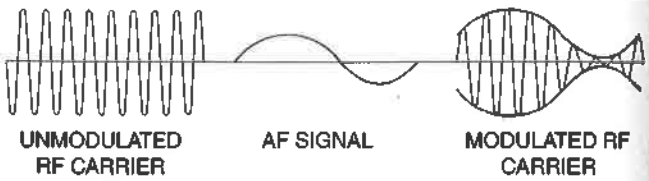


FIGURE 14-25 Modulation of an RF carrier wave.

In this illustration the amplifier output is shown as separate pulses with a frequency of 1000 kHz; the tank current is sustained at 2000 kHz.

The action of a frequency multiplier may be compared to the action of a child in a swing. The swing may be kept going easily by applying a short push at every second or third swing. In Fig. 14-24 the short push is the amplifier pulse, and the swing in motion is the tank current.

The Modulator

The function of the **modulator**, or modulation circuit, in a transmitter is to impress a signal on the RF carrier wave. In communication radios this signal usually consists of an AF sound wave; however, the carrier may also be modulated by means of a digital pulse to produce code signals.

The modulation of a carrier wave is illustrated in Fig. 14-25. As explained previously, this type of modulation is called **amplitude modulation** (AM). In an aircraft radio, amplitude modulation is employed for all voice transmissions. To obtain the greatest efficiency from a modulator, it is necessary that the maximum modulation be of an amplitude that will increase the unmodulated RF carrier to twice its unmodulated amplitude. Likewise, the negative peaks of modulation power should be of a value that will reduce the RF carrier to zero amplitude. When these conditions exist, the modulation is 100 percent. Figure 14-26 illustrates 100 percent modulation. If a smaller degree of modulation takes place, the full potential of the carrier is not utilized. Or if the modulating wave has too great an amplitude, overmodulation will occur, and the signal will be distorted.

In the modulator, the audio signal is applied to the base circuit of a transistor, thus modifying the emitter-collector current. The circuit in Fig. 14-27 illustrates a simple transistorized amplitude modulator. This circuit is not typical of

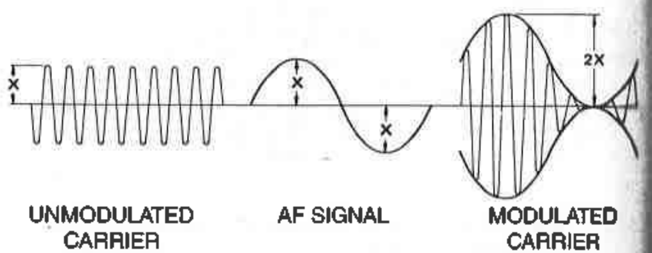


FIGURE 14-26 One hundred percent modulation.

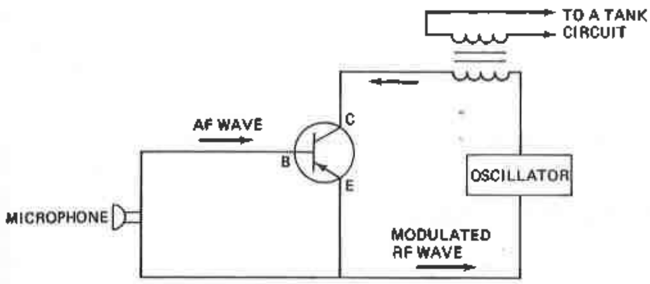


FIGURE 14-27 A simple transistorized amplitude modulator.

those found in radio transmitters; however, it is appropriate to convey the basic modulation principles. In this circuit the microphone signal is sent to the emitter-base circuit of the transistor. As the microphone produces a signal of a given frequency, the transistor connects the emitter-collector circuit at that same frequency. The RF wave produced by the oscillator will travel through the transistor and change amplitude according to the frequency produced by the microphone. The RF signal sent to the emitter-collector circuit is an ac waveform; therefore, the transistor will be reverse-biased for one-half of the RF signal. The resultant transistor output is a half-wave rectified, modulated RF wave. This output signal must be sent to a tank circuit in order to reproduce an ac radio frequency signal.

The AF wave produced by the microphone is illustrated in Fig. 14-28*a*. The modulated RF wave as it leaves the transistor is illustrated in Fig. 14-28*b*. This signal enters a tank circuit, which produces an alternating current RF wave, as shown in Fig. 14-28*c*. As illustrated, point *A* of the AF signal is the peak of the wave produced by the microphone. Points A_1 and A_2 are the peaks of the modulated RF wave. Point *B* of the AF wave is the lowest value produced; points B_1 and B_2 are the lowest amplitude of the modulated RF wave. From this example it is easy to see that the RF wave changes amplitude in the exact pattern as the AF wave sent to the base of the modulating transistor. Once the signal is sent through the tank circuit, amplitude modulation is complete.

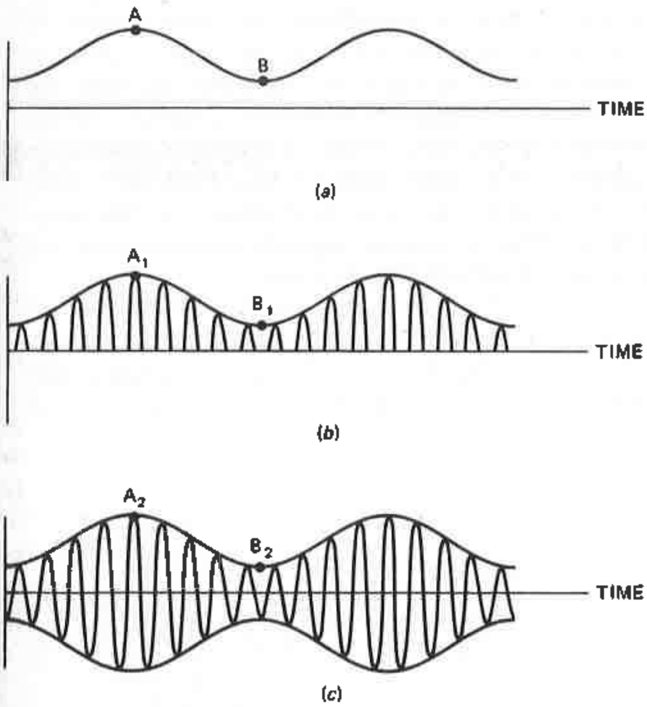


FIGURE 14-28 Waveforms of a modulator: (a) The AF wave; (*b*) half-wave rectified, modulated RF wave; (c) ac modulated RF wave.

Power Amplifiers

The function of the **power amplifier** of a transmitter is to increase the power level of the modulated signal to the point where it meets the requirements of the transmitting system. Radio transmitters employ power transistors that are designed to carry the current required. The output of the power amplifier is coupled to the antenna by means of an antenna coupler circuit.

Class C amplifiers are typically the most efficient type of power amplifier. Class C power amplifiers produce a pulsating dc output; therefore, they must be used in conjunction with a tank circuit to restore the sine wave signal. Figure 14-29*a* illustrates a class C power amplifier and related tank circuit. The signal that enters the transistor emitter-base circuit creates a forward bias only at the peak positive values of the waveform. At any lower positive or negative value, the emitter-collector circuit allows current to flow only for short intervals. This current pulse feeds the tank circuit by instantly creating a strong positive charge on the capacitor. The tank circuit then produces a sine wave signal at an amplified power level that follows the same pattern as the emitter-base signal. The output of the tank circuit is connected to an antenna coupler, which connects the sine wave to the antenna for transmission. Figure 14-29*b* shows the signal sine waveforms that enter and leave the transistor, along with the output signal of the tank circuit. Notice that the input and output waveforms are identical except for power levels.

Antenna Couplers

An **antenna coupler** is a circuit that connects the amplifier of a transmitter to its antenna. An antenna coupler may be a simple isolation transformer, or it may be much more complex, containing *LC* circuits and/or a lightning arrester circuit. The *LC* circuit is used to "tune" or "peak" the antenna to the transmitter. Lightning arresters are used to protect radio circuits from unwanted lightning strikes on the antenna. Figure 14-30 illustrates two types of antenna couplers.

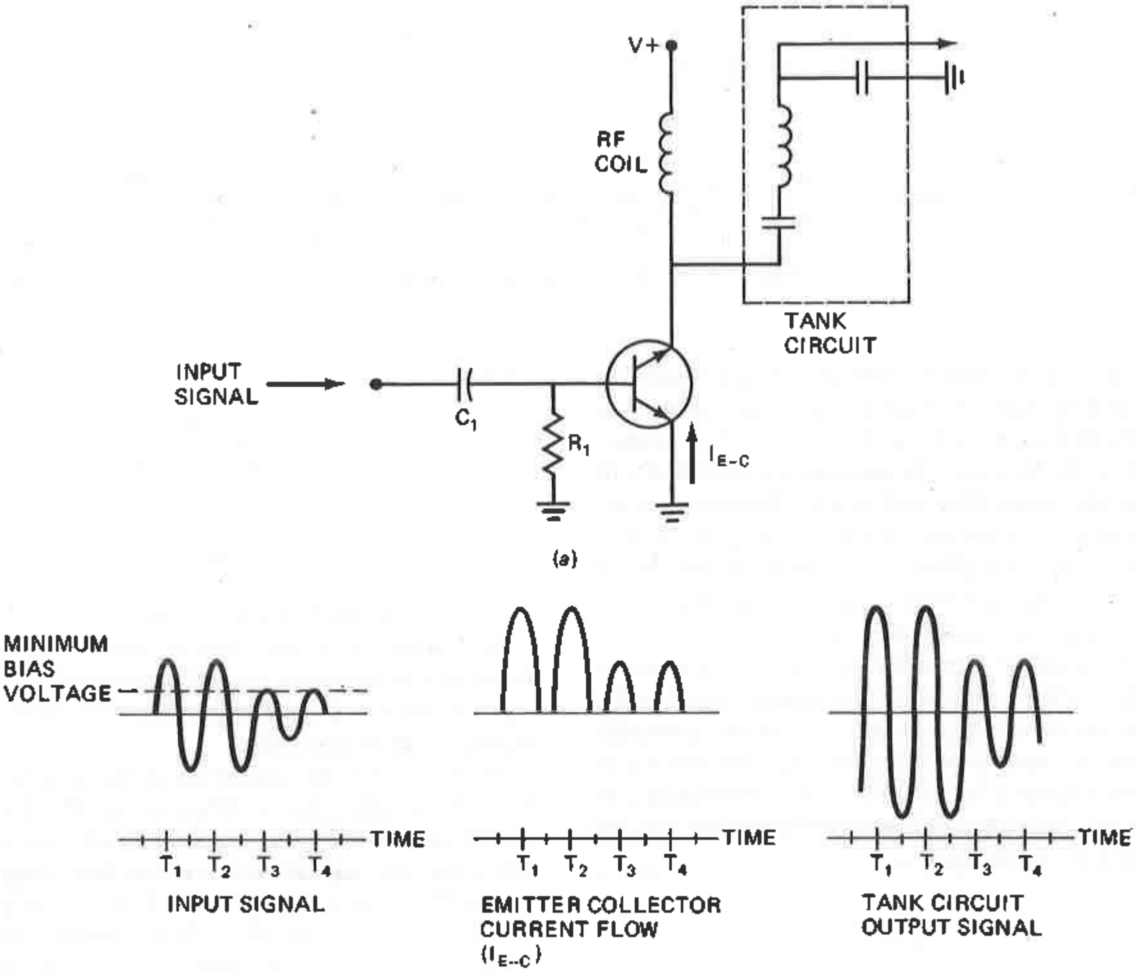


FIGURE 14-29 Class C amplifier: (*a*) the amplifier circuit; (*b*) the associated waveforms.

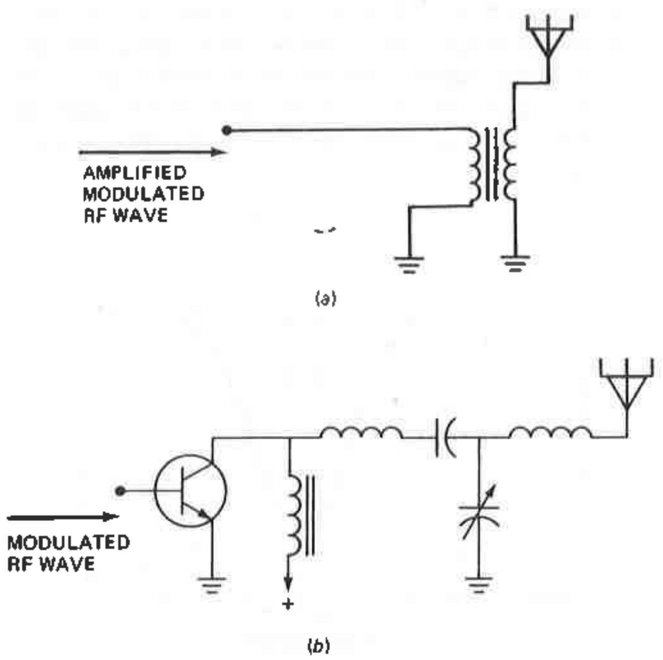


FIGURE 14-30 Antenna couplers: (*a*) An isolation transformer and (*b*) a coupler for a VHF transmitter.

RECEIVERS

Most **radio receivers** must perform multiple functions to produce the desired results. The antenna must receive the transmitted wave and produce a current flow into the antenna coupler. The antenna's current is produced through the process of electromagnetic induction. The tuner selects and passes only one frequency and blocks the others.

One or more preamplifiers are used to amplify the weak signal received from the tuner. In some cases an amplifier is also connected directly to the antenna in order to receive extremely weak signals. Once the input signal is amplified sufficiently, the RF carrier wave is separated from the AF wave by a detector circuit. The AF wave is then amplified again and directed to the receiver output, typically a speaker. A block diagram of a simple radio receiver is shown in Fig. 14-31.

Principles of Tuning

In the design and operation of electronic systems, **resonant circuits** provide the key to frequency control. A **resonator** is a device or system that exhibits **resonance**, that is, it naturally

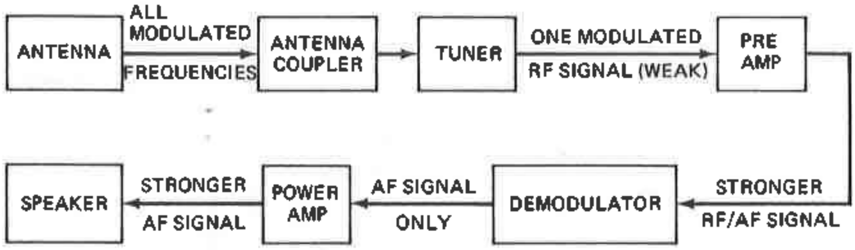


FIGURE 14-31 Block diagram of a radio receiver.

oscillates at some frequencies with greater amplitude than it would oscillate with other frequencies. The frequency at which a resonant circuit will oscillate is called the **resonant frequency**; at this frequency the impedance of the circuit will be low and the current flow will be high. Resonant circuits are key elements in radios and used during the production of RF signals, as is accomplished in oscillator circuits. Resonant circuits are also used when certain frequencies are to be passed or blocked by a radio tuning circuit.

From the study of alternating current, we know that a resonant circuit is one in which the capacitive reactance X_C is equal to the inductive reactance X_L. For any particular combination of capacitance and inductance, we know that the resonant frequency is fixed; that is, the combination can have only one resonant frequency. This frequency may be determined from the equation

$$f = \frac{1}{2\pi\sqrt{LC}}$$

As an example, let us consider the circuit in Fig. 14-32. This is a series LC (inductance-capacitance) circuit containing a capacitance of 10 μF and an inductance of 250 mH. We shall determine the resonant frequency of this circuit as follows, remembering the foregoing equation:

$$f = \frac{1}{6.28\sqrt{10^{-5} \times 0.25}}$$

This may also be expressed as

$$f = \frac{1}{6.28\sqrt{2.5 \times 10^{-6}}}$$
$$= \frac{1}{6.28 \times 1.581 \times 0.001}$$

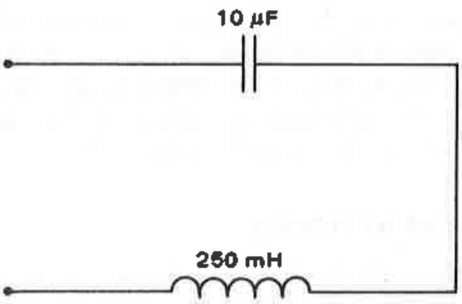


FIGURE 14-32 A series LC circuit.

Then

$$f = \frac{1000}{6.28 \times 1.581}$$

or

$$f = 100.7\ \text{Hz}$$

This is the resonant frequency of the circuit.

In a series LC circuit, such as that just described, the impedance at resonance is equal to the resistance of the circuit, inasmuch as the capacitive reactance and the inductive reactance cancel each other.

In other words, the impedance of the LC series circuit is at its lowest value when the frequency of 100.7 Hz (the resonant frequency) is applied. At any frequency above or below this value, the opposition to current flow (impedance) is greater. The relationship of current flow to frequency for this circuit is shown in Fig. 14-33. The impedance value of the circuit is very low at the resonant frequency and increases as the frequency deviates from 100.7 Hz.

If we consider a parallel LC circuit, such as that shown in Fig. 14-34, we find that at resonance the impedance across the parallel circuit is almost infinite, and if it were not for resistance in the circuit, the impedance actually would be infinite. Figure 14-35 shows a curve that indicates the effect of resonance in a parallel LC circuit. Notice that at zero frequency the impedance is very low and that it then rises as the frequency approaches the resonant value. At resonance the impedance is at a maximum; then it falls off as the frequency increases above resonance.

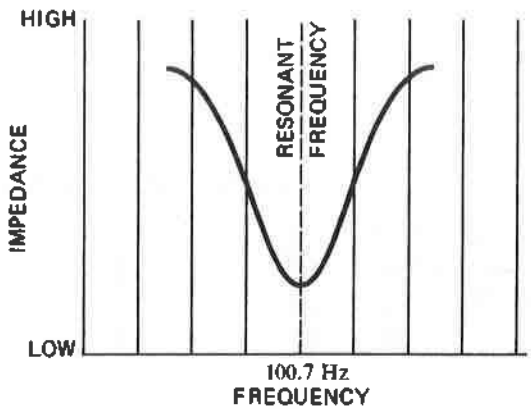


FIGURE 14-33 Relationship of current to frequency in a series LC circuit.

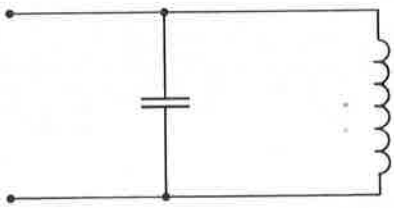


FIGURE 14-34 A parallel *LC* circuit.

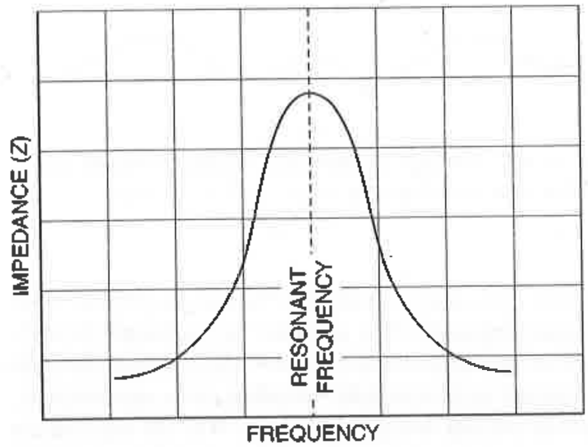


FIGURE 14-35 Relationship of current to frequency in a parallel *LC* circuit.

Filters

The characteristics of resonant circuits, as just described, make them very useful for **filtering** various frequencies in an electronic circuit. Among the types of filters used in electronic circuits are **high-pass** filters, **low-pass** filters, and **band-pass** filters. A high-pass filter tends to pass frequencies in the higher ranges and attenuate, or reduce, the current at frequencies in low ranges. A low-pass filter will pass frequencies in the lower ranges and attenuate, or reduce, the current at frequencies in the higher ranges. A band-pass filter will allow a certain band of frequencies to pass and will reduce the current at frequencies below or above the band range.

A circuit for a **high-pass filter** is shown in Fig. 14-36. Notice that the capacitor is in series with the circuit and that the inductance coils are in parallel with the circuit. Since capacitive reactance decreases as frequency increases, at high-frequency levels current will appear to flow through the capacitor, and since inductive reactance increases as frequency increases, current will decrease through the inductance coils as the frequency increases. This circuit will therefore tend to pass high frequencies and eliminate or reduce low frequencies, since they are simply shorted to ground.

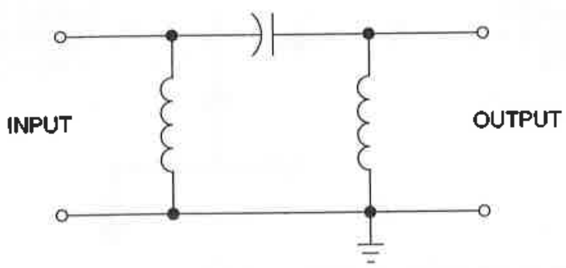


FIGURE 14-36 A high-pass filter.

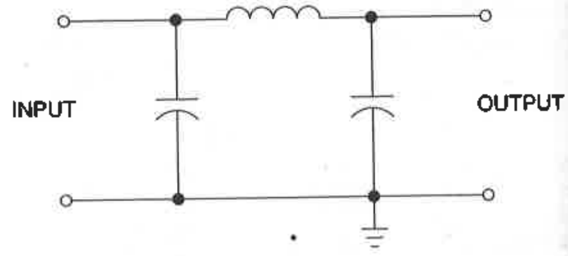


FIGURE 14-37 A low-pass filter.

Figure 14-37 shows a circuit for a **low-pass filter**. In this circuit the inductance coil is in series, and the two capacitors are in parallel. Low frequencies will pass easily through the inductance coil and will be blocked by the capacitors. As frequencies increase, they will be blocked by the inductance coil and passed by the capacitors and connected to ground; therefore, high frequencies are eliminated.

A **band-pass filter** is shown in Fig. 14-38. The impedance of the series *LC* circuit is high except at or near resonant frequency. Therefore, at resonant frequency the current flow will be comparatively high. At resonant frequency the impedance across the parallel portion of the circuit will also be high, thus preventing the current from being bypassed. The bandwidth of a band-pass filter is determined by the number of circuit elements and by the resistance of the circuit: the greater the resistance, the wider the band.

A **band-reject filter** is shown in Fig. 14-39. In this circuit the parallel *LC* circuit is in series with the load, and the series portion or series *LC* circuit is in parallel. With this

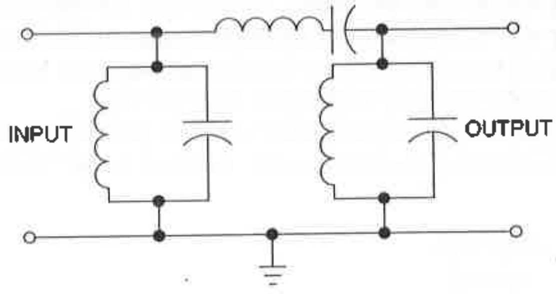


FIGURE 14-38 A band-pass filter.

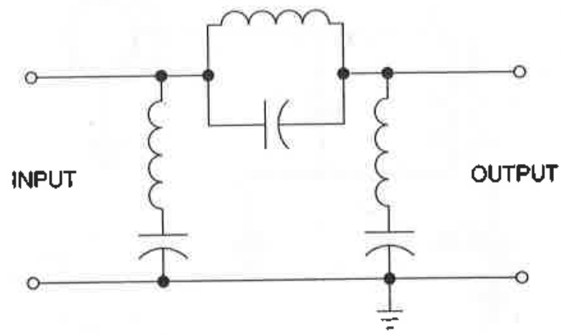


FIGURE 14-39 A band-reject filter.

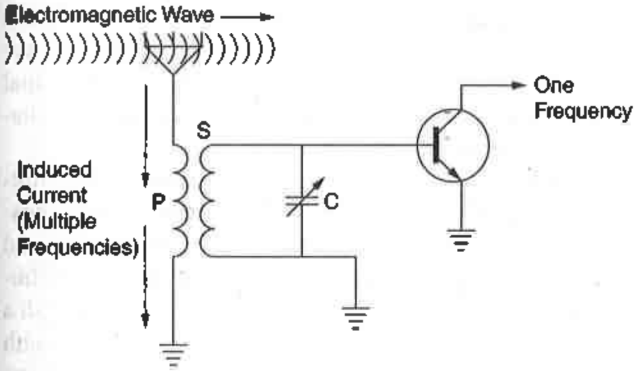


FIGURE 14-40 A simple tuning circuit.

arrangement the resonant frequencies will be bypassed and blocked from reaching the output (shorted to ground). All other frequencies will be passed to the output of the filter.

A filter may be made a **tuning circuit** by making either the inductance or the capacitance variable. A simple tuning circuit consists of a variable capacitor used with a fixed resistor. In some cases, however, the capacitor is fixed, and the inductance is tuned by means of a slug, or movable core, within the inductor. Tuning circuits are usually designed to have fairly high selectivity; that is, they allow only a very narrow band of frequencies to pass and reject all others.

Figure 14-40 shows a simple circuit for a typical tuning unit. The radio signals cutting across the antenna induce signals of various frequencies that flow through the primary winding of the antenna coil to ground. These currents produce electromagnetic waves, which induce voltages in the secondary winding of the antenna coil. Since a variable capacitor *C* is connected across the secondary coil, a maximum of current will flow only at the resonant frequency of the coil and the capacitor. Hence at resonant frequency a maximum voltage will be developed across the capacitor, and this same voltage will be applied to the emitter-base circuit of the transistor. This voltage is the input signal to the transistor, which amplifies the relatively weak signal from the tuner.

In some cases a series resonant circuit is provided in the primary system of the antenna coil, as shown in Fig. 14-41.

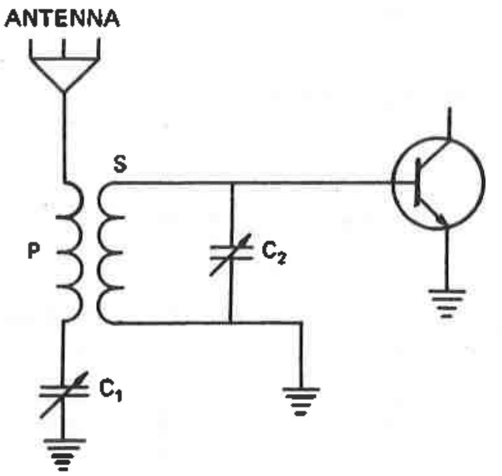


FIGURE 14-41 A tuning circuit with a series resonant circuit.

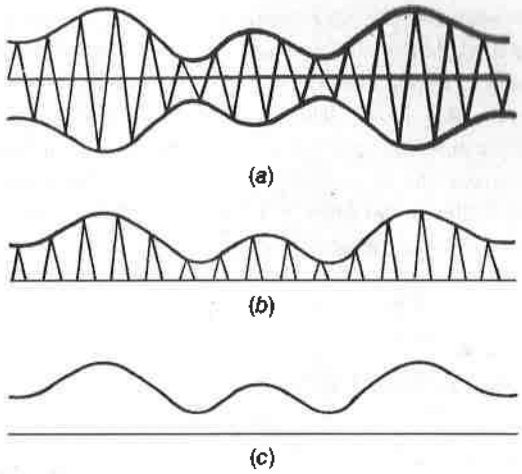


FIGURE 14-42 Principle of detection: (*a*) Modulated RF wave, (*b*) rectified and modulated RF wave, and (*c*) AF wave.

In this case maximum current will flow in the primary only at resonant frequency. This provides for increased selectivity because unwanted frequencies are largely prevented from being induced in the secondary winding of the antenna coil.

The two circuits described are in no way the only means of tuning, but they represent the basic principles used in all tuning circuits in the low and medium frequencies.

Detection

Detection of a radio signal is the process of separating the RF carrier wave from the AF intelligence wave. This is accomplished by rectifying the modulated wave to produce a dc signal and then filtering the remaining wave to remove the high-frequency carrier from the low-frequency audio wave. Detection is often referred to as **demodulation** because it is the opposite of the modulation process.

The principle of detection is illustrated in Fig. 14-42. Figure 14-42*a* shows the modulated carrier wave, Fig. 14-42*b* shows the wave after detection, and Fig. 14-42*c* shows the audio signal after filtering. This audio signal is extremely weak and must be amplified before being reproduced through a speaker.

There are several types of detection circuits, ranging from simple to complex; however, they all rectify and filter a modulated signal. A simple detection circuit is illustrated in Fig. 14-43. The first function performed by the detector is to rectify the modulated wave; the diode performs this function.

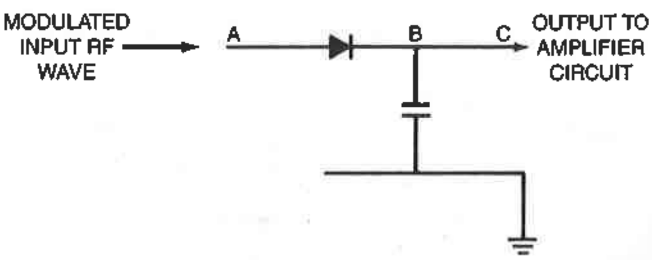


FIGURE 14-43 A simple detection circuit.

The second step is to remove the RF signal; the capacitive filter does this by shorting together the RF input for high frequencies (remember, the RF wave is of a higher frequency than the AF wave). The input wave changes as it passes through the detector. The wave in Fig. 14-42*a*, a modulated RF wave, represents the signal at point *A*. After rectification, point *B*, the signal may resemble Fig. 14-42*b*. Once rectification is complete, an AF signal remains and is sent to the amplifier circuitry. The output signal, point *C*, is represented in Fig. 14-42*c*.

Sound Reproduction

After an AF signal leaves the demodulator, it is typically amplified. An amplifier will typically consist of a transistor circuit used to increase signal strength, along with various filters used to control tone and increase fidelity. Once the signal is amplified, the reproduction of sound is accomplished by the conversion of electric energy into sound waves. This is typically done with headphones, speakers, or a single earphone. Each of these units is often designed with the same basic operating principles shown in the simplified speaker diagram (Fig. 14-44). During operation the audio signal is sent to the speaker voice coil from the radio's amplifier circuit. As current flows through the voice coil of the speaker, it creates a magnetic field energized by the audio signal. Since the current flow of the audio is constantly changing, the magnetic field is also changing. The magnetism produced in the voice coil interacts (attracts or repels) the magnetic field of the permanent magnet mounted at the rear of the speaker. Since the voice coil is mounted to the diaphragm, the diaphragm moves as the voice coil moves. To create more air movement and a louder audio output, a speaker cone is mounted to the diaphragm. This creates a large air movement with each position change of the iron diaphragm, thus producing relatively high volumes. Because of the work involved in moving large quantities of air, a more powerful amplifier is generally needed to drive large speakers. The sound wave radiates due to the vibrations of the speaker cone. Of course, this is a simplified diagram and the actual speaker would require a support structure to allow the diaphragm and cone to move free and easy.

Headphones and earphones can be constructed in a similar fashion; however, a variety of other options are also possible. A typical speaker will employ a paper cone connected to the diaphragm. A common earphone is designed with similar construction; but replaces the paper speaker cone with a small diaphragm constructed of thin metal or high-strength plastic film. A typical earphone or headphone is considerably smaller and produces sound at lower volumes than a speaker.

The Crystal Receiver

The **crystal receiver** is the simplest of all types of radio receivers. The schematic in Fig. 14-45*a* is a series crystal receiver. During operation, the antenna receives an induced current from any passing electromagnetic waves. This induced current is seeking ground; therefore, it travels through the variable inductor and capacitor C_1. These two components filter any unwanted signals, and only the resonant frequency will pass through the tuner into the diode. The diode and capacitor C_2 constitute the demodulator circuit. The diode acts as a half-wave rectifier to produce a dc signal available to the headphones. Capacitor C_2 is an RF filter used to bypass the radio frequency portion of the rectified signal around the headphones, directly to ground. The only signal reaching the headphones is the rectified audio frequency. If a very sensitive headphone set is used, the faint AF signal can be heard.

This type of radio receiver produces its entire audio volume from the energy induced into the antenna. Obviously, only very strong transmitted signals are received and only with an antenna of an extremely long length. To overcome these shortcomings, most receivers utilize an amplifier cicuit

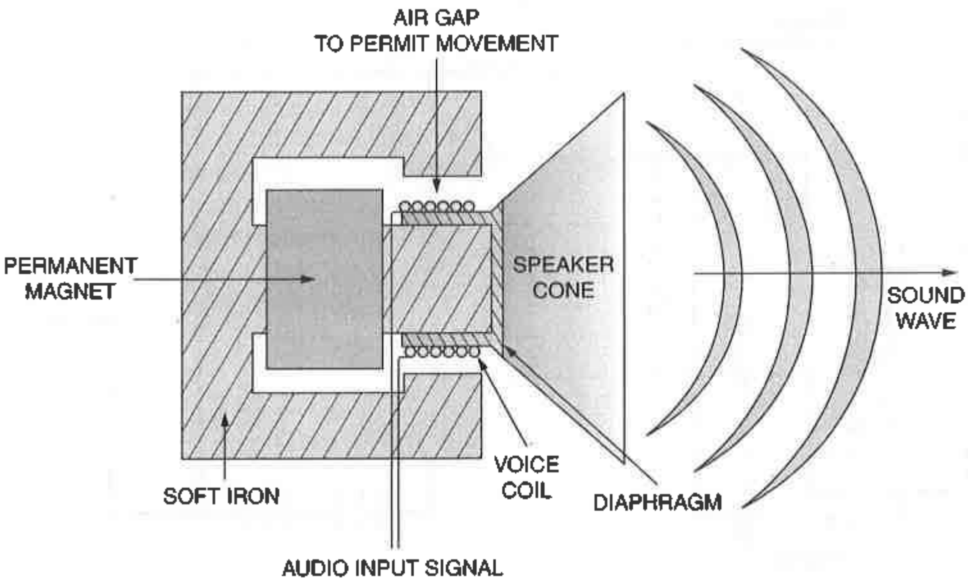


FIGURE 14-44 Common elements of a typical audio reproduction speaker.

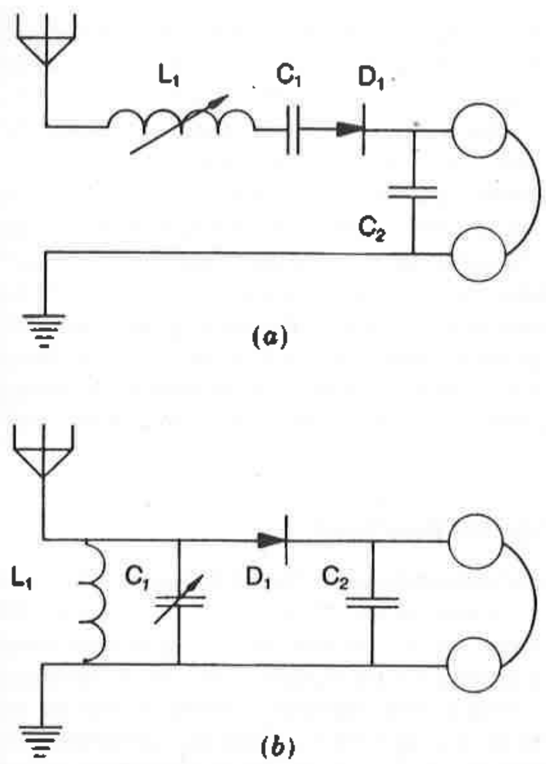


FIGURE 14-45 Crystal receivers: (*a*) series type and (*b*) parallel type.

to improve signal strength. A parallel crystal receiver is shown in Fig. 14-45*b*.

A One-Transistor Radio

One way to improve a radio circuit is to amplify the audio frequency before it is sent to the headphones. Figure 14-46 is a schematic diagram of a one-transistor radio. The transistor amplifies the AF wave so that the radio can produce a louder volume than the crystal radio. This amplifier does not make the radio more sensitive (able to receive more stations); it only amplifies the sound wave sent to the headphones. Additional amplifier circuits are needed to improve a radio's sensitivity. A circuit of this type would amplify the modulated RF wave prior to its entering the radio's detection circuitry. Most radios contain several amplifiers in order to achieve their desired sensitivity and volume.

The Mixer

In order to change the value of RF signals, a circuit known as the **mixer** is used to combine two frequencies in order to create a third frequency of different value. A block diagram of a mixer is shown in Fig. 14-47. Here it can be seen that the mixer receives an RF from the radio antenna and a frequency created by a local oscillator. The local oscillator can create a stable frequency using a crystal and/or tank circuit as previously discussed. In this example, the local oscillator produces a frequency of 1455 kHz, the incoming RF is 1000 kHz. The mixer performs two tasks; the circuit sums the two input frequencies and the circuit subtracts the two frequencies. In this case the outputs of the mixer are the following: 1000 kHz, 1455 kHz, 450 kHz, and 2455 kHz. In most radios, only one of these output frequencies are used and the others are sent to ground.

The Superheterodyne Receiver

The **superheterodyne receiver** derives its name from the fact that a new signal frequency is generated in the receiver by means of a local oscillator often called a **beat frequency oscillator** (BFO). The BFO signal is fed into the converter or mixer system. The word *hetero* is a Greek term for *other*, and the word *dyne* means *power*; thus the term **heterodyne** literally means *other power*. It refers to the intermediate frequency developed in the mixer circuit.

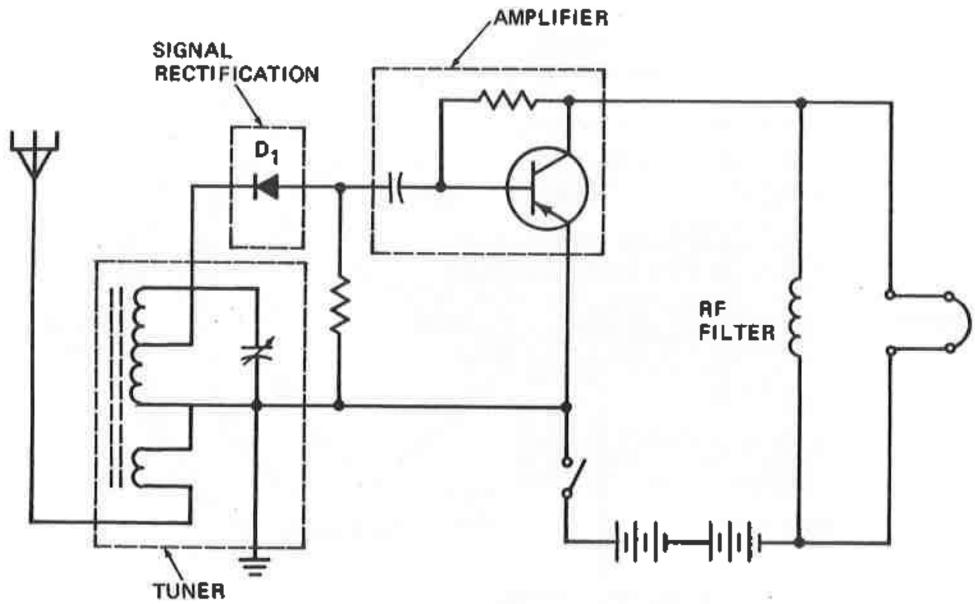


FIGURE 14-46 Schematic diagram of a one-transistor radio.

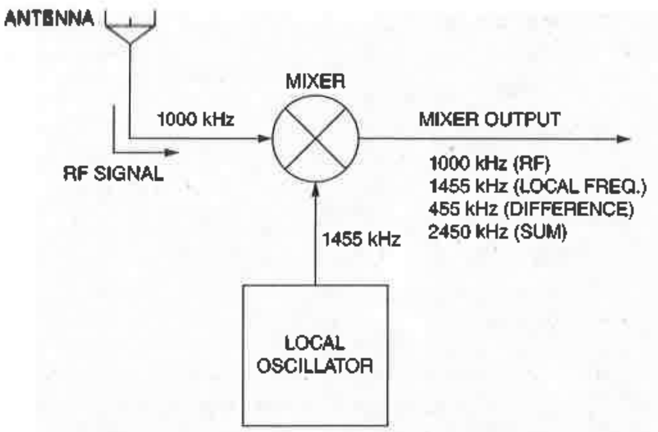


FIGURE 14-47 Mixer and local oscillator circuit.

Today most modern aircraft radios employ superheterodyne receiver technologies.

A block diagram of a superheterodyne receiver is shown in Fig. 14-48. During operation the signal received by the antenna enters the RF amplifier, and the strengthened signal is then passed on to the mixer or converter stage. Here the incoming RF carrier and the local oscillator signal are combined to produce an intermediate signal of 455 kHz. The concepts of a mixer were described in the previous section. The IF signal that leaves the mixer retains the AF signal that was originally carried by the RF received by the antenna.

The IF signal is usually passed through two IF amplifier stages, each consisting of an IF transformer and a transistor with the necessary resistors and capacitors. The two IF circuits are accurately tuned to 455 kHz with a bandwidth of approximately 10 kHz. This means that signals of 450 to 460 kHz will be passed through the IF amplifier stages and that all other frequencies will be attenuated. The 10-kHz bandwidth is necessary to accommodate the audio modulation that may be carried by the IF signal.

After the intermediate frequency has been amplified through the two IF amplifiers, it is passed through the second detector and first audio-amplifier stage. From this point, the signal may be directed to the speaker or to an additional stage of audio amplification.

Superheterodyne receivers are used in many electronic systems other than radios. They have a number of advantages, among which are simplified tuning, improved amplification, high selectivity, and good fidelity. The previous example of the superheterodyne process shows specific values for the RF, local oscillator, and IF frequencies. These frequency values were shown as an example and will only work for a given RF signal. To create a superheterodyne receiver for other frequencies, the values of the local oscillator and mixer will be adjusted accordingly. In some receivers additional mixers are added to allow for the reception of multiple frequencies. In most aircraft communication radios, a variable local oscillator is used so the pilot can make selections to a desired frequency.

Digital Radio Theory

On many aircraft systems digital signals are used to process information. As described in Chap. 7, a digital signal is composed of discrete voltage on and off signals. In terms of radio theory, digital signals can be used within a radio's circuitry to perform the basic radio functions, such as amplification, modulation, and detection. Digital signals can also be transmitted as electromagnetic energy.

In this case, the RF carrier wave is modulated by means of a digital method. To digitize the RF wave, the signal (or portions of the signal) is assigned a distinct digital value when modulated accordingly. For example, when a transmitted RF wave is modulated at 500 Hz, this could mean digital 1; when the wave is modulated at 600 Hz, this could be used to represent digital 0. Simply changing the modulation from

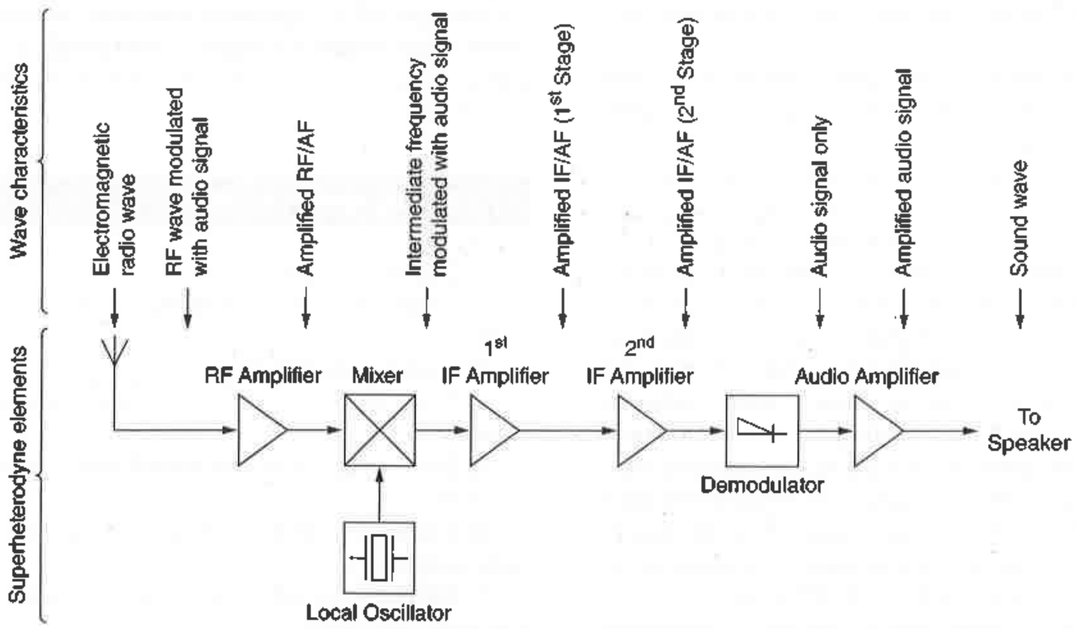


FIGURE 14-48 Elements of a superheterodyne receiver.

500 to 600 Hz hundreds of times a second could produce a usable digital signal. Telephone-based fax machines and computer modems operate using this principle. Of course, this is a simplified example and the actual digitized signal would be relatively complex.

Most aircraft radios transmit analog RF signals. Those using pulse or digital signals include weather radar, GPS systems, distance measuring equipment (DME), and transponder equipment. Also, modern aircraft to satellite communications used for passenger Internet connections and downloads of aircraft data operate using digital signals.

In most aircraft radio systems, the major change that has resulted from advanced digital technologies is improved tuner and oscillator circuits. **Digital tuners** are used in modern receivers to filter out unwanted RF signals. Digital oscillator may be used in radio receivers or transmitter to generate a constant-frequency reference signal. For receivers, the reference signal may be used to create the intermediate frequency (IF). For transmitters, the digital oscillator is used to generate a high-frequency reference signal that is divided into a lower frequency and used for the RF carrier. The use of digital circuits in both transmitters and receivers has improved the accuracy and reliability of aircraft radios.

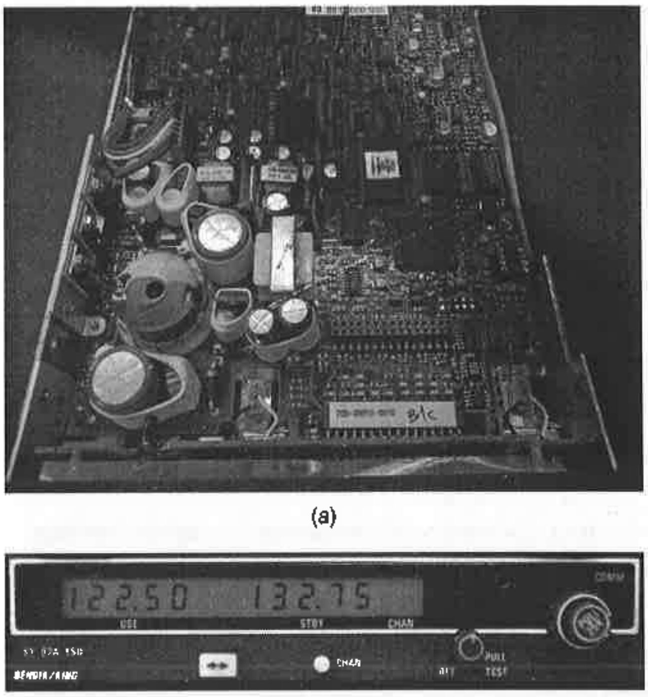
Digital tuning refers to the use of digital circuit generate many frequencies from a single crystal oscillator. The oscillator signal can be used for tuning purposes or to produce a radio frequency carrier or an intermediate frequency.

Analog transceivers use variable capacitors and inductors that tune a local oscillator through a continuous band of frequencies. Aircraft VHF communication frequencies range from 118.000 through 136.99163 MHz. The interval between channels is 8.33 kHz. This is a relatively narrow band to select using a conventional analog tuner. Digital tuning has improved accuracy and is therefore used in all modern aircraft radios. At the time this text was written, aircraft communication radios were available with up to 2280 channels in the frequencies between 118.00 and 136.99163 MHz; however, it is still legal to use many radios that provide only 720 channels.

The digital technique of **frequency synthesis** has been developed to obtain a stable tuning circuit that is capable of 8.33 kHz increments. The process of frequency synthesis requires the use of digital flip-flops and various logic gate circuits.

Programmable dividers, or **counters** are made from flip-flop circuits in various arrangements. Using other logic gates to chain flip-flops together means that a counter can have a different output for each input pulse. A 16-state counter has a binary output of 0 to 15 and requires 16 pulses to make one cycle through the counter. The circuit also contains a reference crystal that oscillates at a higher frequency than the desired output. A programmable divider is set by the frequency selector controls on the front of the transceiver. When the divider is programmed, the counter's output frequency can be used by the receiver for tuning and demodulation. A transmitter can use the counter's output to produce the RF wave.

High-frequency synthesis requires the use of two crystals, one crystal that oscillates in the megahertz frequency range and one crystal that oscillates in the kilohertz frequency range. Using two crystals with programmable dividers yields much more accuracy than adding several oscillators together. When two oscillators are added and then divided to a lower frequency, their frequency error becomes less with each division.



(a)

(b)

FIGURE 14-49 Modern digital aircraft radio: (*a*) internal circuitry showing surface mounted integrated circuits; (*b*) digital display panel. See also color insert.

In summary, most radio circuits found on modern aircraft employ digital technologies to perform the various functions needed to transmit and receive signals. A modern communications radio will incorporate microprocessors and integrated circuit technologies for signal conditioning as well as a digital display showing receive and transmit frequencies (see Fig. 14-49).

REVIEW QUESTIONS

1. Describe a radio wave.
2. What two types of fields are found in a radio wave?
3. Explain wavelength.
4. Compare wavelength and frequency for a radio wave.
5. Give the equation for wavelength if the frequency is known.
6. Explain the different frequency bands assigned to radio systems?
7. What is the difference between radio frequency and audio frequency?
8. Explain the functions of antennas.

9. How does the frequency of the radio waves transmitted or received relate to the length of the antenna?
10. Describe the ionosphere.
11. How does the ionosphere affect radio communications?
12. What is meant by *coupling* an antenna to a transmitter?
13. What are the functional blocks of a radio transmitter?
14. What is the purpose of an oscillator?
15. Describe how an oscillator produces an alternating current.
16. What determines the frequency of the oscillator output?
17. What type of oscillator is commonly used in a radio transmitter?
18. What is the function of a buffer amplifier?
19. Describe the operation of a frequency multiplier.
20. What is 100 percent modulation?
21. What is the difference between AM and FM?
22. How is modulation accomplished?
23. What is the purpose of a power amplifier?
24. Compare the effects of inductive reactance and capacitive reactance.
25. What conditions exist in a resonant circuit?
26. Describe the operation of a high-pass filter and the operation of a low-pass filter.
27. Explain a band-pass filter.
28. What is the principal function of filters in a radio circuit?
29. What is signal detection?
30. By what means is an audio frequency signal converted into sound?
31. Describe the operation of a common speaker or headphone.
32. Describe the operation of a common microphone.
33. What is meant by an intermediate frequency in a superheterodyne receiver?
34. Describe an amplifier.
35. Name three classes of amplification.
36. What class of amplification produces the least distortion of a signal?
37. Explain class B amplification and how it is most commonly used in a receiver.
38. Explain the purpose of the beat frequency oscillator in a superheterodyne receiver.
39. What is the function of the converter in a superheterodyne receiver?
40. Give the principal advantages of a superheterodyne receiver.

Communication and Navigation Systems 15

INTRODUCTION

The use of radio equipment and avionics in general has increased markedly for all types of aircraft during the past century. One of the reasons for this increase is the Federal Aviation Administration's (FAA's) requirement that all aircraft operating in high-traffic areas be equipped with a two-way radio for communication with air traffic controllers and tower operators. Automatic airborne collision avoidance systems, now mandatory on many aircraft, use radio systems to communicate aircraft position and avoidance maneuvers when needed. The most modern aircraft use wireless Internet-based systems to upload data to various electronics. The wireless connections operate using digital radio signals. Other radio systems used for in-flight entertainment and Internet connections have become commonplace on corporate and large passenger aircraft. These systems often employ satellite technologies that send HF radio signals to/from the aircraft. The development of solid-state and digital electronics technology has made it possible to install highly complex and sophisticated systems for communication, navigation, and automatic flight control in all types of aircraft. Previously, such systems could only be utilized in large aircraft because of the size and weight of the system components. Today the term **avionics**, which is a combination of the words *aviation electronics*, encompasses a variety of electronic systems.

Avionic systems installed in aircraft can include communication (COMM) radios, navigation (NAV and RNAV) systems, weather detection systems, and flight management systems (FMSs). The navigation systems may include VHF omnirange (VOR) receivers, global positioning systems (GPS), distance-measuring equipment (DME), the automatic direction finder (ADF), the localizer (LOC) receiver, glide slope (GS) receiver, traffic alert and collision avoidance systems (TCASs), marker-beacon receivers, the identification transponder, the radio altimeter, the encoding altimeter, and numerous indicators. In some cases, on the most modern aircraft, these systems have been combined into an integrated avionics processor system (IAPS). IAPS-type avionics are typically easier to use, weigh less, and require less space on the instrument panel.

All modern avionic systems conform to **Aeronautical Radio Incorporated** (ARINC) standards. ARINC is a corporation established by foreign and domestic airlines, aircraft manufacturers, and transport companies to set standards for aircraft systems. ARINC 500 and 700 standards were developed for communication, navigation, and identification (CNI) systems. Common digital data transfer systems are standardized through ARINC 429, 629, and 664.

COMMUNICATIONS

Voice communication systems for aircraft are primarily for the purpose of air traffic control; however, commercial aircraft also utilize a range of high frequencies for communicating with ground stations and other aircraft for business and operational purposes. Communications for air traffic control are in the VHF band in the range between 118 and 136.99 MHz.

High-Frequency Communication Systems

The high-frequency (HF) communication systems operate in the frequency range of 2.0 to 30 MHz. The HF range is actually a middle-frequency range, inasmuch as it starts just above the standard broadcast band, which ends at approximately 1700 kHz. This frequency group consists of ground waves; therefore, HF communication systems are used for long-distance radio transmissions. The HF system on an airplane is used to provide two-way voice communication with ground stations or other aircraft. HF systems are typically used on aircraft which fly long distances such as intercontinental flights over the Pacific Ocean.

The HF radio control panel is located where it is easily accessible to the pilot or copilot. A typical panel is shown in Fig. 15-1; it includes a frequency selector, a squelch or radio frequency (RF) gain control, and a mode selection switch. On most aircraft the antenna for an HF radio is covered by plastic-type shields. The cover may be of fiberglass or a similar material that will allow electromagnetic waves to reach the antenna. On modern aircraft a flush-mounted antenna is

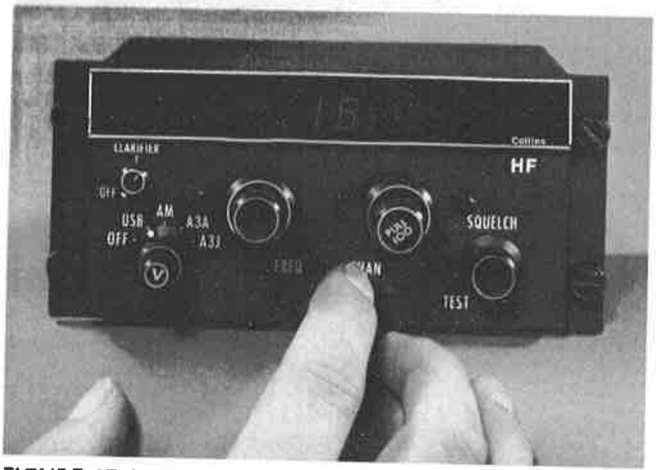


FIGURE 15-1 A typical antenna coupler system. (*Collins Divisions, Rockwell International.*)

used that does not increase induced drag. The probe antenna is used for both receiving and transmitting and is matched to the transmission line at any frequency by means of an **antenna coupler**. The antenna coupler system is necessary to maintain an efficient match between the antenna and the transmitter at a wide range of frequencies.

The complete HF transceiver is installed in an electronic equipment rack and is remotely controlled from the control unit on the flight deck. The system consists of the HF receiver-transmitter, the HF control unit, the antenna coupler system, and the antenna.

Most HF transmissions are used for voice communications; however, digital data can also be transmitted using the HF system. These digital transmissions can be thought of as an e-mail or a text-type message broadcast on HF. This type of transmission is often referred to as **data mode** and is used for digital-type information that is linked to equipment external to the HF radio system. The data communication system is known as the **air-ground data link**, or **data link**.

HF communication systems are long-distance communication systems and are not employed on all aircraft. Airlines may or may not utilize these systems, depending on their particular requirements. HF systems are not usually found in light aircraft. Many airlines that employ HF communication systems do so because these systems provide for an extended range of communications between aircraft and from aircraft to ground stations. On some aircraft long-distance communications now use satellite technologies instead of HF systems. However, satellite communications are still very expensive so it is likely the the HF radio will continue to be used into the foreseeable future.

VHF Communication Systems

As explained previously, VHF communication systems are employed largely for controlling air traffic. These systems are installed in all types of aircraft so the pilot may be given information and directions and request information from air traffic control centers, control towers, and flight service stations. On the approach to any airport with two-way radio facilities, the pilot of an aircraft calls the tower and requests information and landing instructions. In airline operations and all instrument flights, the flight of an aircraft is continuously monitored by air traffic control (ATC), and the aircraft's crew is given instructions as necessary to maintain a safe flight.

VHF communication systems operate in the frequency range of 118 to 136.99 MHz. For international operations the frequencies may extend to 151.975 MHz. The nature of radio-wave propagation at these frequencies is such that communication is limited to line-of-sight distances. The advantage of VHF communication, however, is that the signals are not often distorted or rendered unintelligible by static and other types of interference.

VHF communication radios are currently available with 720, 760, or 2280 channels. In 1976 the FAA changed the minimum frequency spacing for VHF systems from 50 to 25 kHz between 118 and 135.975 MHz. This change made the 720-channel radio possible. In 1990 the FAA and FCC authorized the general use of frequencies up to 136.975 MHz. This change added 40 channels to increase the selection to 760 channels. At this time the 360-channel radios became illegal to operate because they could not restrict transmissions to a narrow frequency spectrum. The latest modifications to the VHF radios further refined the frequencies and number of available channels. Today, there are 2280 channels available for aircraft VHF communications. Some 720- and 760-channel radios cannot meet the strict frequency requirements and are now unairworthy. It is important for aircraft technicians to ensure that all radios are airworthy and meet all FCC requirements during aircraft inspections.

VHF communication equipment for light aircraft is typically combined with a VHF navigation (NAV) radio system. A common VHF light-aircraft radio is shown in Fig. 15-2. Figure 15-3 shows the interior arrangement of the system. The transceiver shown in Figs. 15-2 and 15-3 is a solid-state, digital system that can receive or transmit on any one of the 720 channels in the COMM range of frequencies. Frequencies are selected simultaneously for both the receiver and the transmitter by rotating the frequency selector knobs. The large outer knob is used to change the megahertz portion of the frequency display, and the smaller concentric knob changes the kilohertz portion.

Like many modern systems this radio can store both an active and a standby frequency. The active frequency is labeled USE on the radio faceplate; the standby frequency is labeled STANDBY (see Fig. 15-2). The double-sided arrow on the front of the radio is used to switch the frequencies between USE and STANDBY.

The STANDBY mode will store the selected frequency to allow for a "quick switch" of the frequency being used by

FIGURE 15-2 Elements of a superheterodyne receiver.

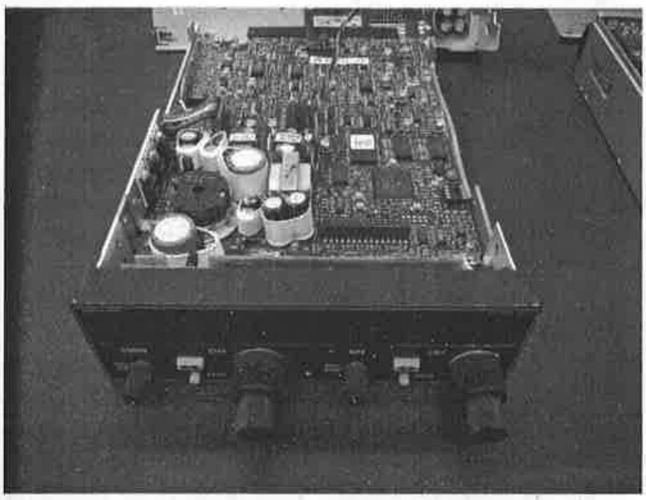


FIGURE 15-3 Interior of a modern VHF radio. (Notice the integrated circuits.)

the receiver. This becomes very helpful while operating an aircraft in crowded airspace in which several communication frequencies are used for air traffic control.

Control panels for VHF communication systems vary in design, depending on the manufacturer of the equipment and the requirements of the aircraft manufacturer. Typically, the control panel located in the flight deck contains the frequency selectors and the digital displays for the main and standby frequencies. In some cases the radio's volume is controlled by a separate audio panel. Many larger aircraft use a radio tuning unit (RTU) for control of communication and navigation systems. The RTU is a multifunction control panel for operation of all navigation and communication radios. The design saves weight and space by integrating all controls on one panel; RTUs will be discussed later in this chapter.

Most VHF systems for corporate and transport-category aircraft use a separate radio control panel, and the receiver-transmitter (r-t) is located in the electric equipment center. Also on these aircraft, the VHF communication radio system is often independent of the VHF navigation system. A typical VHF communication receiver-transmitter is shown in Fig. 15-4. The unit measures approximately 4.5 in. wide,

FIGURE 15-4 A VHF communications transmitter/receiver LRU for a typical corporate aircraft.

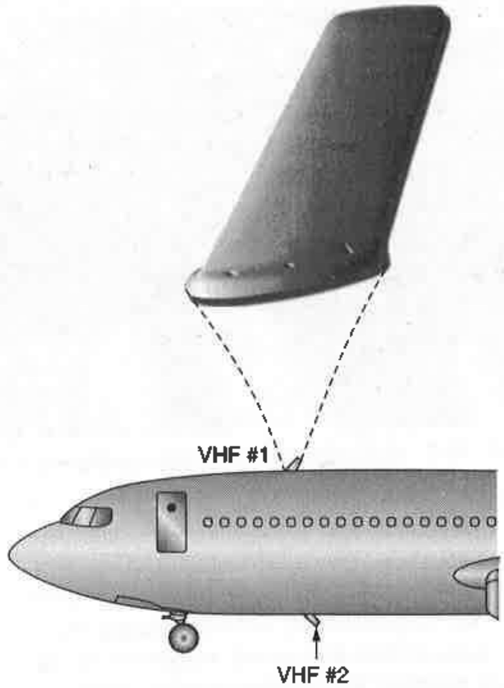


FIGURE 15-5 VHF antenna configuration.

4 in. tall, and 12 in. deep; it is typically installed in the electrical equipment bay. On light aircraft the r-t and control panel are often one unit mounted in the instrument panel. This type of unit is shown in Fig. 15-3.

Antennas for VHF systems are low-drag aerodynamic units extending from the top and bottom centerline of the airplane. The antennas are used for both transmitting and receiving. A typical VHF antenna configuration is shown in Fig. 15-5.

VHF communication transmitters provide AM voice-communication transmission between aircraft and ground stations or between aircraft. Transmission is on the same number of channels and frequencies as provided in the receiver. Because of the nature of VHF radio signals, the average communicating distance from aircraft to ground is approximately 30 mi [48 km] when the airplane is flying at 1000 ft [305 m] and approximately 135 mi [217 km] when the airplane is at 10000 ft [3048 m]. Transmitting frequency is determined by the position of the selector switches on the VHF control panel. The transmitter is tuned at the same time and to the same frequency as the receiver.

The most modern VHF communication radios incorporate the latest digital design features. In general, the use of microprocessors and digital circuits has allowed for a 50 percent reduction in parts count and an 80 percent reduction in internal shop adjustments as compared with the use of analog circuits. A modular design of a modern digital system reduces maintenance time by providing easy access to all circuit boards and components.

Built-in test equipment (BITE) systems and data interface systems are also available on some communication radios. A BITE system uses an LED display to indicate faulty "plug-in" modules within the radio. A data interface system allows for the transmission of binary data through the communication radio system. The data to be transmitted may be created by a manually operated keyboard or an airborne computer. While information is being transmitted through the data interface, the voice characteristics of the communication radio are still operable. This system therefore makes better use of the crowded RF spectrum in which the transceivers operate. Data interface systems will be discussed in greater detail in the ACARS section of this chapter.

Theory of Operation of VHF Communication Systems

To aid in the explanation of the VHF communication transceiver, the receiver will be discussed separately from the transmitter. The receiver portion of a VHF communication system is typically the superheterodyne type (Fig. 15-6). The antenna receives an induced signal from the electromagnetic fields passing the antenna. This signal is sent through a band-pass filter to an RF amplifier. Once amplified, the signal passes through a low-pass filter and into the first-stage mixer. The mixer converts the RF into an intermediate frequency (IF). The IF is a lower frequency and is easier to control through the receiver. The IF is amplified to produce a stronger signal, which is sent to the second-stage mixer where again a lower frequency is produced. This signal is amplified and sent to the detector, where the audio wave is separated from the carrier wave. The audio signal is then amplified by the buffer and broadcast into the aircraft by the speaker. The buffer amplifier receives input from the AGC (automatic gain control) circuit, which ensures correct signal amplification at varied input signal strengths.

The transmitter receives an input signal from the microphone or data inputs. This signal is amplified by the audio

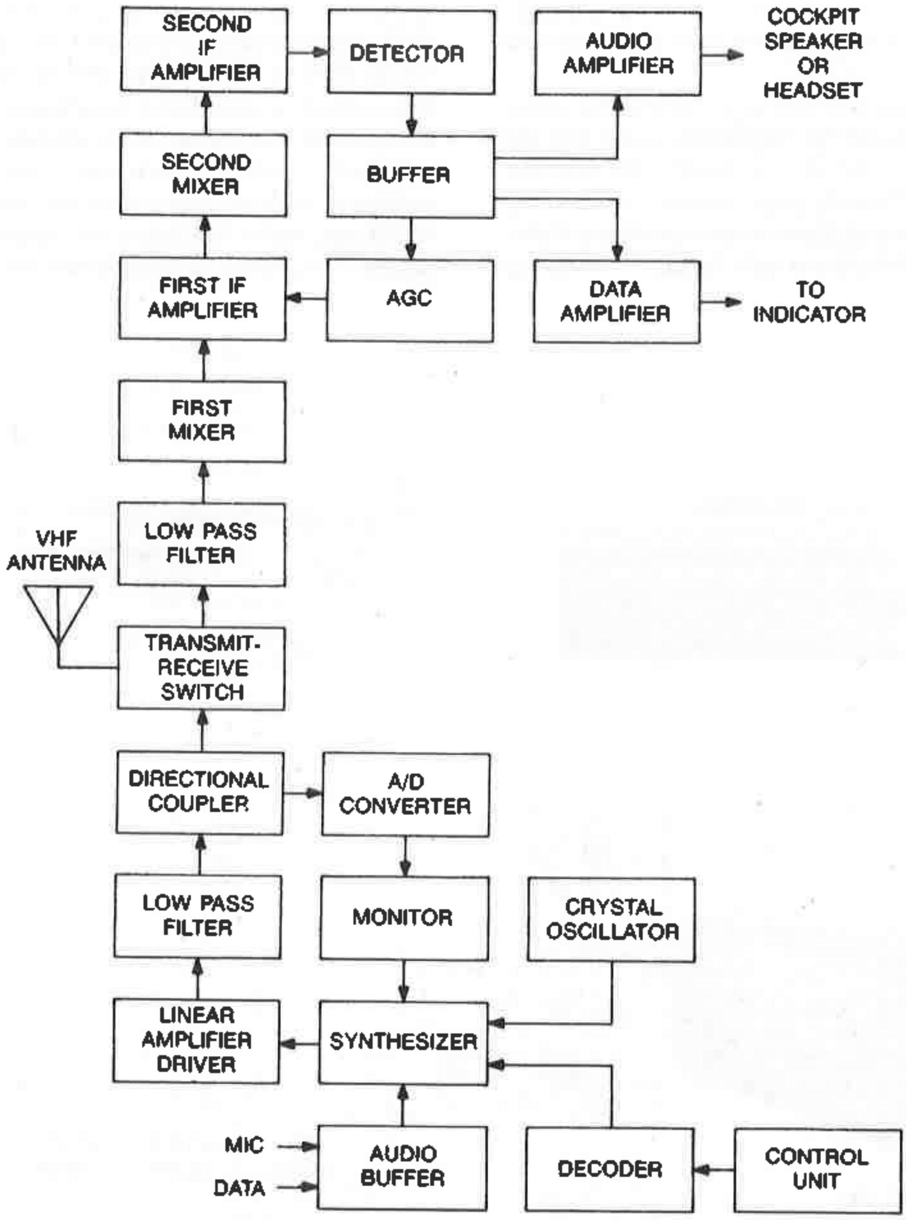


FIGURE 15-6 Block diagram of a typical VHF communication system for a large aircraft. *(Collins Divisions, Rockwell International)*

buffer and sent to the modulator (synthesizer). The modulator produces an AM signal, which is filtered, amplified, and sent to an ALC (automatic level control) circuit. Similar to the AGC in the receiver, the ALC ensures that a consistent output signal is sent to the antenna, even at varying input signal strengths. More details of radio theory can be found in Chap. 14.

Selcal Decoder

The word **Selcal** is derived from the term **selective calling**, and the **Selcal decoder** is an instrument designed to relieve the pilot and copilot from continuously monitoring the aircraft radio receivers. The Selcal decoder is, in effect, an automatic monitor that listens for a particular combination of tones that are assigned to the individual aircraft. Whenever a properly coded transmission is received from a ground station, the signal is decoded by the Selcal unit, which then alerts the pilot to an incoming radio transmission. The system automatically activates the correct radio for the flight crew or will simply alert the flight crew of an incoming radio transmission.

Ground stations equipped with tone-transmitting equipment call individual aircraft by transmitting tones that will key only an airborne decoder set to respond to that particular combination of tones. When the proper tones are received, the decoder operates an external alarm circuit to produce a chime, light, or buzz, or a combination of such signals.

A ground operator who wishes to contact a particular aircraft by means of the Selcal unit selects the four-tone code that has been assigned to the aircraft. The tone code is transmitted by an RF wave, and the signal can be picked up by all receivers tuned to the frequency used by the transmitter. The only receiver that can respond and produce the alert signal for the pilot is the receiver and decoder system that has been set for the particular four-tone code.

The Selcal decoder is typically a separate LRU installed in the equipment rack of the aircraft along with the VFH and HF radio transceivers. As shown in Fig. 15-7, the LRU has a four-digit display used to enter the aircraft Selcal identification code. A small panel must be installed on the flight deck to control (turn on/off) the Selcal system for the various communication radios.

ACARS

The **Aircraft Communications Addressing and Reporting System** (ACARS) is a digital system that operates using the VHF communications equipment on frequencies between 129.00 MHz to 137.00 MHz. The ACARS airborne equipment contains a control unit, located on the flight deck, and a management unit, located in an equipment bay. The ground equipment contains antennas and r-t units, a data link via a land-based Internet connection to the central ground facility in Chicago, and a data link to the various airline operation centers. The ground facilities cover the continental United

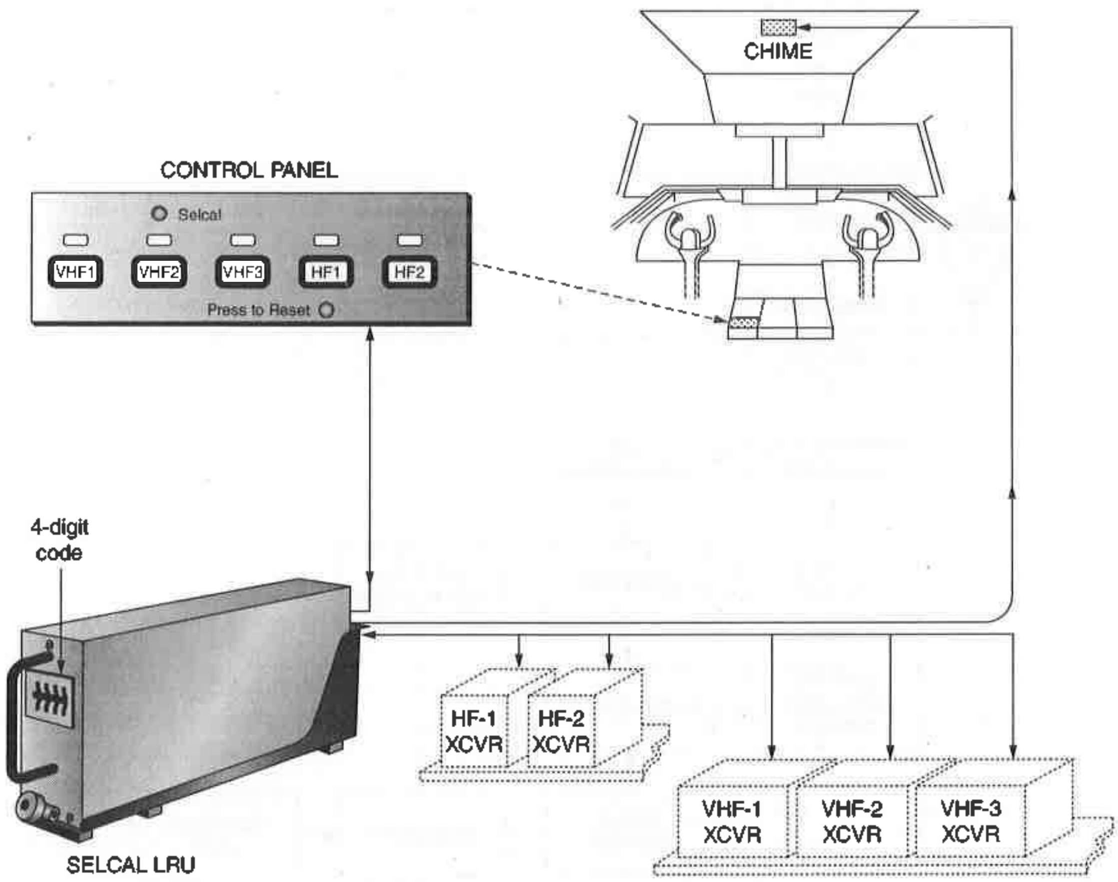


FIGURE 15-7 Typical Selcal system for an airliner.

States and portions of Canada and Mexico. In the Americas ACARS is operated by ARINC. Once called Aeronautical Radio Incorporated, ARINC is a major provider of transport communications and systems engineering for the aviation industry. SITA, a multinational information technology company specializing in telecommunication services, offers an ACARS system in Europe and other parts of the world. Since ACARS is a digital-based information transfer system using radio signals, it can easily be compared to text messaging using cell phones.

Since ACARS operates on a limited number of frequencies, all transmitted messages must be as short as possible. To achieve a short message, a special code block using a maximum of 220 characters is transmitted in a digital format. If a longer message is needed, more than one block will be transmitted.

ACARS operates in two modes: the demand mode and the polled mode. The **demand mode** allows the flight crew or airborne equipment to initiate communications. A block diagram of an ACARS is shown in Fig. 15-8. To transmit a message, the management unit (MU) of the airborne system determines if the ACARS channel is free from other communications. If the channel is clear, the message is transmitted; if the frequency is busy, the MU waits until the frequency is available. The ground station sends a reply to the message transmitted from the aircraft. If an error reply or no reply is received, the MU continues to transmit the message at the next opportunity. After six attempts (and failures), the airborne equipment notifies the flight crew.

In the **polled mode**, the system operates only when interrogated by the ground facility. The ground facility routinely uplinks "questions" to the aircraft equipment, and when a channel is clear, the MU responds with a transmitted message. The MU organizes and formats flight data prior to transmission. Upon request, the flight information is transmitted to the ground facility. Information for ACARS is collected from several aircraft systems, including the flight management system (FMS), the aircraft integrated data system (AIDS), and the central maintenance computer system (CMCS).

Satellite Communication

Some aircraft are equipped with receivers and transmitters that utilize orbiting communication satellites to extend their useful range. **Satellite communication** (SATCOM) equipment is typically found on aircraft that make intercontinental flights. Common HF communication radios will transmit long distance; however, they are very susceptible to interference. SATCOM equipment utilizes frequencies that are relatively static-free but normally limited to line-of-sight transmission characteristics. During SATCOM operation the RF wave is transmitted from the aircraft radio to an orbiting satellite. The satellite relays the radio signal to the ground-based receiver. This process extends the range of a typical VHF communication radio to cover any area between latitudes 75° north and 75° south.

A SATCOM system is made up of three subsystems: the ground earth station, the aircraft earth station, and the satellite

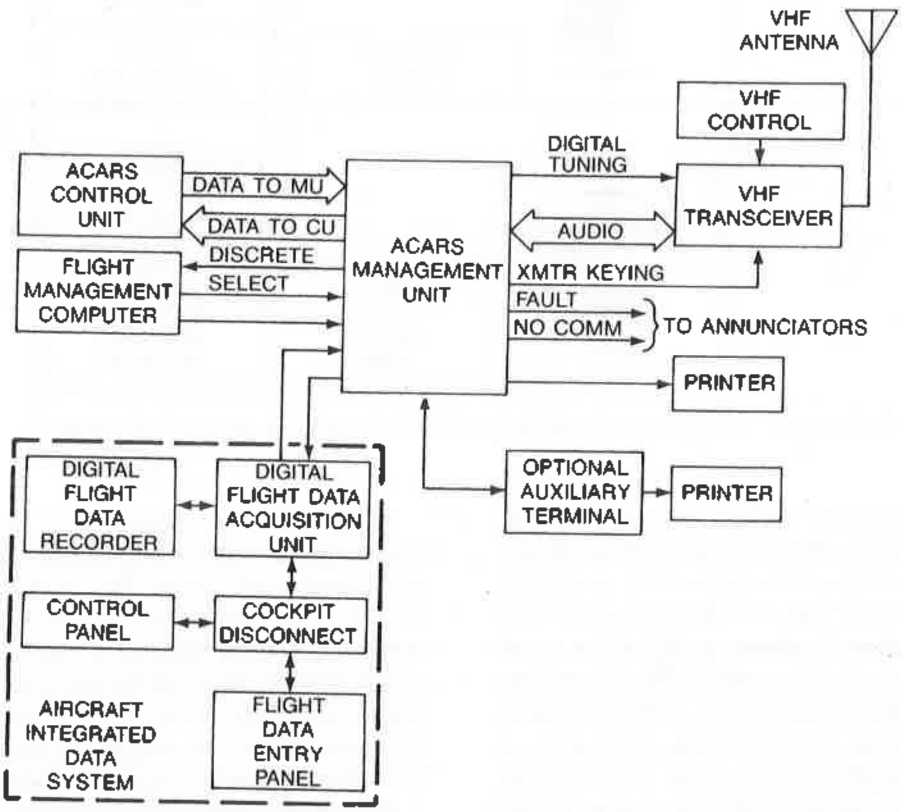


FIGURE 15-8 A block diagram of a typical ACARS system. (*Collins Divisions, Rockwell International.*)

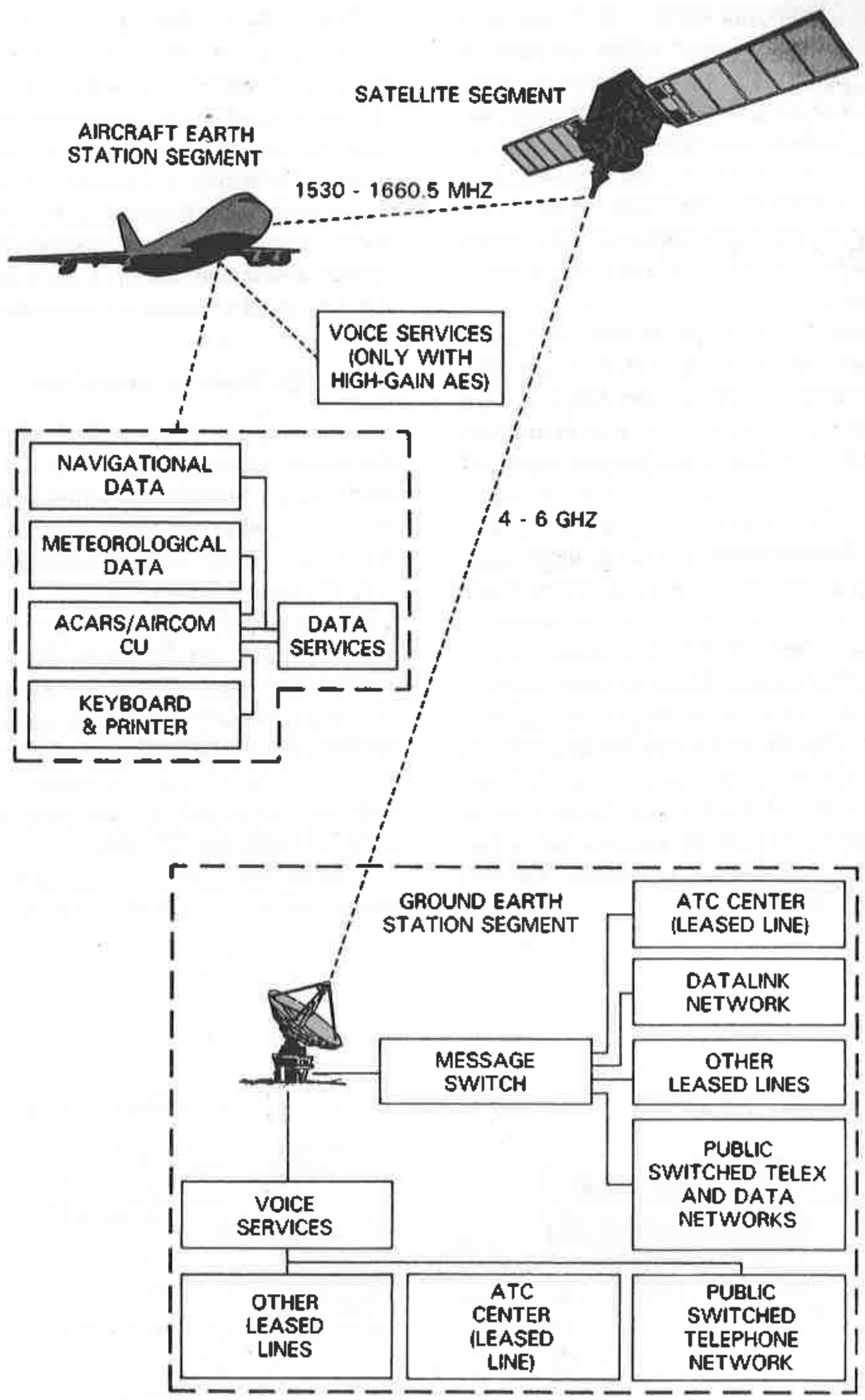


FIGURE 15-9 The SATCOM system segments. (*Collins Divisions, Rockwell International.*)

system (Fig. 15-9). The aircraft earth station unit transmits on L-band frequencies between 1530 and 1660.5 MHz. The aircraft is capable of transmitting information from several different sources, such as AIRCOM, ACARS, flight-crew voice communications, passenger telephone, telex, and fax. A satellite data unit (SDU) is used to interface information from other aircraft systems that are linked to the SATCOM system. The SDU works in conjunction with a radio frequency unit (RFU), a high-power amplifier (HPA), a low noise amplifier (LNA), and a beam-steering unit (BSU) to send an L-band signal to the transmitting antenna and on to the satellite.

Satellites that are located in a geosynchronous orbit receive signals transmitted from either a ground earth station or an aircraft earth station. The satellites receive and transmit in L-band frequencies when communicating with aircraft and in C-band frequencies when communicating with ground stations. The satellites act as a relay station for the various SATCOM signals. For example, a signal received from an aircraft is converted into a C-band frequency, amplified, and transmitted to a ground station.

The ground stations provide coordination for the various satellites and aircraft transmissions. The network of ground stations allows an aircraft to communicate with virtually any user of the network. The ground stations transmit to the satellites at a frequency between 4 and 6 GHz (C-band microwave frequencies). The ground stations communicate to other ground equipment through a telephone communications network.

Airborne Broadband Internet

Modern passengers flying today have become accustomed to Internet connectivity for both business and pleasure. Today many corporate and large passenger aircraft have installed an Airborne Broadband System (ABS) for passenger convenience. The ABS technologies allow laptops, Wi-Fi enabled PDAs (personal digital assistants), and other wireless devices a means of connection to the World Wide Web during flight. In order to create this connection, satellites, radio signals, control units, onboard Wi-Fi networks, and ground-based units are all connected through airborne equipment dedicated to Internet access.

Currently in the United States a company called **GoGo**, formally known as **Aircell**, offers in-flight broadband service to the passengers on over 6000 aircraft; and it is likely additional aircraft will offer ABS in the future. The technology for ABS is rapidly changing and services are likely to continue to improve. Currently, the third-generation (3G) multiple access cellular technology is used by GoGo to provide the ABS connection. This allows all passengers to be on a single broadband frequency. The speed of data transmission is dependent on the number of passengers using the system within the aircraft and the number of planes sharing a cell site. This system uses a ground-based segment consisting of a network of cell sites and the related circuitry for a terrestrial-based connection to the Internet. Figure 15-10 shows the basic configuration of the aircraft to Internet connection for an airborne broadband system. The cell sites are basically special frequency cell towers designed to transmit/receive signals to/from the aircraft. Each cell is connected to the Internet through a ground-based Internet connection.

The major challenge for this type of system is created by the speed of most aircraft. As the aircraft travels, the coverage of several towers can be traversed quickly. This requires a sophisticated control system for proper operation. GPS positioning data is used to help locate and control proper aircraft to cell tower connections.

As systems become available, the company plans to use Ka-band satellite communications to further improve the capabilities of the airborne equipment. By using aircraft-to-satellite-to-ground connections, many of the challenges created by land-based cell towers will be eliminated. As technology changes, the specifics of the airborne broadband system will no doubt improve. Exactly how is still unclear; however, one thing seems certain: passengers have become accustomed to Internet connectivity and the aircraft industry will do all they can to keep people connected.

Federal Communications Commission Regulations

Because of the very nature of radio waves and their effect on many activities of modern life, all electromagnetic emissions are controlled by a single government agency. In the

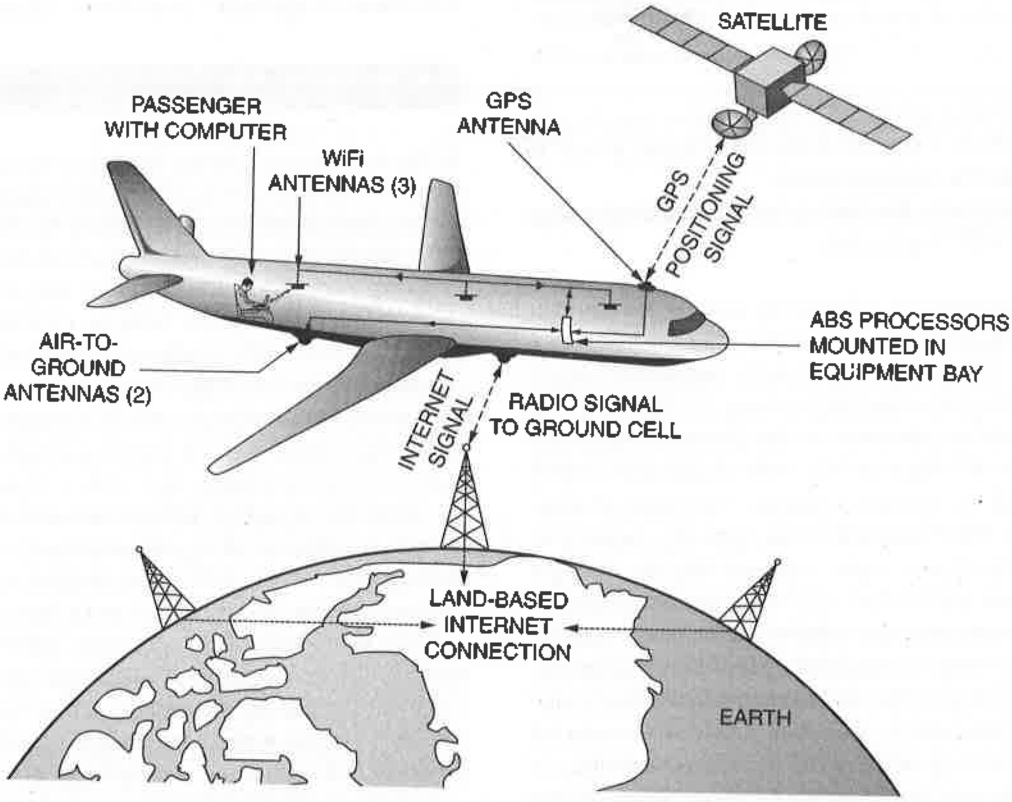


FIGURE 15-10 Airborne Wi-Fi system.

United States this agency is the **Federal Communications Commission** (FCC). It is the responsibility of this body to supervise all radio transmissions in the United States and its territories and possessions. The FCC licenses radio operators, technicians, amateur stations and operators, commercial radio stations, marine radio stations, television stations, mobile phones, WiFi, and various special radio or television operations. Furthermore, the FCC assigns frequency ranges for different types of operations and assigns specific frequencies to individual stations. The agency also cooperates with international agencies to work out agreements to prevent, as much as possible, interference between stations of different nationalities.

Some typical FCC regulations are listed below, but not necessarily in the actual language of the law:

1. All radio transmitters installed in operating aircraft must be licensed.
2. Distress calls or messages have priority over all others.
3. The distress call for radio/telephone is *Mayday*. The digital distress call is • • • - - - • • •, which may be interpreted as SOS.
4. The penalty for willfully violating the Communications Act is a $ 10 000 fine or imprisonment for a term of not more than two years or both.
5. No fraudulent signals shall be transmitted.
6. Information received by radio and not intended for the person receiving such information shall not be divulged to any person other than the one for whom it is intended; neither shall the existence of the information be divulged.
7. No unnecessary communications shall be transmitted.
8. No operator of a radio station shall violate the provisions of any treaty to which the United States is one of the parties.
9. The operating power of a radio station may be permitted to vary from 5 percent above the assigned power to 10 percent below the assigned power.
10. A person's radio license may be suspended or revoked for violation of FCC regulations.

The above laws are only a few of the most important relating to the operation of radio transmitters. A person who is to be involved in the operation of a radio transmitter should obtain all the necessary information from the FCC and then apply for the license appropriate to the operation concerned.

The operator of a light-aircraft radio transmitter usually does not require an operator's license. Operators of commercial aircraft radio transmitters are typically required to be licensed. Any aircraft radio receivers may be operated without a license. Technicians who work on certain aspects of radio equipment may also require one or more licenses. It is important to keep in mind that aircraft are regulated by the FAA and radios are regulated by the FCC (Federal Communications Commission). In some cases, certification or licensure from both agencies is required for maintenance or installation of aircraft radio equipment. Today many aircraft are maintained by certified repair stations; in this case, licensing requirements may be necessary for the repair facility not the individual technician.

Testing of a Communications Radio

Testing of a communications radio in small aircraft used in general aviation may be accomplished in accordance with procedures appropriate for the airport and area in which the test is made. Testing on the ground with the engine or engines not operating can be accomplished as follows:

1. Turn on the aircraft power with the master switch.
2. Turn on the transceiver.
3. Select the frequency of the station with which the test is to be conducted.
4. Listen to the receiver to be sure there is no radio traffic in progress at the selected frequency.
5. If no radio traffic is heard, press the transmit switch and call the selected station.
6. Upon receipt of a reply, request a radio check.
7. If reception and transmission are satisfactory, turn the transceiver off. Be sure to do this before turning off the aircraft's master switch.

If a receiver or transmitter is found to be defective, it can easily be removed from the aircraft and sent to an appropriate avionics repair facility. The aircraft technician may inspect for defective items within the system, such as microphones, circuit breakers, or wiring. However, an aircraft technician may never make repairs or alterations to any part of the radio system that may adversely affect the radio transmission signal. In most cases, it is best to have a certified repair station perform all maintenance on radios or related equipment.

NAVIGATION SYSTEMS

In the early days of airplane operation, navigation instruments either did not exist or, at most, consisted of a magnetic compass and an airspeed indicator. When flying by visual reference, the early pilot would usually navigate from one landmark to another, following roads and railroads or rivers and valleys. Flights were made at comparatively low altitudes providing a view of the ground that was usually good enough for the pilot to clearly identify objects there. Under the flying conditions that existed when the airplane was considered a novelty, complex navigation instruments and systems were not in great demand. As the use of airplanes increased and flights were made at higher altitudes, above the clouds and at night, it became necessary to develop reliable navigation techniques along with instruments indicating attitude, heading, airspeed, and drift so that the pilot could determine the airplane's position by computation and map plotting.

From the 1930s to the present time, great strides have been made in the development of electronic navigation systems. Today a pilot can fly an airplane across the continent from takeoff to landing without touching the controls, all the navigation and pilotage being accomplished electronically.

It is the purpose of this section to describe and explain some of the electronic navigation systems and equipment on modern aircraft. It is beyond the scope of the text to describe the details of circuitry and all the electronic principles employed. To do so would require far more space than is available; however, the general principles of operation and the individual components will be explained.

Automatic Direction-Finder Systems

The function of an **automatic direction-finder** (ADF) system is to enable the pilot to determine the heading, or direction, of the radio stations being received. The ADF system operates on a frequency range of 90 to 1800 kHz, a range that makes it possible for the system to receive radio-range stations in the LF band and standard broadcast stations. By use of the ADF system, a pilot can determine the aircraft's position, or the pilot can "home in" on a radio broadcast station or a radio beacon station by flying directly toward that station using the indication of the radio compass or radio magnetic indicator. To find the aircraft's position, the pilot or the navigator determines the headings of two different radio stations and then plots the headings on a navigation chart. The point at which the heading lines cross is the location of the aircraft.

ADF systems utilize the directional characteristics of a loop antenna to determine the direction of a radio station. A simple direction finder may be made by using a loop antenna with an ordinary radio receiver. By rotating the antenna, the strongest reception can be determined and also the point at which the signal fades out. This point is called the **null position**, and from it a fairly accurate indication of the station direction can be determined. This phenomenon can be demonstrated while listening to a commercial AM radio station. If the radio (and its loop antenna) is rotated, the quality of reception changes. When the reception is the worst, the antenna is in its null position.

ADF equipment is especially valuable in areas of the world where special navigational aids are not available but where the pilot may tune in to a standard broadcast station.

Theory of Operation. As explained in Chap. 14, radio waves are propagated in the form of electromagnetic and electrostatic lines of force that travel at a speed of approximately 186 300 mi/s [300 000 000 m/s] from the radio transmitter. When these lines of force cut across a radio antenna, a voltage is induced in the antenna. This voltage is amplified and demodulated so that the intelligence contained on the radio wave may be determined. If a loop antenna is placed in such a position that it is at 90° to the direction of wave travel, equal and opposite voltages will be induced in the sides of the antenna, as shown in Fig. 15-11. The voltages thus induced in the loop will cancel each other, with the result that the loop will have no output. If the loop is connected to a radio receiver, the signal will disappear at this point. When the plane of the loop is parallel to the direction of wave propagation, the strongest signal will be developed. The loop antenna of this diagram is for explanation purposes; a modern ADF system contains a loop antenna that rotates electronically and has no actual movement.

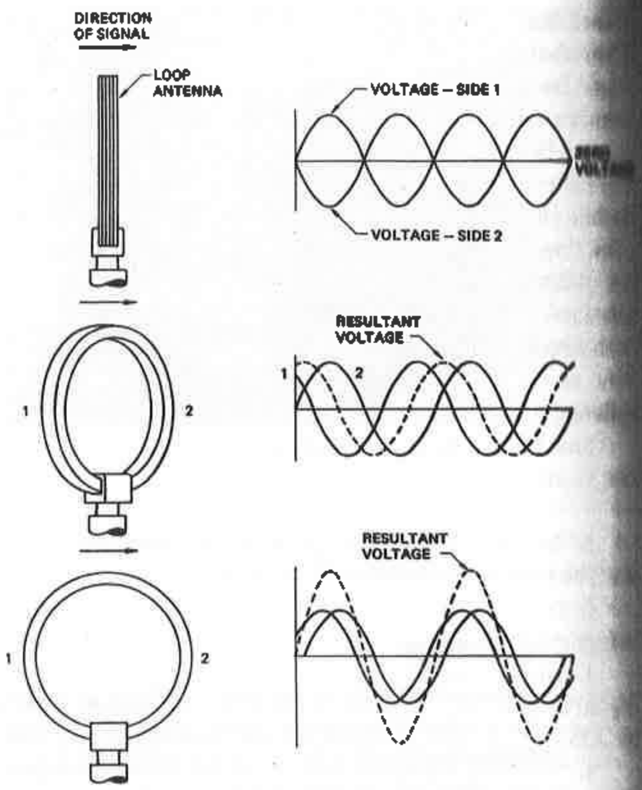


FIGURE 15-11 Operation of an ADF loop antenna.

The components of a typical ADF system include the radio receiver, a control panel (these two elements may be combined), the loop and sense antennas housed in one assembly, and the ADF indicator called the RMI. A typical ADF control panel is shown in Fig. 15-12. This ADF system is used on light aircraft and contains the radio receiver directly behind the control panel. A digital tuner and an LED frequency display are used to reduce the number of moving parts, thereby increasing the system's reliability. The **radio magnetic indicator** (RMI) shown in Fig. 15-13 provides visual information for the pilot and copilot concerning the data received by the ADF equipment. The instrument displays the magnetic heading of the aircraft and the magnetic bearings of

FIGURE 15-12 A panel-mounted ADF receiver.

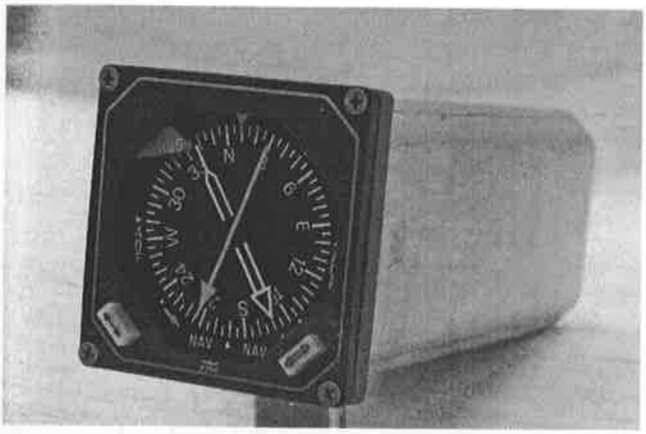


FIGURE 15-13 Typical ADF indicator.

two radio stations. The bearings of the two radio stations are provided by two separate ADF receivers.

VHF Omnirange

VHF omnirange (VOR) is an electronic navigation system that enables a pilot to determine the bearings of the VOR transmitter from any position in its service area. This is possible because the VOR ground station, or transmitter, continually broadcasts an infinite number of directional radio beams or radials. The VOR signal received in an airplane is used to operate a visual indicator from which the pilot detemines the bearings of the VOR station with respect to the airplane.

As shown in Fig. 15-14, a VOR ground station contains an elaborate antenna array with one omnidirectional antenna located in the center of the structure and multiple antennas equally spaced in a circle on the outer edge of the station. Each antenna is used to broadcast a specific signal from the station. The center antenna broadcasts an FM reference signal; the outer array is used to broadcast an AM variable signal. The reference signal is broadcast in all directions around the station; the highly directional variable signal changes phase compared to the reference signal

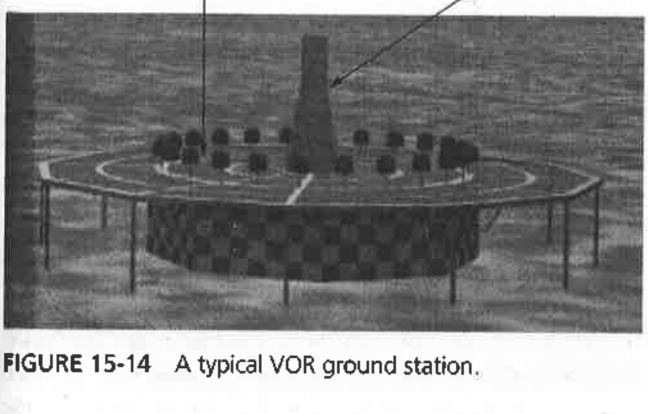


FIGURE 15-14 A typical VOR ground station.

30 times a second. The signals are precisely timed so the phase (between reference and variable) changes as the antenna array "electronically spins" the variable signal. The rotation of the variable signal is such that when the antenna transmits 90° from the north, the variable signal is 90° out of phase with the reference signal. Figure 15-15 shows both signals as they exit the VOR ground station.

In a clockwise direction around the VOR station, the radiated signals become increasingly out of phase. At 90° clockwise from the due north direction, the signals are 90° out of phase; at 180° they are 180° out of phase; at 270° they are 270° out of phase; and at 360° (0°) they are back in phase. The phase difference of the two signals makes it possible for the receiver to establish the bearings of the ground station. The directional bearings of VOR stations are set up in accordance with the earth's magnetic field so that they may be compared directly with magnetic-compass indications on the airplane.

The carrier frequency of the VOR station is in the VHF range, between 112 and 118 MHz. A modulation of 9960 Hz is placed on the carrier of the reference signal to provide a subcarrier, which is modulated by a 30-Hz signal. The 9960-Hz modulation on the original carrier wave is AM, and the 30-Hz signal on the subcarrier is FM. The carrier wave for the variable-phase signal is amplitude-modulated by a 30-Hz signal.

The VOR receiver mounted in an airplane may be an independent unit, or it may operate in conjunction with the VHF communication radio. Light aircraft typically use the combined unit, known as a VHF NAV/COM radio. Whenever using a VOR to determine position, the aircraft is said to be on a given radial from that station. Each radial extends in the direction of compass points from the center of the station as shown in Fig. 15-16.

The omnirange indicator includes an azimuth dial, a LEFT-RIGHT deviation needle, and a TO-FROM indicator. When the VOR receiver on an airplane is tuned to a VOR ground station, the LEFT-RIGHT indicating needle will be deflected either to the right or to the left unless the selected course on the omnirange indicator is in agreement with the bearing of the VOR ground station.

Once the pilot has tuned to the correct ground station frequency and selected the correct course, the unit is ready for navigation. For example, if the course-deviation indicator bar moves to the left, the pilot knows the intended course is to the left of the aircraft. To correct the flight path, the pilot must turn the aircraft to the left.

Two indicators used on light aircraft to display VOR information are shown in Fig. 15-17. The indicator on the left is used for VOR, localizer, and glide slope information as denoted by both vertical and horizontal indicator needles; the display on the right shows VOR indications only. The traditional electromechanical display is still used on most aircraft; however, flat panel indicators are now installed on most new aircraft. In either case the VOR controls must employ some type of omni bearing selector (OBS), and the OBS scale around the outside of the instrument, used to set the desired course. A course deviation indicator (CDI) is

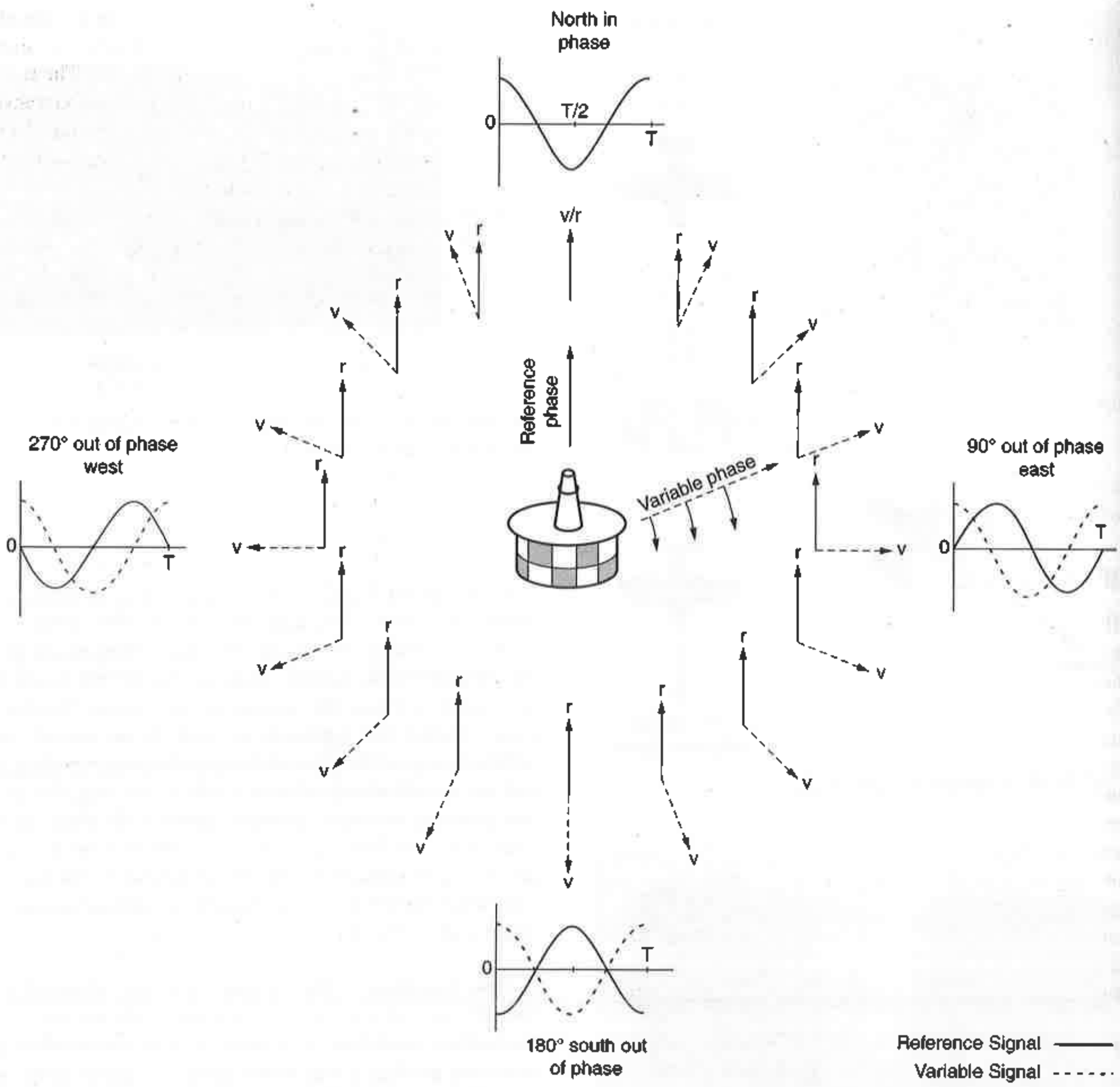


FIGURE 15-15 VOR reference and variable signals.

used to show aircraft position relative to the desired radial. The CDI is centered when the aircraft is on the selected course, or gives left/right steering commands to return to the desired course. An "ambiguity" TO-FROM indicator shows whether following the selected course would take the aircraft **to**, or away **from** the station.

Testing for Accuracy. In accordance with the flight regulations of FAR Part 91, any VOR receiver that is to be used under instrument flight rule (IFR) conditions must be checked periodically. The pilot can perform this accuracy check by comparing the indication of two VORs within the same aircraft or by comparing the VOR's indication with a known VOR test point. A certified VOR test (VOT) station may also be used if there is one available in your area. Since this test must be performed at least every 30 days, a log entry must be recorded in a dedicated VOR logbook.

Instrument Landing System

The **instrument landing system** (ILS), as the name implies, is designed to allow pilots the opportunity to land their aircraft with the aid of instrument references. A typical ILS system will allow the pilot to bring an aircraft to within $\frac{1}{2}$ mi of the runway and less than 200 ft above the runway without any external visual references. At these minimums (the **decision height**) the pilot must identify the **runway environment** in order to continue the landing process. If the runway environment cannot be identified, the pilot must execute a missed approach procedure. There are three categories of ILS approaches: Category I, II, and III. Category I, the least precise, can provide guidance to land as low as 200 ft above ground level, when visibilities are as low as 2400 ft. If the pilot does not see all runway environments at the 200-ft decision height, the aircraft must execute a missed approach and abort the landing. The extremely accurate ILS, called the

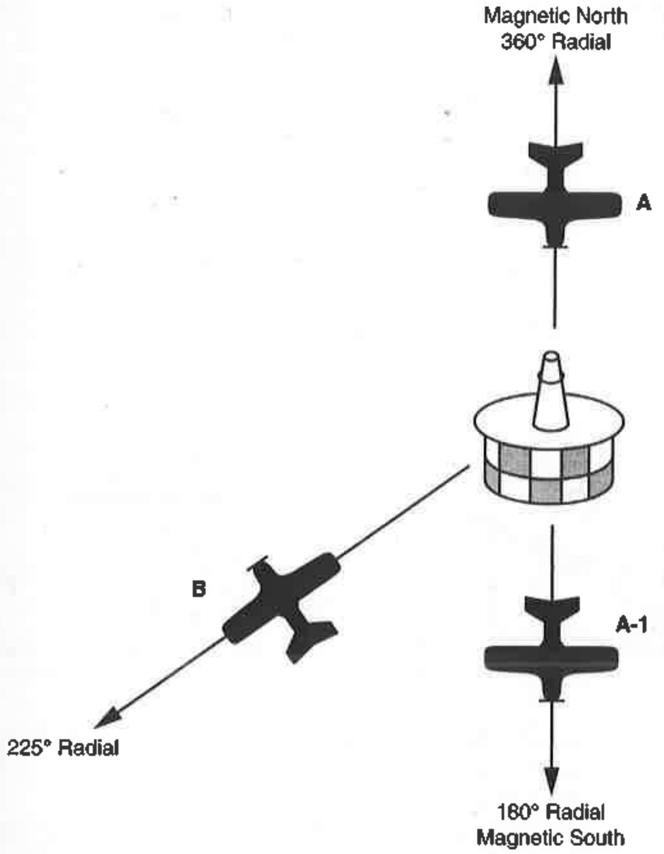
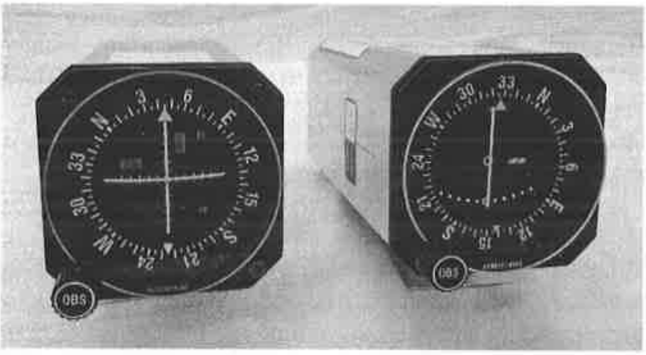


FIGURE 15-16 Example of VOR radials.



(a) (b)

FIGURE 15-17 Two electromechanical VOR indicators: (*a*) VOR and localizer/glide slope and (*b*) VOR.

Category IIIC approach, will allow for aircraft landings with near zero visibility. Both the airport facilities and the aircraft must be correctly equipped and certified for each category approach.

The ILS provides a horizontal directional reference and a vertical reference called the **glide slope**. The directional reference signal is produced by the runway **localizer** transmitter, which is installed approximately 1000 ft [305 m] from the far end of the runway and operates at frequencies of 108 to 112 MHz. The glide slope signal is produced by the glide slope transmitter, which is located near the side of the runway at the point where airplane touchdown occurs. This point is generally about 15 percent of the runway length

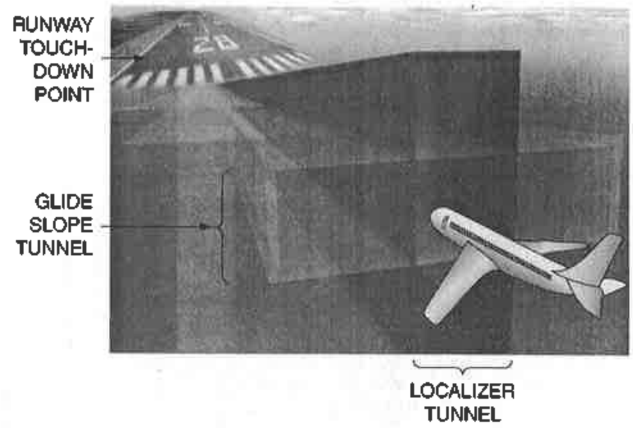


FIGURE 15-18 The "electronic tunnel" created by an instrument landing system.

from the approach end of the runway. The glide slope transmitter operates at a frequency of 328.6 to 335.4 MHz.

As seen in Fig. 15-18, the two main components of the instrument landing system create a type of "electronic tunnel" used to direct the aircraft to the runway touchdown point. During the approach to land, if the aircraft stays within the tunnel the plane will reach the proper landing spot and no outside visual reference will be needed. The localizer provides the lateral guidance; left or right of the runway centerline. The glide slope provides the vertical guidance; above or below the glide path. The glide path is an imaginary line which extends from the touchdown pointing upward at a slight angle above the surface of the earth.

The Localizer. The localizer consists, essentially, of two RF transmitters and an eight-loop antenna array. The transmitters broadcast a complete system of radiation patterns that produce a null signal along the center of the runway. The radiation pattern is such that when an airplane is approaching the runway for a landing, the signal to the right of the localizer path will be modulated with 150 Hz, and the signal to the left of the localizer path will be modulated with 90 Hz. The localizer signal pattern is shown in Fig. 15-19.

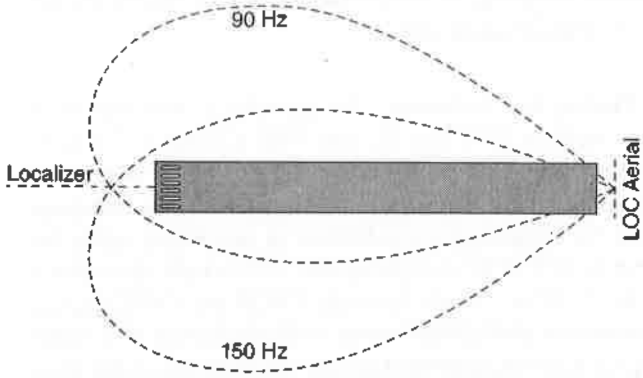


FIGURE 15-19 Radiation pattern for ILS localizer.

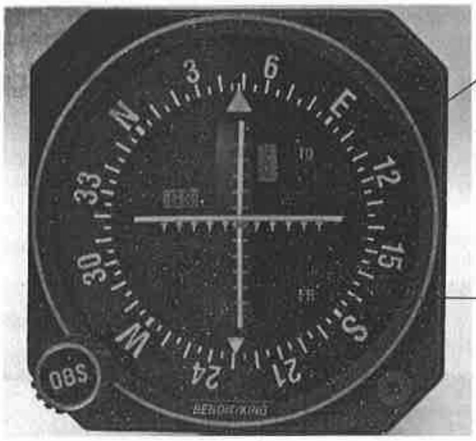


FIGURE 15-20 Course-deviation indicator (CDI).

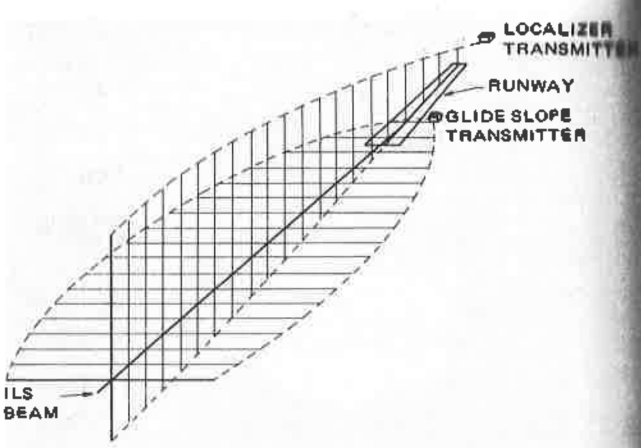


FIGURE 15-22 ILS transmission pattern from localizer and glide slope.

The localizer receiver on board an airplane is able to discriminate between the 90- and 150-Hz signals. The output of the receiver is fed to the vertical needle of a **course-deviation indicator** (CDI), as shown in Fig. 15-20. The localized information could also be displayed on a CRT or a flat panel as part of a flight guidance system. If the airplane is to the right of the localizer centerline, the 150-Hz modulation signal will predominate, and the vertical needle of the indicator will point to the left of the centerline, indicating that the pilot should fly left in order to return to the centerline of the localizer beam. A general rule is that when off course the pilot should always "fly toward" the needle. This will return the aircraft to the correct flight path.

The Glide Slope. The glide slope transmitter operates on a principle similar to that of the localizer. As previously mentioned, the glide slope transmitter is located at a distance from the approach end of the runway, approximately 15 percent of the length of the runway. A schematic diagram illustrating the radiation pattern from the glide slope transmitter is shown in Fig. 15-21. If an airplane is approaching the runway and is above the glide path, the 90-Hz signal will predominate; and if the airplane is below the glide path, the 150-Hz signal will predominate. The glide slope receiver will provide an output for the cross-pointer indicator in such a way that the pilot will have a visual indication of the airplane's position with respect to the glide path. If the horizontal pointer is above the center of the indicator, the airplane is below the glide path.

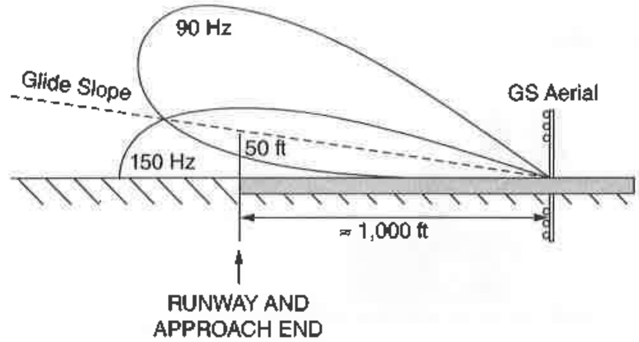


FIGURE 15-21 Radiation pattern from a glide slope transmitter.

A diagram of the beam provided by the combination of localizer and glide slope transmitter is shown in Fig. 15-22. The beam is electronically exact and provides a precise path by which an airplane may approach a runway and reach the point of touchdown. Today and into the foreseeable future, it is quite likely that ILS will remain the most accurate navigation aid available.

On larger aircraft the ILS and VOR control panels are usually combined and located on the instrument panel; the receivers are typically separate units located in the radio equipment rack. Light-aircraft ILS receivers are usually combined with the receiver for VHF omnirange (VOR) and are often designated as VOR LOC receivers. On most modern aircraft the indications for several systems are combined into one display; traditional systems use electromechanical indicators and newer aircraft employ electronic displays. In either case, the two common navigational indicators are the attitude director indicator (ADI) and the horizontal situation indicator (HSI). When the ADI and HSI are combined into one display, it is called the primary flight display (PFD). A typical PFD found on a corporate jet aircraft is shown in Fig. 15-23; the top part of the display contains ADI information and the lower part contains the HSI data.

Navigation Receivers

A basic navigation (NAV) receiver is designed to receive VOR signals and display course, bearing, and heading information on an RMI, an HSI, or some other instrument. If the receiver is equipped to receive localizer (LOC) and glide slope (GS) signals, the system will include a course-deviation indicator (CDI) or a similar instrument to show the pilot where the aircraft is tracking the ILS beam as it approaches a runway.

A typical NAV receiver is shown in Fig. 15-24. This receiver is equipped with a standby frequency provision so a frequency may be preselected and held in readiness for use when needed. The frequencies are selected by means of the

FIGURE 15-23 An electronic primary flight display for a corporate or commuter type aircraft.

FIGURE 15-24 Panel-mounted VHF navigation receiver.

frequency selector knobs at the right of the panel. The outer knob selects the megahertz portion of the frequency, and the inner knob selects the kilohertz portion. Some NAV receivers use push-button panels for selecting frequencies.

As mentioned previously, NAV receivers and COM transceivers are often combined into one unit of equipment. This saves weight and space and simplifies the installation. A unit of this type is called a NAV/COM unit and may include ILS receivers for LOC and GS.

Distance-Measuring Equipment

In order to determine distance between the aircraft and a given navigational aid, a system known as distance-measuring equipment (DME) was developed. Aircraft use **DME** to determine the slant distance from a land-based transponder by sending and receiving a pulsed radio signals. The DME ground stations are typically colocated with VORs, commonly called VOR/DME. A tactical air navigation system, commonly referred to by the acronym TACAN, is a distance-measuring navigation system used by military aircraft. The DME portion of the TACAN system is available for civil use; called VOR/TAC. In general, there is little difference in the systems and the terms can be used interchangeably. A typical DME ground transponder for en route or terminal navigation will transmit on a UHF channel with a peak power of 1 KW. When using the VOR/DME navigation system, both distance and direction from a given ground station can be determined; hence the exact position of the aircraft will be identified.

The operation of DME units is similar to that of radar beacons. That is, the communication between the airborne unit, called the **interrogator**, and the ground station is by means of pulses similar to those utilized in radar. The ground DME unit is called a **transponder**. During operation of VOR, when the pilot selects a particular ground-station frequency by means of the control, the coded pulse is automatically selected in the DME interrogator associated with the VOR. The interrogator transmits pairs of coded pulses to the transponder (ground station), where the signal is amplified and transmitted back to the airborne receiver (see Fig. 15-25). The time interval between transmission of the signal by the interrogator and receipt of the signal sent by the transponder determines the distance of the airplane from the ground station. Remember that approximately 6.19 μs is required for a radio wave to travel 1 mi [1.8 km].

The DME challenge sent by an aircraft, when a particular VOR station is selected, consists of spaced pulses in the frequency range of approximately 987 to 1213 MHz. The ground-station transponder will accept only signals that are spaced correctly and have the correct frequency.

The DME equipment mounted in an airplane consists of **timing** circuits, **search** and **tracking** circuits, and the **indicator**. The timing circuits measure the time interval between the interrogation and the replay, thus establishing the distance

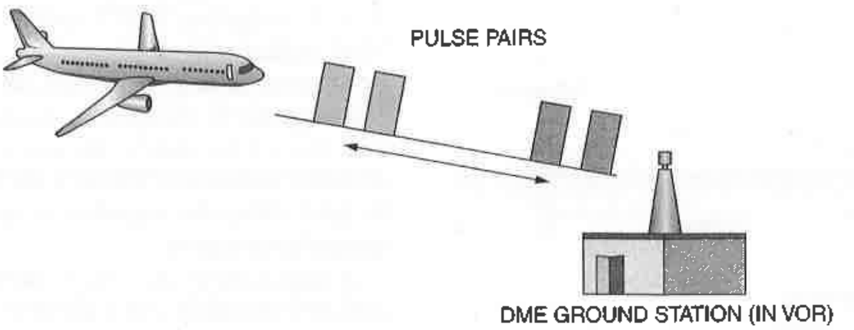


FIGURE 15-25 Concepts of a DME interrogation signal to determine distance.

of the ground station from the airplane. The search circuits cause the airborne equipment to seek a reply after each challenge, a function accomplished by triggering the receiver into operation after each interrogation. When the receiver picks up a reply of the correct code, the tracking circuit will operate and enable the receiver to hold the received signal. The time interval is measured and converted into a distance reading, which is then displayed on the DME indicator. If the airborne receiver picks up a signal with an incorrect code (that transmitted from another aircraft), the equipment automatically rejects that signal. Any airborne DME receiver will accept only signals that were originally transmitted by its own equipment. This means of signal discrimination allows several aircraft to navigate using the same DME ground station.

DME distance indications are displayed digitally on one or more panels or instruments. As an airplane equipped with DME is approaching a DME station and is receiving DME information, the distance readout will continue to change as the distance from the station changes. The rate of change is fed to a computer that produces a ground-speed indication. In many of the advanced navigation systems, the time required to reach a given station or waypoint is also displayed.

Airborne receivers for DME are provided with an audio system that receives identification codes from DME stations. This makes it possible for the pilot to identify positively the station that the DME has locked onto. In the majority of VOR/DME receivers, when a particular VOR frequency is selected, the associated DME frequency is automatically selected for that station.

In the installation of DME equipment in an aircraft, the location of the antenna is critical. The antenna is a short stub, approximately 2.5 in. [6.35 cm] long, usually mounted on the bottom of the fuselage. Care must be taken in locating the antenna, because it can be blanked out easily by obstructions such as landing gear or other antennas nearby. It is recommended that manufacturer's instructions for installations in similar aircraft be observed when making a new installation.

Marker Beacons

A marker beacon is used in conjunction with an ILS and transmits a very narrow VHF radio signal. The marker beacon provides a means to determine position along an established route such as a runway approach. There are three types of marker beacons that may be installed as part of a common ILS; the **outer**, **middle**, and **inner** markers. Figure 15-26 shows the locations of the three marker-beacon signals along with the localizer and glide slope for a typical ILS approach. The marker-beacon transmitter operates at a frequency of 75 MHz and produces both aural and visual signals. The outer-marker transmitter produces a 400-Hz intermittent signal that causes a blue indicator light on the instrument panel to glow intermittently. The midmarker transmitter produces a signal modulated at 1300 Hz that causes the amber marker-beacon light on the instrument panel to glow. Thus when an airplane is approaching the runway and is approximately 5 mi from its end, the blue light will flash. A short time later, when the airplane is within $\frac{2}{3}$ mi of the runway, the amber light will flash.

Some airports also employ an inner marker located approximately 1500 ft from the end of the runway. By modulating the RF wave with a 3000 Hz signal, the inner marker will illuminate a white panel light when the aircraft is over the appropriate position. This system provides an excellent indication of the plane's distance from the runway. The white lamp is usually labeled "FM/Z" because the 3000-Hz signal is also produced by en route airway, or "Z," markers.

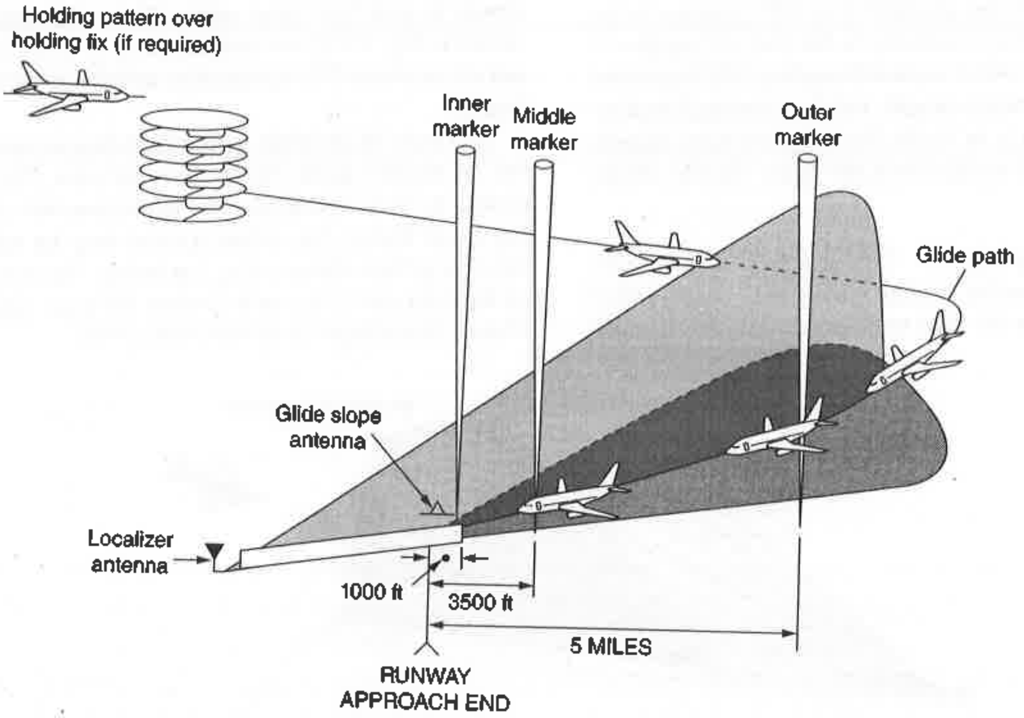


FIGURE 15-26 The three-marker-beacon signal associated with an instrument approach.

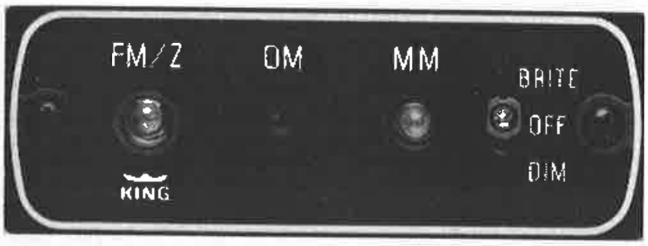


FIGURE 15-27 A typical marker-beacon display panel. *(Bendix King by Honeywell.)*

Marker-beacon receivers are typically located in the aircraft's equipment rack. A display panel, as illustrated in Fig. 15-27, is mounted on the aircraft's instrument panel. No control unit is required for a marker-beacon receiver. The unit typically turns on when the avionics master switch is activated.

Microwave Landing System

A microwave landing system (MLS) is a precision approach intended to replace or supplement the ILSs. MLS has a number of operational advantages, including a wide selection of channels to avoid interference with other nearby airports, excellent performance in all weather, and a small "footprint" at airport installations. The extensive vertical and horizontal "capture" angles employed by MLS allow aircraft to approach from a wide area around the airport; ILS permits an approach only on a narrow path or tunnel.

Although some MLS systems became operational in the 1990s, the widespread deployment initially envisioned by its designers never became a reality. The implementation of GPS-based systems has eliminated the need for MLS in the United States. MLS continues to be of some interest in Europe, where concerns over the availability of GPS continue to be an issue. A widespread installation in the United Kingdom is currently underway, which included installing MLS receivers on most British Airways aircraft, but the continued deployment of the system is in doubt. Probably the most famous vehicle to use MLS navigation is the Space Shuttle orbiter operated by NASA.

Principle of Operation. The principle of operation for the TRSB microwave landing system may be illustrated as shown in Fig. 15-28. Two transmitters, one for azimuth and one for elevation, transmit fan-scanning beams toward approaching aircraft. The precise timing of the scanning beams provides exact information for the pilot regarding the position of the aircraft. Beams are scanned rapidly "to" and "fro" throughout the area shown in the drawing. In each complete scan cycle, two pulses are received by the aircraft. One pulse is received during the "to" scan and the other during the "fro" scan. The aircraft receiver derives its position angle directly from the measurement of the time difference between the two pulses. The receiver-processor computes the information and prepares it for display on a conventional course-deviation indicator (CDI). In addition, a digital display of the information is presented on the control panel.

Distance information for the system is derived from conventional distance-measuring equipment (DME).

Radio Tuning Systems

On many modern corporate or transport-category aircraft, **radio tuning units** are used to help eliminate instrument panel clutter and simplify radio operations. These units are designed to allow the pilot access to several radios using one control-display unit. As shown in Fig. 15-29, a typical system can operate the VHF communication; VOR/ILS, DME, ADF, ATC transponder, and GPS radios. Radio tuning units are typically part of a complete radio package supplied by one particular manufacturer. Most units communicate with the other radio systems using both analog and digital ARINC 429 signals.

Audio Control Systems

On aircraft with multiple radios, there must be some system to control the input (microphone) and output (speaker) signals to and from those radios. The **audio control panel** shown in Fig. 15-30 controls as many as three transceivers and six receivers. This system also includes a marker-beacon display.

Two rows of alternate action push-button switches control the receiver audio distribution functions. The pilot may choose to listen to a headset by depressing the corresponding lower button. The cabin speaker may be activated by depressing the corresponding top button. The rotary switch on the right side of this unit controls the input signals to one of three transmitters or an intercom system.

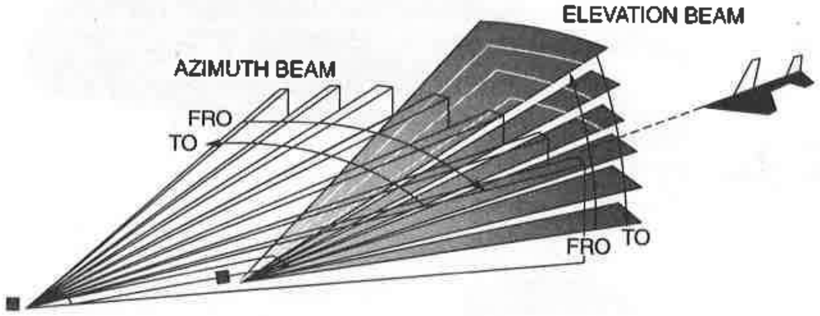


FIGURE 15-28 Scanning-beam pattern for a microwave landing system. *(Bendix, Aerospace Electronics Group, Communications Division.)*

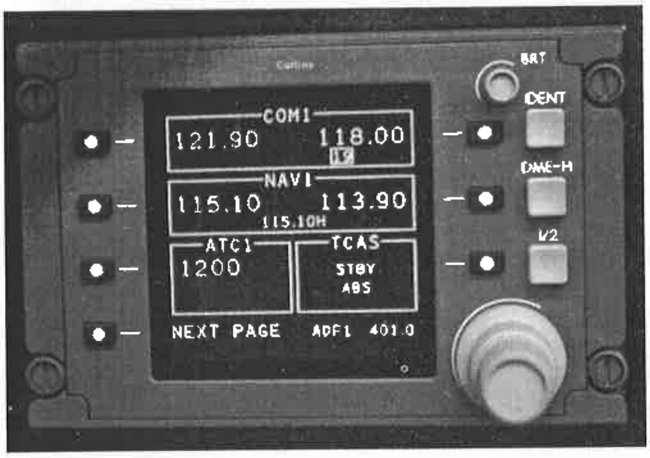


FIGURE 15-29 A typical radio tuning unit (RTU) for a corporate aircraft.

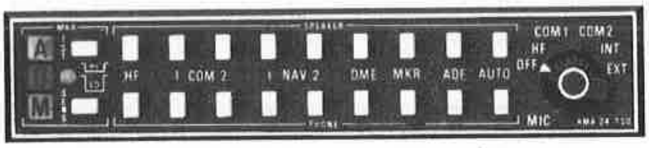


FIGURE 15-30 Typical audio control panel. (*King Radio Corporation.*)

An audio panel is found on nearly every light aircraft that contains more than one radio; larger aircraft may contain multiple audio panels, one for each flight crew member. Whenever operating any aircraft radio system be sure the audio control panel is properly set for the functions you desire.

Due to the size of a typical passenger jet, like the Airbus A-380, an elaborate communication system is necessary in order to provide safe aircraft operations. For example, transport-category aircraft must have a system designed to allow communications between flight crew and passengers, between pilots and flight attendants, between pilots and the ground crew during preflight operation, as well as pilots and the FAA air traffic control (ATC) during taxi and flight operations. On most aircraft of this type, the flight deck controls for communication systems are integrated into a multifunction control panel. Figure 15-31 shows a detail of the radio and audio management panel (RAMP) found on the Airbus A-380; these units are located on the center pedestal and overhead panel of the flight deck. The RAMP is used to control all HF, VHF, and satellite communications, as well as the passenger address system, and the flight, cabin, and service interphone systems. In order to provide redundancy, transport-category aircraft will use two or three control panels installed at different crew stations.

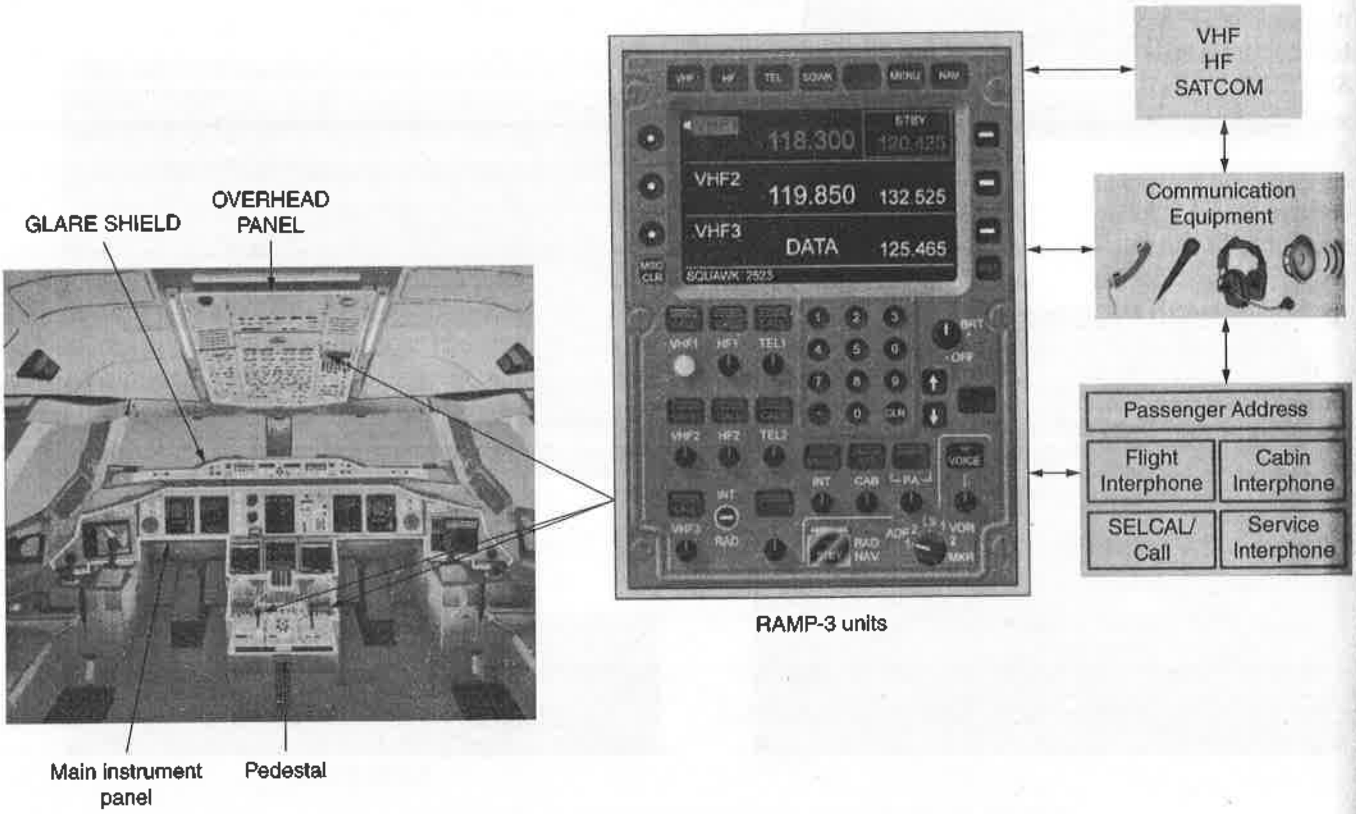


FIGURE 15-31 Locations of the radio and audio management panel (RAMP) on the Airbus A-380.

Integrated NAV/COMM Systems

After the turn of the century, aircraft began to employ technologies which allowed for greater integration of a variety of electronic systems. All modern aircraft produced today utilize integrated systems which include navigation, communication, and autoflight (autopilot) functions. Many light- and medium-sized aircraft now utilize a system developed by Garmin International that integrates functions using multiple processor units, multifunction control panels, and flat panel displays. Of course, specific radios still require individual antennas located on the outside of the aircraft. Figure 15-32 shows the Garmin instrument panel installed on a Cirrus light single-engine aircraft. As can be seen in the top inset (Fig. 15-32), the communication frequencies and related controls are located in the top of the left display unit. A similar set of navigation controls are located on the right display. The flight management and audio control panels are located on the center console between the two front seats. It should be noted that several Garmin systems are similar to the units being discussed here; although they all share many commonalities, they often go by specific names assigned to a series of aircraft. The Garmin G-1000 is typical of these systems.

The navigational displays for a typical integrated Garmin avionics system are incorporated onto either two or three flat panel displays. Generally speaking, more complex aircraft utilize three displays and smaller light aircraft employ two displays. In either case, certain navigation and communication data always has priority display status; that is, in the event of a partial system failure critical information will remain available to the pilot. The integrated Garmin system will be discussed in greater detail in Chap. 17.

Area Navigation Systems

Area navigation (RNAV) is a method of navigation that allows an aircraft to choose any course within a network, or "area" of navigation stations. Using VOR or VOR/DME, the pilot must navigate directly to and from the ground stations. Using the RNAV direct point to point navigation can conserve flight distance, reduce congestion, and ultimately make a more efficient air traffic system. Area navigation used to be called "random navigation," hence the acronym RNAV. Area navigation permits aircraft operation on any desired course within the coverage area of the referenced navigation site (VOR or VOR/DME).

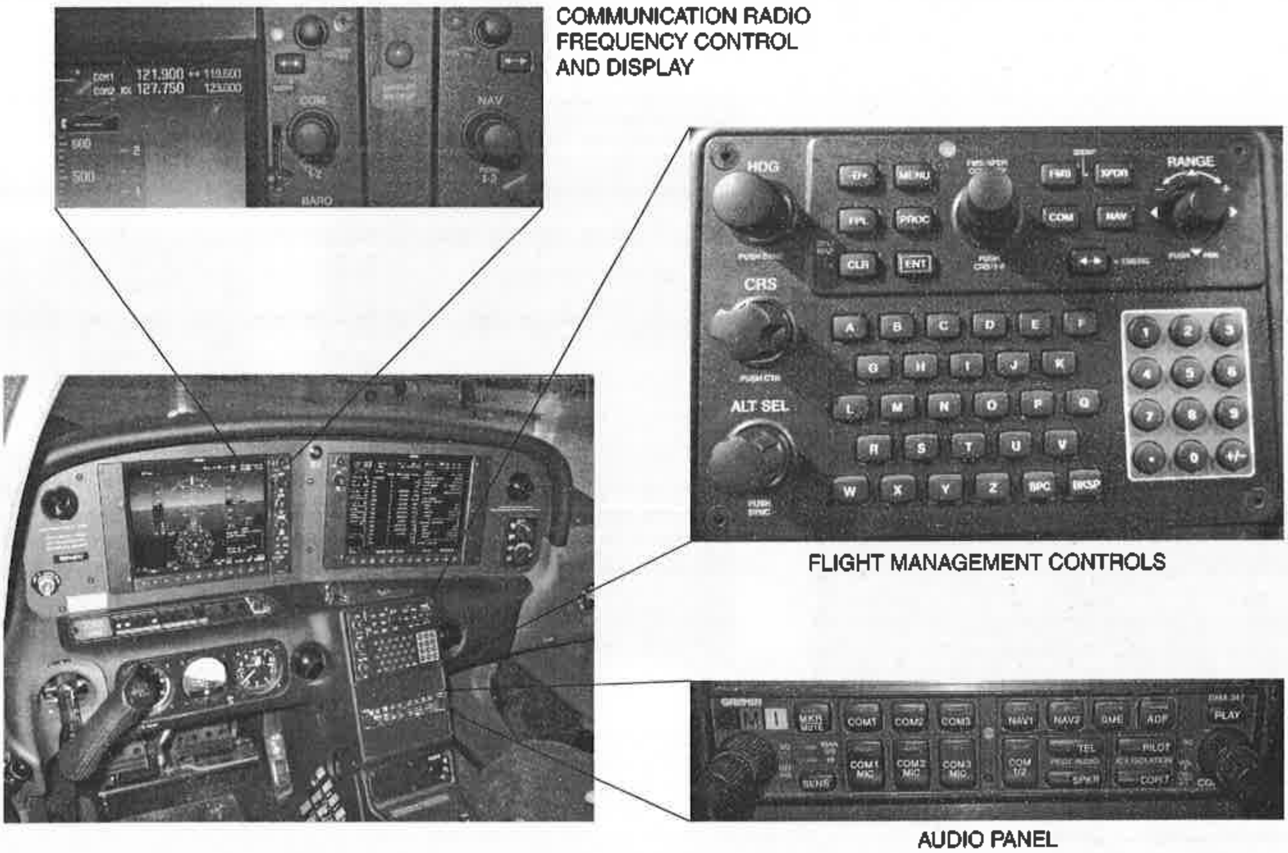


FIGURE 15-32 Typical integrated controls for a modern light aircraft.

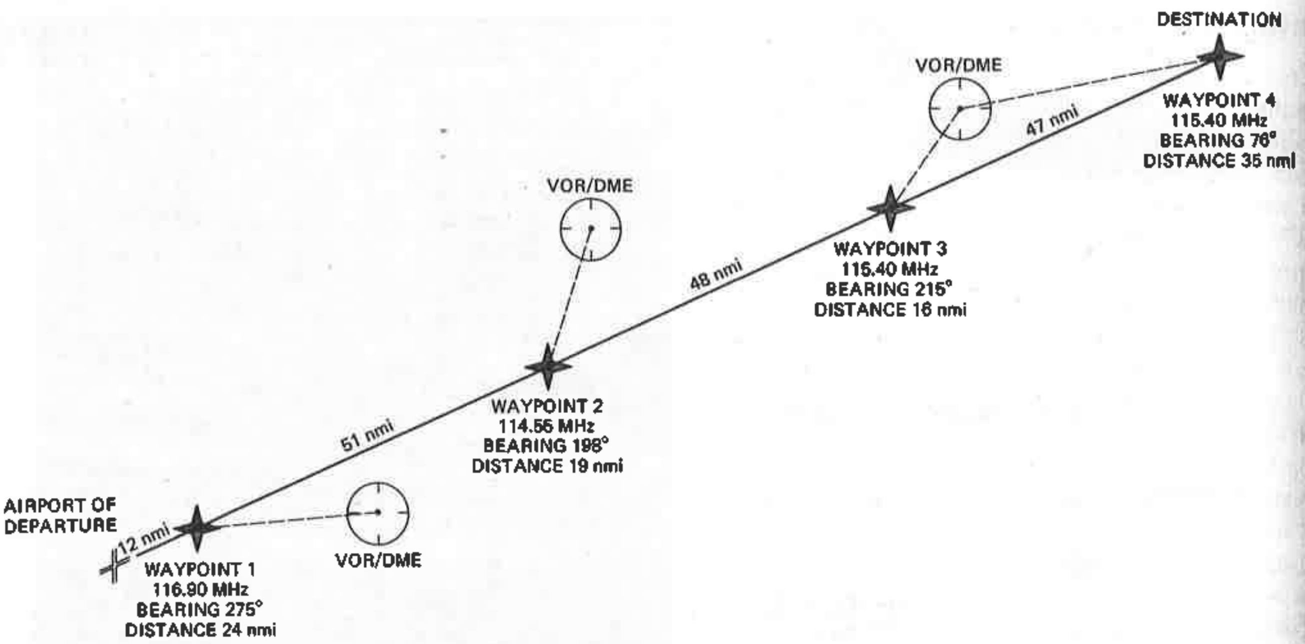


FIGURE 15-33 Direct flight by RNAV utilizing VOR/DME stations.

Figure 15-33 shows an RNAV course set between three different VOR stations. The RNAV system will allow the plane to navigate to one or more pilot-assigned waypoints instead of to/from the VOR stations. The RNAV system eliminates a dogleg flight and allows the pilot to fly directly from departure to destination.

A waypoint is a pilot-assigned reference used for navigation; it can be assigned in any location within the reception area of a VOR or other navigational aid. Simply put, the RNAV system continually monitors and analyzes aircraft position; using mathematical formulas the system computes aircraft position and needed course corrections. The RNAV unit would then send the appropriate signal to a navigation display and/or the autopilot system. Most modern RNAV equipment is integrated with the aircraft's flight management and autoflight systems; this provides a complete navigation package for today's aircraft. The control panel for a typical RNAV system is shown in Fig. 15-34.

FIGURE 15-34 Push-button control panel for a navigation system.

The RNAV system, in effect, makes it possible to "move" a VOR/DME station electronically from its actual location to a location on the proposed flight route. The mathematics of this operation is handled by the large-scale integrated (LSI) circuitry of the microprocessor. Figure 15-33 is a drawing of a proposed flight route showing how three VOR/DME stations are employed to produce four waypoints along the route. To set up these way-points, the pilot or some other operator uses the control panel such as that shown in Fig. 15-34.

Inertial Navigation System

The advantage of an **inertial navigation system** (INS) is that it requires no external radio signals. This concept makes it extremely valuable for military aircraft and spacecraft. Civilian aircraft also employ an INS in order to take advantage of its desirable characteristics for long-range navigation. As its name implies, an inertial navigation system depends on the laws of inertia to determine an aircraft's position. That is, once the starting point of a flight is known by latitude and longitude, the INS computer will determine any new positions by measuring the inertial forces acting on the aircraft.

There are three basic laws of inertia that were described by Sir Isaac Newton over 300 years ago; they are as follows:

1. *Newton's first law* A body continues in a state of rest, or uniform motion in a straight line, unless acted on by an external force.
2. *Newton's second law* The acceleration of a body is directly proportional to the sum of the forces acting on that body.
3. *Newton's third law* For every action there is an equal and opposite reaction.

Applying these laws to aircraft navigation, we find that an aircraft will not move or change its motion unless acted on

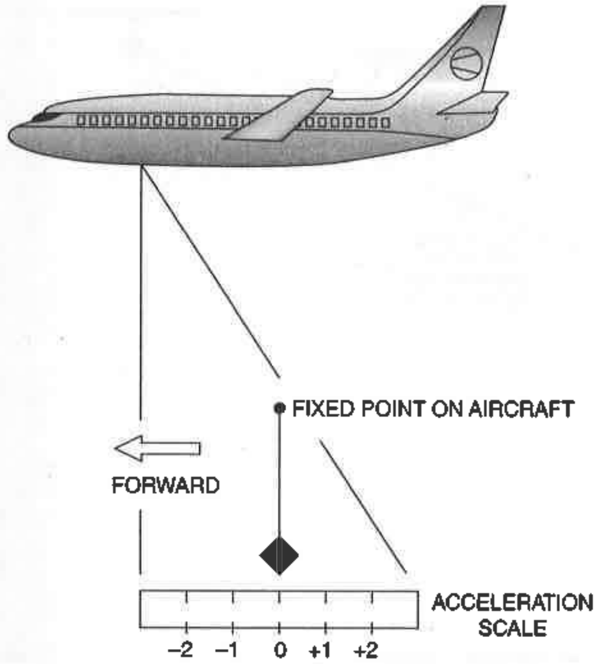


FIGURE 15-35 Example of a simple accelerometer.

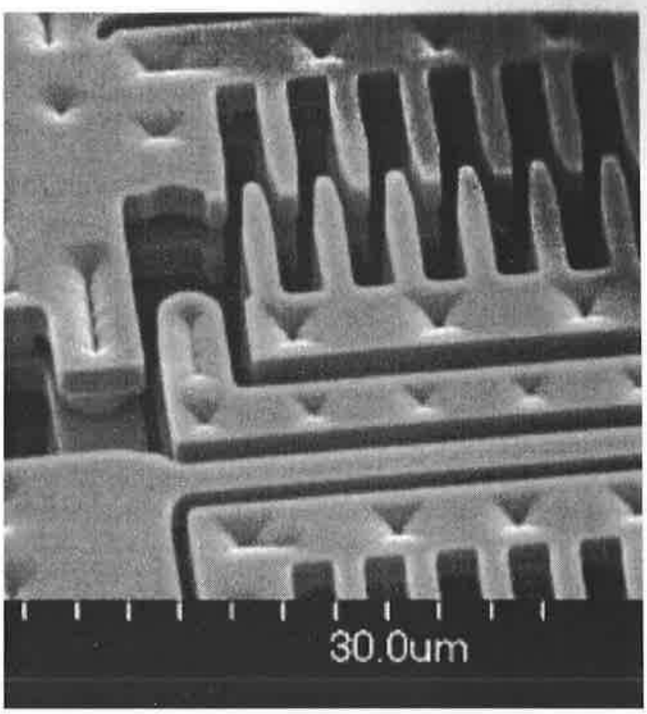


FIGURE 15-36 MEMS technologies used to create an accelerometer.

by an external force (engine thrust, wind drag, gravity, and wing lift). Since the change in motion (acceleration) is proportional to the applied force, we can determine acceleration by measuring the external forces acting on the aircraft. Since there is a reaction force for every external force that acts on the aircraft, we can measure the reaction force to determine the aircraft's acceleration and therefore its velocity and position.

The instrument used to detect acceleration is called the **accelerometer**. At least two accelerometers are required for each INS system. One measures accelerations in the north-south direction; the other measures east-west accelerations. Most aircraft INS systems contain at least three accelerometer systems, one for each axis of the aircraft. An acceleration force has both magnitude and direction; therefore, both acceleration and deceleration are measured. As shown in Fig. 15-35, a simple accelerometer could be a pendulum-type device. That is, it must be free to swing in two directions. The reaction force (opposite the external forces applied to the aircraft) causes the pendulum to swing. The pendulum swing is measured by an extremely accurate sensor that creates an electrical signal. Of course, an aircraft accelerometer must be more sophisticated than a simple pendulum. Modern accelerometers employ extremely sensitive, capacitive, inductive, and piezoelectric technologies. Each type of sensor converts a small mechanical motion (acceleration) into an electrical signal. The signal is sent to a processor which combined with other information is then used to calculate aircraft position. Another type of modern accelerometer consists of extremely small cantilever beams (see Fig. 15-36). The beams are so small and delicate that when subject to the slightest acceleration, they change position; this movement creates a change of capacitance between the beams. The change of capacitance is directly proportional to the acceleration force on the sensor. A modern technology known as microelectromechanical systems (MEMSs) is used to construct this type of accelerometer. MEMSs are created using a process similar to the systems used to create modern integrated circuits and microprocessors.

A basic accelerometer accurately detects acceleration only if it remains perfectly level. Since aircraft are seldom perfectly level during flight, all airborne accelerometers must be mounted on a **gimbal platform**. As illustrated in Fig. 15-37, a gimbal platform contains two gyroscopes, which stabilize the unit. This combination of gimbals and gyroscopes creates a platform that remains level in any aircraft attitude. Since the accelerometer remains level, it does not sense changes in aircraft attitude; therefore, the accelerometer's output signal accurately measures changes in acceleration. The output signal of the accelerometer is amplified and sent to the INS measurement computer. If the aircraft's initial location and destination are recorded into the computer, the INS system

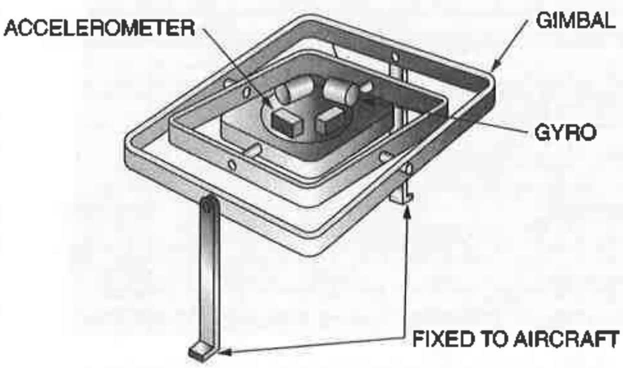


FIGURE 15-37 Diagram of a gimbal platform.

is capable of continuously updating flight deck displays of position, ground speed, heading and distance, and time to a destination. This information can be monitored directly from flight deck instruments or fed into an autopilot, thus forming a complete autoflight system.

Another type of INS known as the **strapdown inertial navigation system**, uses a solid-state (no moving parts) accelerometer system. The heart of the strapdown system is the laser gyro, which replaces the older rotating-mass gyroscope. This system will be discussed in greater detail in Chap. 17.

All inertial navigation systems have a **drift-rate error**, which accumulates during usage. This error ranges from about 1 mi of error for each hour of operation to 1 mi of error for every 10 h of operation. The newer strapdown system has a lower drift-rate error. To compensate for this error, all inertial navigation systems require a periodic update from another navigation source.

Global Positioning System

The **navigation satellite timing and ranging global positioning system (Navstar GPS)**, more simply called the GPS, is quickly becoming the system of choice for aircraft navigation. The GPS consists of three independent segments: the space segment, the control segment, and the user segment. As seen in Fig. 15-38, the complete **space segment** was originally designed with 24 satellites which complete two orbits each day, repeating the same ground track with each orbit. Since inception, satellites have been added to the GPS space segment. The additional satellites improve GPS accuracy by providing redundant measurements. Today about nine satellites are visible from any point on the ground at any one time, well over the minimum of four satellites needed to establish position. The satellites orbit approximately 11 000 miles above the Earth's surface. The satellites transmit extremely accurate timing pulses and a code system defining the precise location of the satellites at the time of data transmission.

The **control segment** consists of various ground-based monitoring stations and one master control station. The monitors receive the satellite transmissions at least once each day and relay that information to the master control station. The master station computes any drift that has occurred in the satellites' orbit or timing pulse. A correction signal is then sent to the satellites, and that correction is included in the location code transmitted from the satellites to the user.

The user segment is composed of tens of millions of civil, commercial, and scientific users of the standard positioning service commonly called GPS. The aviation industry has now embraced GPSs which are one of the primary navigational systems for both en route and approach flight segments. It could easily be said that GPS has created a navigation revolution. GPS now enters all facets of modern life, from cell phone use to tactical military applications; this system has become the primary navigation and positioning system for a multitude of applications.

The user segment is often a simple GPS receiver composed of an antenna, the receiver-processor circuitry, a stable timing device, and some type of output interface, such as an LCD moving map display. The antenna must be tuned to the frequencies transmitted by the GPS satellites. The receiver-processor circuitry along with the highly stable clock (often a crystal oscillator) performs the mathematical calculations necessary to determine the aircraft position. The receiver is often described by its number of channels; this signifies how many satellites it can monitor simultaneously. On a modern aircraft, the output of the processor is sent to an integrated flat panel display and to the autoflight system if the aircraft is so equipped. A typical aircraft GPS navigation receiver/processor is shown in Fig. 15-39. This unit contains all necessary receiver and processor circuits, as well as a built-in display with moving map features. A moving map continually updates the aircraft position and the map display "moves" as aircraft position changes. The moving map has become the standard for all modern GPS displays.

For proper operation, the GPS must receive a minimum of four satellite signals; in most cases more than four signals can easily be established. The most modern equipment can process all GPS signals simultaneously and refresh aircraft position almost instantaneously. In order to receive proper satellite

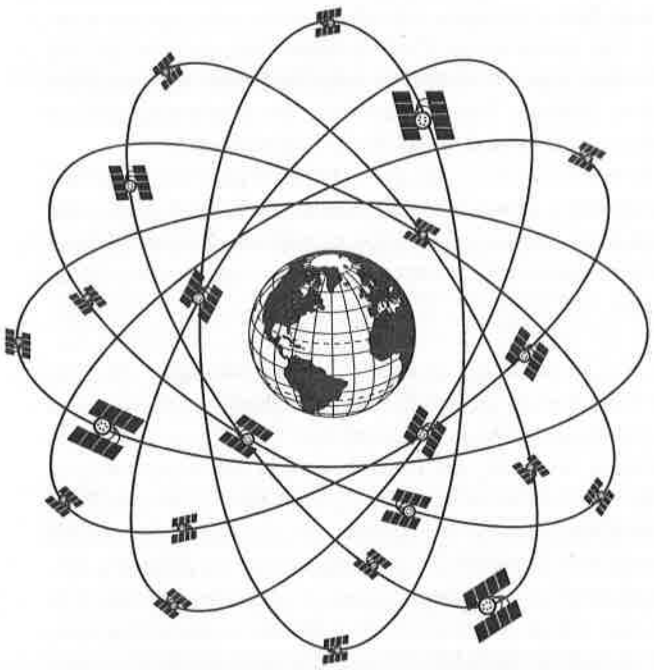


FIGURE 15-38 Orbiting satellites for a GPS.

FIGURE 15-39 A typical panel-mounted GPS navigation receiver/processor for light aircraft.

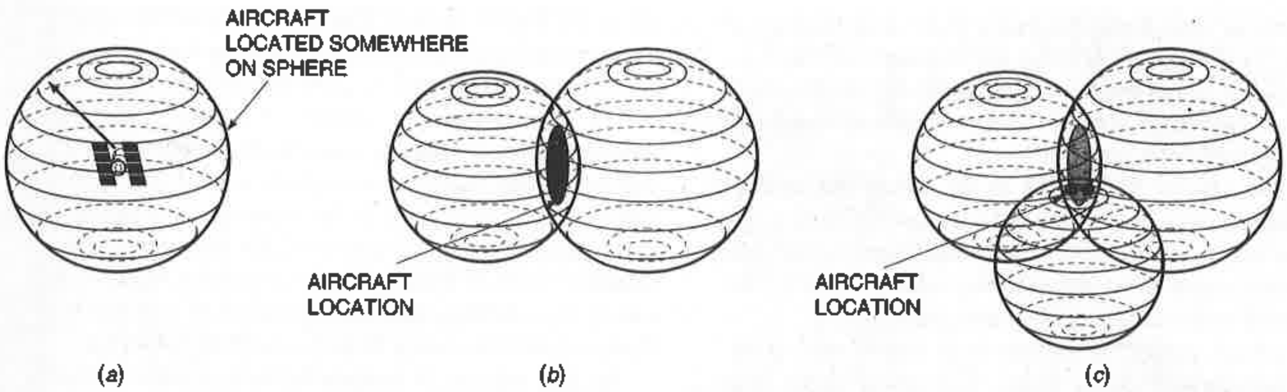


FIGURE 15-40 GPS theory of operation: (a) Aircraft location from one satellite, (b) aircraft location from two satellites, (c) aircraft location from three satellites.

signals, an external GPS antenna is typically mounted on the top of the aircraft, or the antenna can be internal, installed behind a plastic panel that will not degrade the GPS signal.

The GPS theory of operation is based on basic geometry. If you know the distance and location of three or more points, your exact location can be determined. The satellites transmit a location and timing signal to the user's receiver. The distance to a satellite is determined by measuring the travel time of the transmitted signal. Knowing the speed of radio wave propagation (the speed of light), the receiver calculates the distance to the satellite.

To better understand the theory of operation, study the example in Fig. 15-40. Knowing the distance from one satellite (15000 mi) places your aircraft on the outside of a sphere 15000 mi from that satellite (Fig. 15-40*a*). Knowing the distance from a second satellite (14200 mi) places the aircraft at the intersection of the two spheres (Fig. 15-40*b*). Figure 15-40*c* shows that receiving the distance from three satellites will locate the aircraft at one of two points along the outside of the three spheres. The measurement from the fourth satellite will determine the aircraft's exact location.

GPS Augmentation Systems

Since inception, the space, control, and user segments of the GPS have all improved performance and reliability. However, much of the accuracy, reliability, and dependability needed for aircraft navigation was still lacking. To overcome these limitations, the FAA developed the Wide Area Augmentation System (WAAS) and the Local Area Augmentation System (LAAS). Currently WAAS is operational in the entire United States; LAAS however, is still under development. Essentially, WAAS is intended to enable aircraft to rely on GPS for all phases of flight, including a landing approach to any airport within its coverage area. WAAS uses a network of ground-based reference stations, in North America and Hawaii, to measure small variations in the GPS satellites' signals (see Fig. 15-41). Measurements from the reference stations are routed to master stations, which in turn send a correction message to the geostationary WAAS communication satellite. The WAAS communication satellite broadcasts the correction messages back to the aircraft.

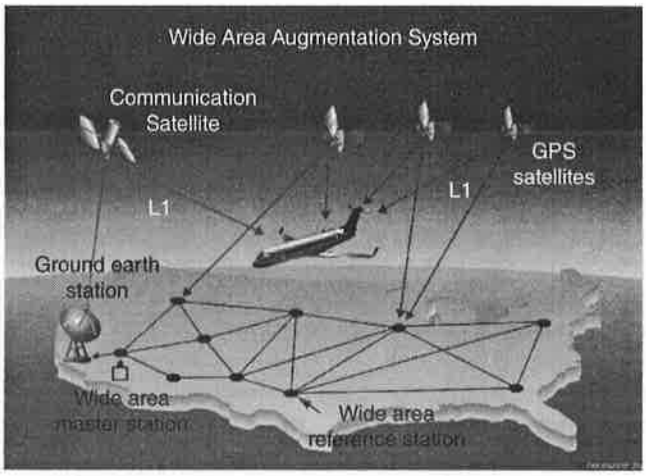


FIGURE 15-41 The GPS Wide Area Augmentation System (WAAS).

The airborne WAAS-enabled GPS receiver uses the correction data to compute aircraft position with extreme accuracy. The International Civil Aviation Organization (ICAO) calls this type of system a satellite-based augmentation system (SBAS). Europe and Asia are developing SBASs similar to the system found in the United States.

In order to improve the use of GPS for precision approach and landings, a more accurate system is needed; LAAS is the technology chosen by the FAA to perform this task. LAAS functions similar to WAAS, except on a more refined level. As seen in Fig. 15-42, the GPS correction data is transmitted to the aircraft from a local ground station; for this reason, LAAS coverage is limited to approximately 25 NM. The LAAS is an all-weather aircraft landing system based on real-time differential correction of the GPS signal. Local reference receivers are located around an airport at precisely surveyed locations. The signal received from the GPS constellation is used to calculate the position of the LAAS ground station, which is then compared to its precisely surveyed position. This data is used to formulate a correction message which is transmitted to aircraft using a VHF data link. A receiver on an aircraft uses this information to correct any error in the GPS signals. The airborne GPS processor

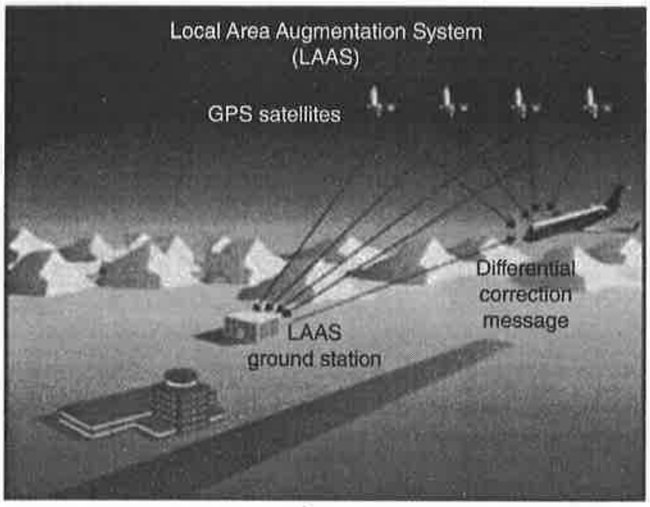


FIGURE 15-42 The GPS Local Area Augmentation System (LAAS).

then provides a standard ILS-style display for use during the approach.

When GPS was first introduced for civilian aircraft, it could only be used as supplemental area navigation equipment; in other words, pilots could not solely rely on GPS for navigation. Eventually, the FAA allowed GPS use as a primary navigation source for en route flight only. In 1996 the technical standard order TSO-C129a was released; receivers that meet this standard can be used for nonprecision approaches however conventional navigational equipment is still required onboard the aircraft. TSO-C146a was released in 2002; equipment certified under this standard could utilize the WAAS with no other navigational equipment required. This TSO allows for stand-alone GPS systems that do not require pilots to monitor traditional navigation equipment for en route or nonprecision approach navigation. Aircraft GPS equipment which meet TSO-C146a are now found on all modern aircraft.

ATC Transponder

Because of the diffculty that flight controllers had in identifying aircraft on radarscope in tower stations and control centers, radar devices called **ATC** (air traffic control) **transponders** were developed. In general, a transponder is an automatic receiver and transmitter that can receive a signal (be interrogated) from a ground station and then send a reply back to the station. The term **transponder** is short for transmitter-responder. The transponder equipment is part of the secondary surveillance radar (SSR) system. SSR is considered "secondary" to distinguish it from the "primary radar" that works by passively bouncing a radio signal off the skin of the aircraft. Primary radar determines range and bearing to a target aircraft with reasonably high fidelity, but it cannot accurately determine aircraft altitude. SSR uses an airborne transponder beacon to transmit a response back to the ground station whenever it senses the beam of the primary radar hitting the aircraft. This response most often includes the aircraft's pressure altitude and a four-digit octal code identifier.

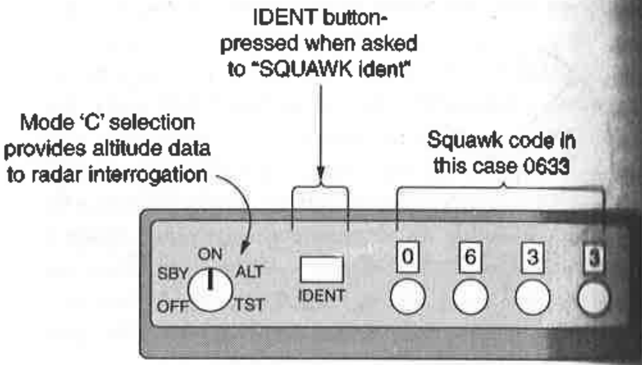


FIGURE 15-43 Controls of a typical ATC transponder used on light aircraft.

When flying into controlled airspace, a pilot may be requested to squawk a given code by the air traffic controller via the radio, using a phrase such as "Beechcraft 613UM, squawk 0633." The pilot then selects the code 0633 on his or her transponder display; the air traffic control radar screen will become associated with that identifier. Figure 15-43 shows the controls of a common transponder.

A controller who wishes to obtain positive identification of an aircraft will request that an "IDENT" signal be returned from the transponder. The pilot of the aircraft will then press the IDENT button on the transponder control panel to send a special-image signal that the controller will recognize for identification.

A typical transponder unit found in light aircraft is shown in Fig. 15-44. The controls, display, and receiver-transmitter unit are all one assembly, which is designed to be panel-mounted in a standard radio rack. The transponder power would typically be connected to the avionics bus and the antenna located on the bottom of the aircraft. The aircraft transponder antenna is known as an L-band antenna, in reference to the radar frequencies used by the SSR system.

In the OFF position of the function selector switch, all power is off and the transponder is inoperative. In the ON position, the switch places the unit in the mode for normal operation. The transponder is ready to reply to interrogations from a ground station after a 1-min warm-up period.

In the STBY position of the selector, the transponder power is turned on, and power is applied to the transmitting system. STBY may be used at the request of the ground controller to selectively clear the radarscope of traffic. Turning to STBY will keep the transponder from replying to interrogations but will allow instant return to the operating mode when the unit is switched to ON.

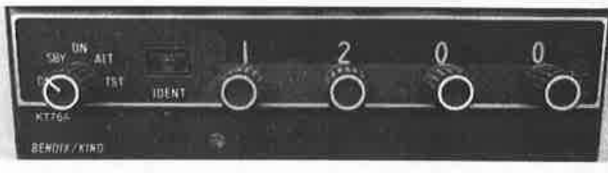


FIGURE 15-44 Light-aircraft transponder set to the VFR code 1200.

There are currently three modes (types) of transponders that can be used on various aircraft. **Mode A** is a transponder that provides a (nonaltitude-reporting) four-digit coded reply when interrogated by the ground-based ATC radar. The four-digit code is set by the pilot in accordance with ATC requests. **Mode C** is an airborne transponder that provides a coded reply identical with that of mode A; however, mode C also transmits an altitude-reporting signal. **Mode S** is a transponder with mode A and mode C capabilities, but it also responds to TCAS-equipped aircraft. TCAS is a collision avoidance system; it will be discussed in the next section of this text.

The ALT position of the selector switch activates **mode C**, the altitude-reporting capability of the transponder. When used with an **encoding altimeter**, the unit will automatically transmit altitude information. The altitude is given as standard-pressure altitude, which is converted into real altitude by ground computers. The encoding altimeter sends standard pressure altitude data to the airborne transponder equipment; the transponder then includes altitude data in all transmissions.

The REPLY lamp and PUSH IDENT button are contained within a single assembly. The REPLY lamp automatically goes on when the transponder is replying to ground interrogation or when the function selector switch is placed in the TEST position. The PUSH IDENT button is used to send the special position identification pulse (spip). When the pilot is asked by the ground controller for an "IDENT," the pilot presses the button and activates a special signal that "paints" an instantly identifiable and unmistakable image on the controller's radarscope. This signal must be used only when requested by the controller, because use at any other time could interfere with the spip being sent by another aircraft. If the ground radar system is so equipped, the transponder may activate a special code sequence on the controller's scope. This code may identify the aircraft's destination, altitude (mode C operation), airspeed, and identification number.

The **code selector** comprises four 8-position rotary switches providing a total of 4096 active settings available for selection of the identification code. The code selector sets up the number of spacing of the pulses that are transmitted at the transponder frequency of 1090 MHz.

The airborne transponder equipment uses digital pulse technologies to transmit information. Both the identification codes and altitude data are transmitted in a series of pulses imbedded onto the RF carrier wave (see Fig. 15-45). All modern aircraft are assigned a unique International Civilian Aviation Organization (ICAO) 24-bit digital address; formally called the mode-S **hex code**. The address is assigned according to a national registration and becomes part of the aircraft's permanent documents. Normally the address is never changed even when the aircraft is sold. There are 16 777 214 unique ICAO 24-bit addresses. The addresses can be decoded and converted among each aircraft or ground facility in the system.

All ATC transponders must be tested every 24 calendar months. This test is required under the FAA flight regulations; however, it is often performed during an annual

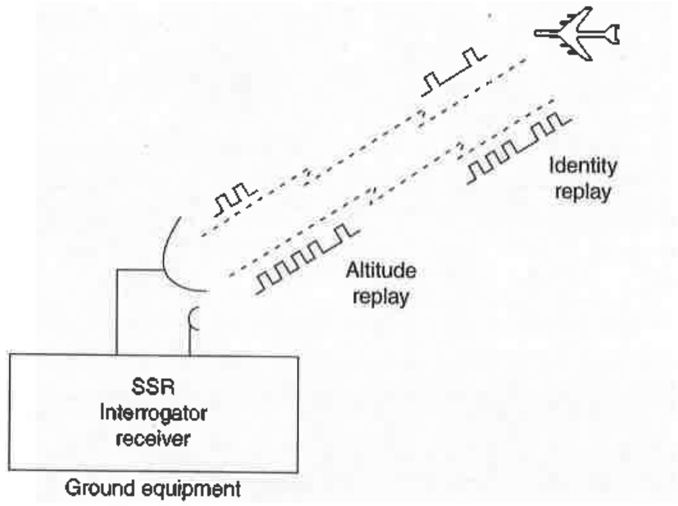


FIGURE 15-45 Pulse codes used by an aircraft transponder and ground interrogator.

inspection if requested by the owner. The test must be conducted by an authorized avionics repair facility.

Satellite Communications

Space-based communications are growing in popularity on many corporate and transport-category aircraft. The ability to communicate virtually anywhere around the world and the reliability of HF signals (satellites operate in extremely HF range between 30 and 300 GHz) are a few advantages of satellite communications. The main disadvantage becomes the cost; since there are only a limited number of satellites available, usage cost can be relatively high. ARINC 741 specification covers satellite communications equipment and allows for digital signals which may or may not be encrypted for security reasons. Both voice and data can be transmitted/received from the aircraft to a satellite; and then from the satellite to a ground facility as shown in Fig. 15-46. Once on the ground,

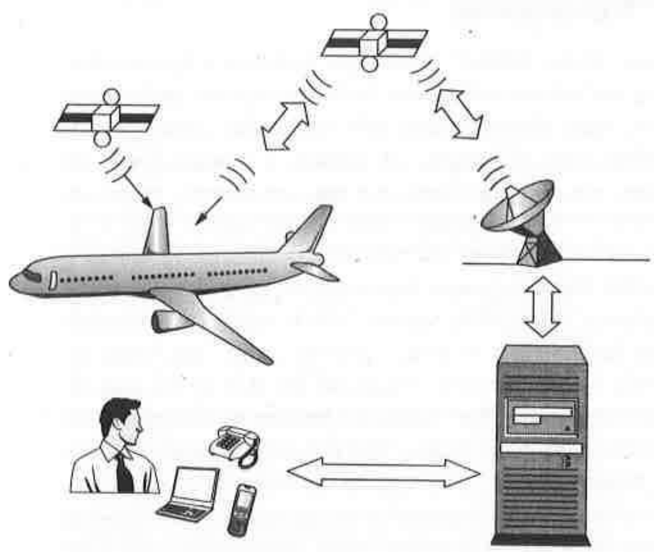


FIGURE 15-46 Data or voice transmission using satellite communications.

the communications can be linked to any other ground-based or airborne location connected to the system. There are several companies which currently offer satellite communications for the aerospace industry; one of these systems will be discussed next.

Inmarsat is a British satellite telecommunications company, which provides mobile telephone and data services to users worldwide; including the aviation industry. The company was originally called **International Maritime Satellite**; hence the name **Inmarsat**. Today the Inmarsat system uses 11 satellites in orbit above the Earth's equator. The exact number of satellites may change as older units retire and new satellites are launched. The **aeronautical** division of Inmarsat offers three levels of voice, fax, and communication service for aircraft. The levels are **Aero-L** (low-gain antenna) primarily for packet data including ACARS, **Aero-I** (intermediate-gain antenna) for low-quality voice and fax/data at up to 332 Kbit/s and **Aero-H** (high-gain antenna) for medium-quality voice and fax/data at up to 432 Kbit/s. These transmission speeds will no doubt increase as system technologies advance.

The performance level of any airborne satellite communications system is greatly affected by the design of the airborne equipment. Systems designed for high-speed data transfer are more complex and require a better antenna system; low-speed systems are of a simpler design. In general, the airborne equipment, both hardware and software, is typically specific to a given satellite provider. Typically, the antenna design for satellite communications is called a phased-array system; it means there are several antennas all linked to create an antenna network. By using a phased-array system, the patterns and direction of the transmitted signal can be electronically controlled. The effect is a steerable antenna without the need to physically move any components. Of course, this type of system may require the installation of multiple antennas on the aircraft and sophisticated control circuitry.

Emergency Locator Transmitter

Distress radio beacons, also known as emergency locator transmitters (ELTs), are tracking transmitters which aid in the detection and location of aircraft and people in distress. The ELT is designed to work in conjunction with the worldwide service of Cospas-Sarsat, the international satellite system for search and rescue (SAR). When activated, the ELT transmits a distress signal that is monitored by a series of nongeostationary satellites. The system can determine the location of a distressed aircraft by some combination of GPS and Doppler trilateration. The aircraft ELT is designed to activate automatically due to an excessive G-force; the purpose of which is to send a distress signal in the event of an aircraft crash. Many units can also be manually activated; this may be done by a pilot after an emergency landing in a desolate area.

There are actually three categories of distress radio beacons compatible with the Cospas-Sarsat system: (1) emergency position-indicating radio beacons (EPIRBs) signal maritime distress; (2) ELT signal aircraft distress; (3) personal locator beacons (PLBs) are for personal use such as by hikers in remote areas. These units may use either a digital or analog rescue signal. The digital signals are usually longer range and monitored by the satellite system. Analog beacons are useful to search parties and SAR aircraft, though they are no longer monitored by satellite. All newer systems transmit the digital signals on a frequency of 406 MHz; these ELTs may also contain a small integrated analog (121.5 MHz) homing beacon. The original, older, ELTs operated on a frequency of 121.5 and 243 MHz. A typical digital 406-MHz ELT designed for light aircraft is shown in Fig. 15-47. This system includes a removable antenna and remote test/arm switch; in most cases this unit would be installed with the antenna externally mounted. Notice the ELT placard shows the direction of installation and the approved TSO information.

Beginning in February 2009, only 406-MHz beacons were detected by the international Cospas-Sarsat SAR satellite system. This affects all EPIRBs, ELTs, and PLBs. As of that time, Cospas-Sarsat has ceased satellite detection and processing of 121.5/243 MHz beacons. These older beacons are now only detectable by aircraft or ground-based receivers and the FAA will not certify new installations of the 121.5 beacons. However, it is currently still legal to operate aircraft with an older 121.5 beacon; when that ELT is no longer airworthy, it must be replaced with a newer digital 406-MHz unit.

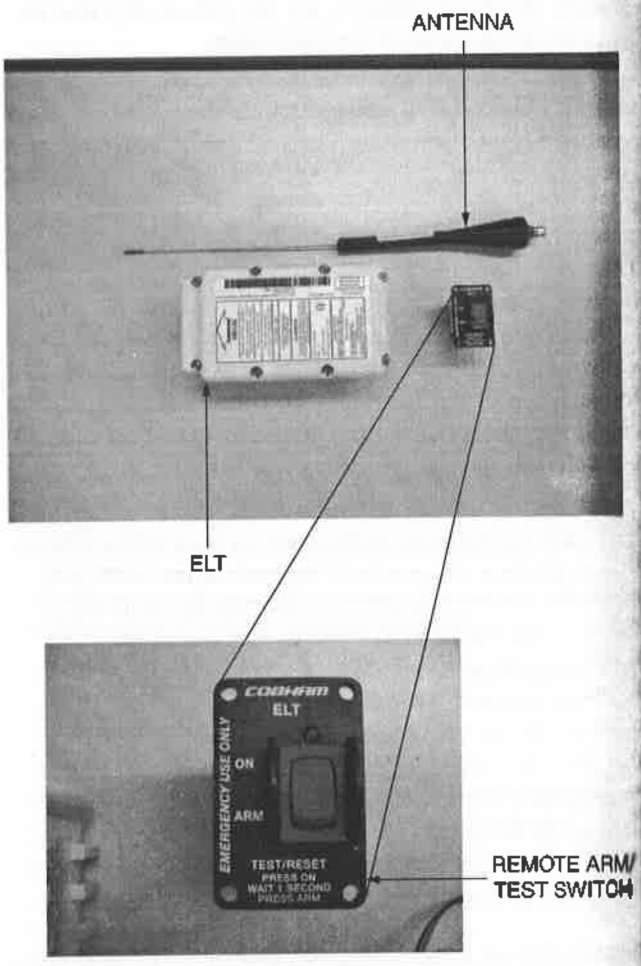


FIGURE 15-47 Components of a 406-MHz ELT.

The 121.5 MHz frequency continues to be used as a voice distress frequency for aviation.

One big advantage of the newer digital 406 ELTs is the transmitted rescue signal contains a unique 15-digit hexadecimal identification code. This code can be used by the authorities to identify the type of aircraft in distress and identify the registered owner; information that can aid in rescue operations. ELTs transmit 406 MHz for a quarter of a second immediately when activated, and then transmit a digital burst once every 50 seconds thereafter. The rescue code is transmitted until the ELT battery loses power or the unit is manually turned off. The transmitter is designed to be a 5-W pulse transmitter; much stronger than the analog 121.5 units. In general, the response to newer digital beacons is very swift; SAR response can be activated within approximately 10 minutes of beacon activation.

Most general aviation aircraft in the United States are required to carry an ELT, depending upon the type or location of operation; flights by scheduled air carriers are not. In commercial aircraft, a cockpit voice recorder and/or flight data recorder must contain a locator beacon which will operate on land or underwater. All ELTs installed today must meet the FAA certification of TSO C126. This technical standard order (TSO) details the requirements for the new 406-MHz ELT. The ELT must be installed in an area of the aircraft likely to receive minimal damage during a crash; typically in the tail or fuselage aft of the seating area. Many units must also be installed facing the correct direction in order to accurately detect a potential crash.

Testing of ELTs

According to the FAA, ground testing of type 121.5 MHz ELTs must be conducted during regular aircraft inspections, such as a 100-h or annual inspection. The test must be conducted within the first 5 min of each hour and limited to three audio sweeps. To perform this test, simply tune an aircraft communications radio to receive on a frequency of 121.5, turn on the ELT to be tested and listen for the audio tone through the aircraft speaker or headphones. The newer 406 MHz units have a self-test feature that transmits a special signal to the Cospas-Sarsat satellite system. Some units also have a 121.5 MHz signal and should be tested as just described. To perform a typical test, the remotely mounted ELT switch must be activated according to instructions; in most cases, it is a 1-minute test then the control is set back to the **ARM** position (see Fig. 15-47). The self-test must then be verified by the technician. This can be done through a web-based service that automatically records the ELT test. Since all 406-MHz ELTs are programmed with a specific aircraft identifier, the Cospas-Sarsat system can verify the self-test for any given aircraft. Some units have an indicator light to show a successful test; another method is to use an ELT test unit. The ELT test unit is used to verify the transmission of the digital aircraft identifier. A successful self-test must then be recorded in the appropriate maintenance documents.

Service for an ELT. An ELT requires a minimum of service; however, certain procedures are necessary to assure satisfactory operation. The battery pack must be changed in accordance with the date stamped on the unit. Typically, the batteries are replaced every 2 years for 121.5 MHz units, and every 6 years for 406 MHz units. The replacement date must be clearly marked on the battery's data plate; otherwise, the battery is not airworthy. The ELT should be tested regularly to assure satisfactory operation. An inspection of the ELT mounting and antenna should be made periodically to ensure firm attachment to the aircraft.

Regulations regarding the operation of ELTs are set forth in FAR Part 91.52. Technicians involved with the installation and service of ELTs should be familiar with these regulations and manufacturer's data.

Flight Data and Cockpit Voice Recorders

Two different recording units used to help analyze the cause of an aircraft accident are the **flight data recorder (FDR)** and the **cockpit voice recorder (CVR)**. Although these units are painted with heat-resistant bright orange paint, they were sometimes called "the black box" and contain homing beacons in order to help SAR teams find both the recorders and the aircraft. Following an accident, the recovery of the FDR and CVR is usually a high priority for the investigating body, as analysis of the recorded parameters can often detect and identify causes or contributing factors of the crash. Due to their importance in investigating accidents, these units are carefully engineered to withstand the force of impact and intense fire; the units are typically mounted in the tail section of an airplane to maximize the likelihood of its survival. A typical FDR is shown in Fig. 15-48.

An FDR is an electronic device employed to record any instructions sent to most electronic systems on an aircraft. It is a device used to record a minimum of 88 specific aircraft performance parameters, such as engine and control surface settings, airspeed, Greenwich Mean Time, position, and altitude. Many modern FDRs record more than the required

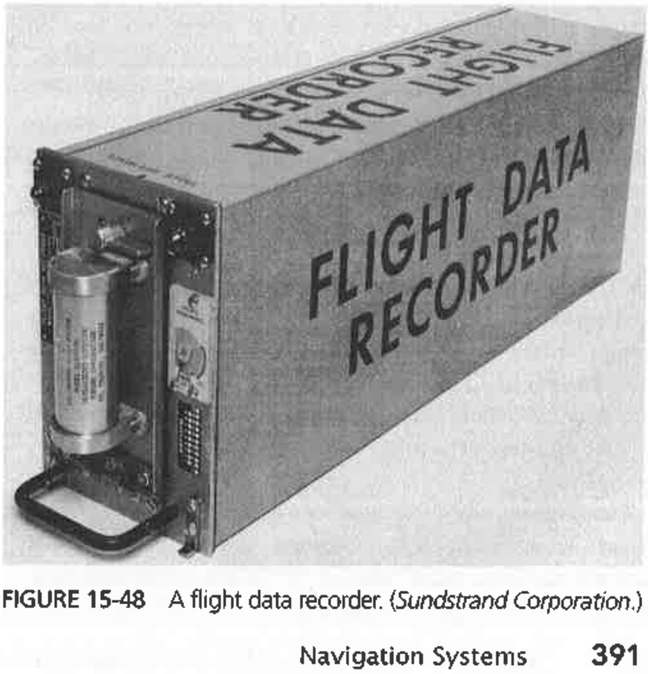


FIGURE 15-48 A flight data recorder. (*Sundstrand Corporation.*)

88 parameters. Generally each parameter is recorded a few times per second, though some units store "bursts" of data at a much higher frequency if the data begins to change quickly. Most FDRs record approximately 17 to 25 h of data in a continuous loop. Early FDRs used a fire-resistant recording tape for storage of the data; newer units employ solid-state memory and typically have a much higher recording capacity. It is required that an FDR verification check be performed during routine aircraft inspections to ensure all mandatory parameters are recorded. In the United States, any registered multiengine turbine-powered aircraft with 10 or more passenger seats must have an FDR; the FDR must record for 25 continuous hours, withstand water pressure up to 20 000 ft and contain an underwater operational rescue beacon which will operate for 30 days.

Some modern aircraft also monitor flight data for analysis of optimum fuel consumption and potentially dangerous flight crew habits. The data from the FDR is transferred to a solid-state recording device and then periodically analyzed by the airline operations staff. Data can also be downloaded from the aircraft's quick access recorder (QAR), either by transfer to a portable solid-state recording device or by direct upload to the operator's headquarters via a WiFi or satellite link. This type of analysis is often called flight operational quality assurance (FOQA), pronounced PHO-kua. The simple purpose of FOQA is to analyze data generated by an aircraft moving from one point to another. Applying the information learned from this analysis helps to find new ways to improve flight safety, increase overall operational efficiency, and reduce operational costs.

The CVR is a recording device designed and constructed similar to the FDR; however, the CVR is designed to monitor the signals of the pilots' microphones, earphones, and headsets as well as a flight deck microphone. CVRs are required on any U.S. registered multiengine turbine-powered aircraft that require two pilots for operation and contain six or more passenger seats; CVRs are certified under TSC C123b. Figure 15-49 shows the locations of a typical CVR and FDR system. A modern CVR is capable of recording four channels of audio data for a period of 2 hours; original equipment would record only 30 min. Thirty minutes was found to be insufficient in many cases because significant parts of the audio data needed for accident investigation had occurred more than 30 min before the end of the recording.

INSTALLATION OF AVIONICS EQUIPMENT

Power for all avionics equipment is supplied by the aircraft's alternator or generator system during normal operating conditions. When additional equipment is installed, the person responsible must make sure that the aircraft's electrical system has sufficient capacity to supply all the aircraft's requirements.

Plans for mounting avionics equipment in aircraft should include careful consideration of location, strength of mounting structures, reduction of vibration and shock, bonding and shielding, and serviceability. Hazards to personnel and to the aircraft must be avoided, since high voltages are developed in some types of equipment and since some units may develop sufficient heat to ignite any particularly flammable material in the immediate vicinity. The manufacturers provide complete information for the installation of avionics equipment and all installations must be made in accordance with FAA-approved data.

Avionics equipment, controls, and indicators should be located in the positions most convenient to those who must operate them; in light aircraft, the controls and indicators should be easily accessible to the pilot. Sufficient ventilation should be provided for equipment subject to heating so that it will not exceed its normal operating temperature. To avoid the danger of fire, equipment that naturally operates at high temperatures must be sufficiently removed from flammable materials.

The actual attachment of avionics-equipment units to the aircraft must be such that there is no danger of a unit becoming loose because of vibration. Fastening devices include standard bolts, nuts, and screws with effective locking devices such as self-locking nuts, lock washers, safety wire, and cotter pins. Self-locking hold-down clamps and snap slides are hold-down devices specially designed for radio equipment.

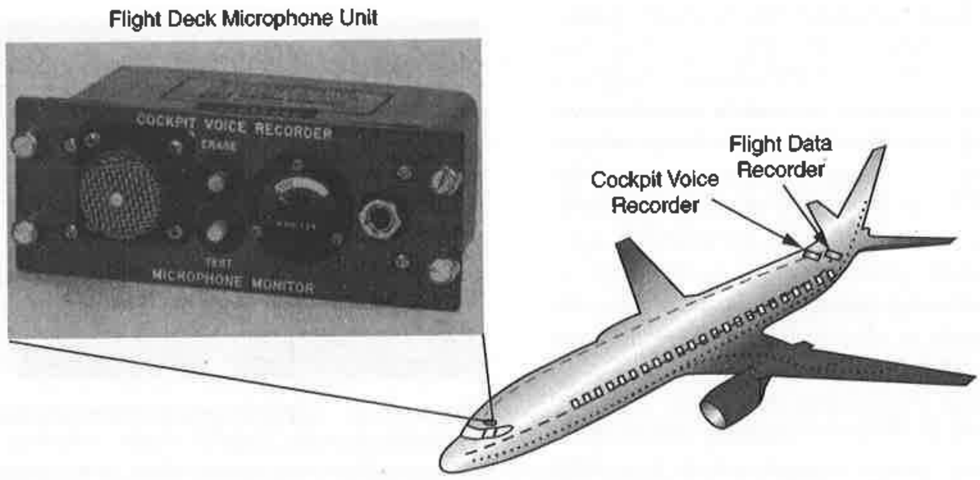


FIGURE 15-49 Locations of typical CVR and FDR equipment.

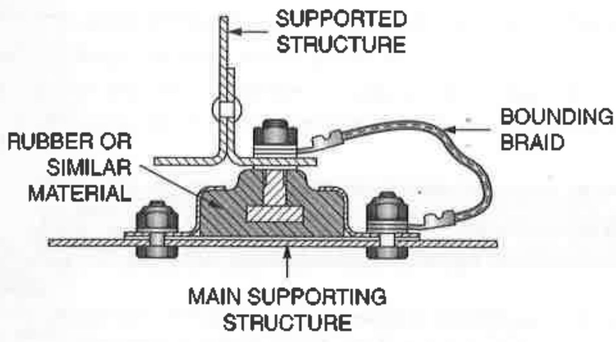


FIGURE 15-50 A shock-mounting diagram.

Radio units in light aircraft may be mounted on brackets attached to the rear of shock-mounted instrument panels, or they may be secured on shock-mounted brackets or racks attached to a solid structure of the airplane. In any event, shock mountings must be placed between the actual radio equipment and the basic aircraft structure. In some cases shock-mounting bases designed especially to fit particular units are attached directly to the airplane. One type of shock mounting is shown in Fig. 15-50.

Because shock mountings utilize rubber, synthetic rubber, plastic, or some other insulating material as the shock-absorbing agent, it is essential that grounding or bonding jumpers be connected from the aircraft structure to the avionics-unit case. These serve as a part of the ground circuit for the equipment and also help to reduce noise from static and other types of interference. Bonding and shielding information is given in Chap. 4.

Avionics mounting racks are usually designed to ARINC (Aeronautical Radio Incorporated) standards, and equipment cases are designed to fit such racks. This is particularly true for large commercial aircraft; however, mounting racks and avionics equipment for smaller aircraft are also being designed according to ARINC standards. Technicians installing avionics equipment should ensure that equipment and racks are compatible.

The installation of avionics equipment is often a complicated task and beyond the scope of this text; however, some simple rules apply: (1) Install only equipment certified for aircraft use. Most equipment will be certified under a specific technical standard order (TSO). (2) Use only components, wire, connectors, and miscellaneous hardware approved for aircraft. (3) Follow all current manufacturers technical data related to the installation. The design of most installations will generally be approved by a supplemental type certificate (STC). (4) Perform a thorough preinstallation assessment of your aircraft. This will help determine if the aircraft's electrical system and other components can "accept" the new equipment installation. In most cases, the assessment will include an electrical load and weight and balance analysis. (5) After the installation and testing is complete, be sure to submit all necessary paperwork. This may include but would not be limited to logbook entries, flight test results, weight and balance changes, and the FAA form 337 for major alterations.

ANTENNAS

The performance of radio systems on aircraft is profoundly affected by the design and placement of antennas. This is particularly true of antennas for transmitters, since the antenna system is a tuned circuit, and its ability to radiate energy into space is determined by its length in relation to the frequency to be transmitted. In general, the higher the frequency, the shorter the antenna. In practice it is possible to adjust the length of an antenna electronically by means of an inductance coil in series with the antenna. As radio systems become more sophisticated, antenna lengths become less critical; that is, a sophisticated low-frequency radio may operate perfectly with a relatively short antenna. On this type of system the effective length of the antenna is changed by means of electronic circuitry.

It is common practice to use one antenna for both transmitting and receiving if the radio equipment is to be used only for communications, provided that the length of the antenna is such that it will accommodate the frequencies to be transmitted and received. When a single antenna is used, it is normally connected to the receiver and switched to the transmitter for broadcasting by means of a relay and a push-to-talk switch on the microphone. The unit that performs the connection-disconnection function is called a **duplexer.**

Navigation and communications antennas are manufactured in many sizes and shapes, depending on their particular functions. As explained earlier, the length or size of an antenna is determined by the frequency range in which it is intended to operate. Special designs such as loops, dipoles, and phased-array antennas are used for certain types of signals and provide directional references. A few typical antennas are shown in Fig. 15-51. The antennas numbered 1 and 2 are designed to receive VOR navigation signals to provide bearing information. An antenna coupler is shown between the two sections of number 2. The antennas identified by the numbers 3, 4, and 5 are VHF communications antennas. Number 6 is a DME and a transponder antenna, and number 7 is a marker-beacon antenna. The mounting locations of

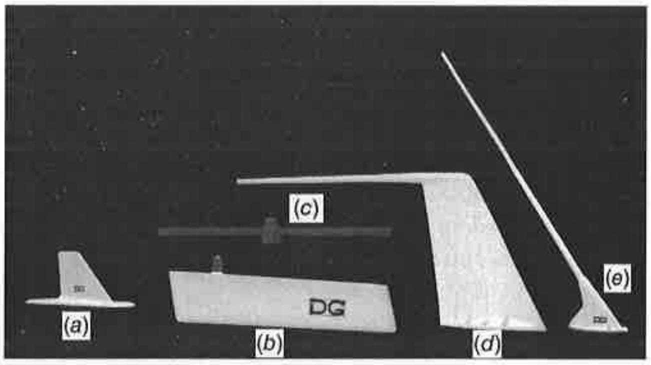


FIGURE 15-51 Common avionics antennas: (*a*) Transponder, (*b*) marker beacon, (*c*) glide slope conformal, (*d*) VHF communications, top-loaded blade, (*e*) ELT whip. (*Dayton-Granger, Inc.*)

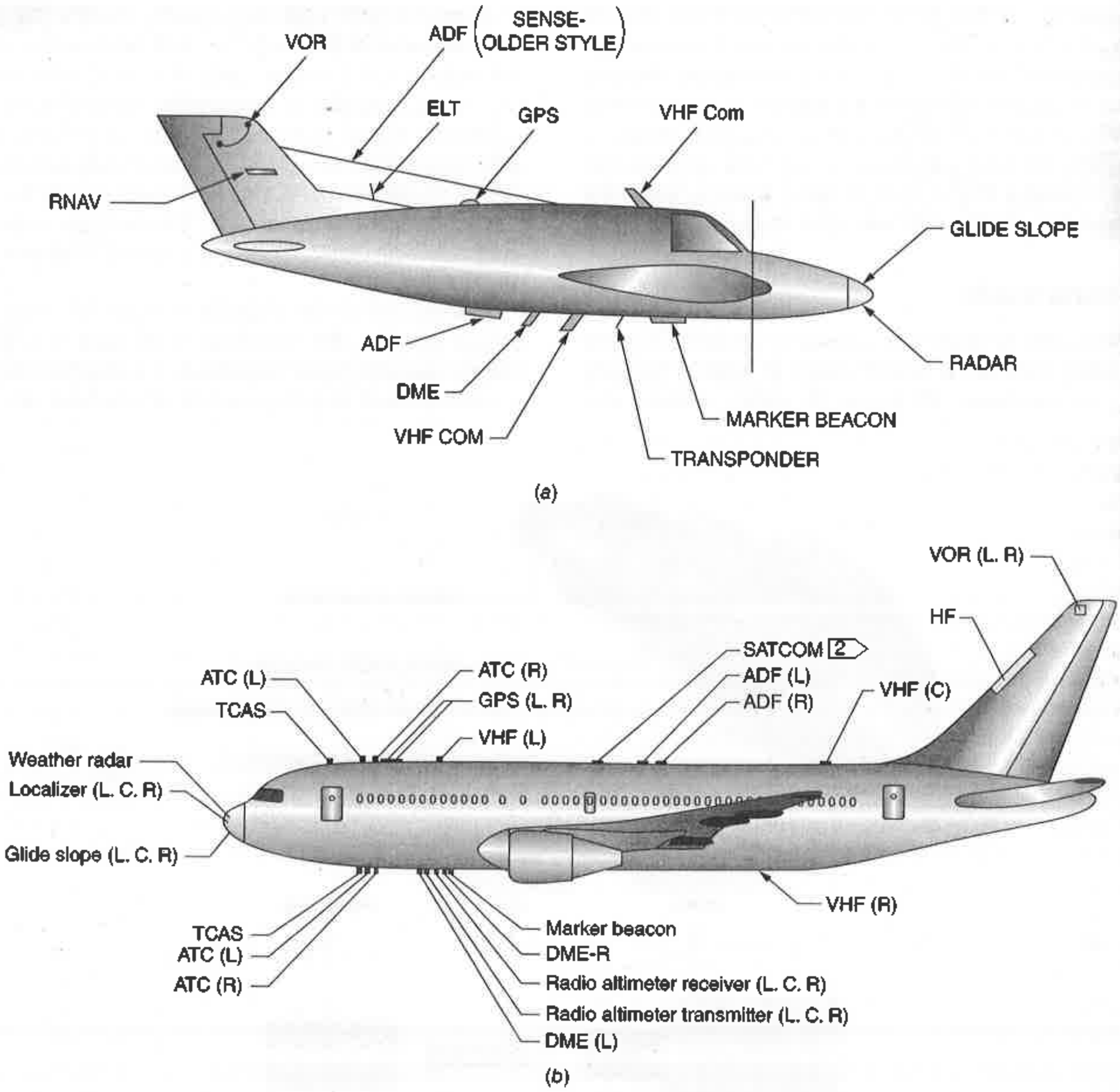


FIGURE 15-52 Typical antenna locations: (*a*) Light aircraft and (*b*) Boeing 767.

these antennas are shown in Fig. 15-52. This illustration represents typical locations; the exact locations often depend on the aircraft and radio equipment used. Even though modern antenna elements are surrounded by an aerodynamic housing, they can still produce substantial drag and reduce efficiencies; especially on high-speed aircraft. So whenever possible it is always advantageous to install flush-mounted antennas to reduce induced drag on the aircraft. Today with the use of modern composite materials and high-strength plastic panels, antenna elements can often be located on the inside of the aircraft. In some cases, the antenna can be a simple metal foil bonded to the inside of a nonmetallic panel, which is designed to install flush with the aircraft exterior.

There are two basic types of exterior-mounted antennas found on modern aircraft: the mast antenna and a whip antenna (see Fig. 15-53). An antenna designed with an aerodynamically shaped exterior housing is typically called a

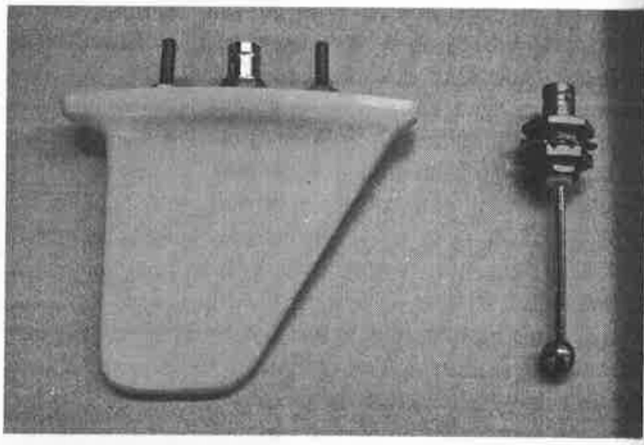


FIGURE 15-53 Two common transponder antennas: (*a*) Mast - aerodynamic plastic housing, and (*b*) whip-exposed antenna element.

mast antenna. In this design, the actual electrical element is simply a wire of the correct size and shape encapsulated in a waterproof housing. The housing provides the structure needed to support and mount the antenna. A whip antenna contains no external housing and the electrical element is exposed to the environment. In general, high-speed aircraft always contain a mast or flush-mounted antenna; most whip antennas are only found on low-speed aircraft.

Antenna Cable

The wire used to connect an antenna to the radio receiver/transmitter must be of special design in order to properly carry the low-power, RF signal. In reality, antenna wire is actually a cable with very specific characteristics. The most common transmission line used between the antenna and radio is called coaxial cable. A coaxial cable contains two electrical conductors separated by an insulator known as a dielectric. Figure 15-54 shows that the inner conductor is a solid copper wire; the outer conductor is made with multiple strands of fine wire woven into a braided pattern that completely surrounds the inner wire. The dielectric is designed to be a specific dimension which is critical to proper signal transmission.

Antenna cables are designed to carry HF radio wave energy; therefore, the impedance of the cable is critical. In order to maintain proper impedance, it is important the cable is never pinched, kinked, smashed, or otherwise deformed;

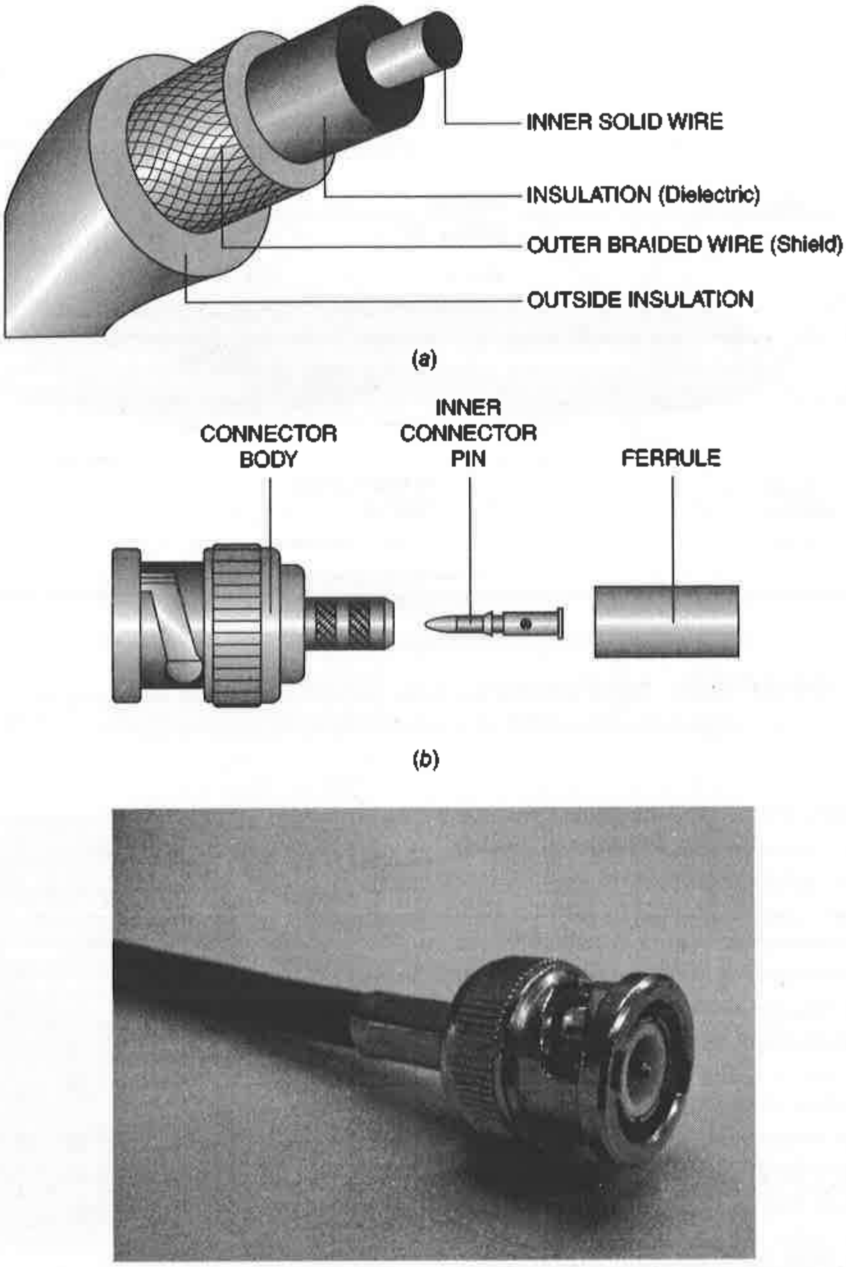


FIGURE 15-54 Antenna cable and connector: (*a*) coaxial cable, (*b*) BNC connector components, and (*c*) connector installed on cable.

the minimum bend radius of many cables is also critical. The length of the cable can also affect radio performance; only cut cables to the dimensions stated by the manufacturer. The termination of coaxial cable typically requires a special BNC connector (see Fig. 15-54). The pin is soldered to the inner conductor of the coaxial cable; the ferrule is crimped around the outer conductor and adds rigidity to the assembly. The connector body incorporates a twistlock to guarantee a tight fit. This design ensures the outer conductor completely surround the inner wire at the connection point; therefore, reducing the possibility of radio interference. Other connectors that resemble the BNC may also be found on aircraft.

Antenna Installation

Whenever making an antenna installation, it is important to consider the location of the antenna, the aircraft structure, and the electrical bonding of the antenna to the airframe. When choosing the antenna location, one must consider the direction in which the radio signal will be received/transmitted. For example, since GPS relies on satellite communications, the antenna will always be placed on the top side of the fuselage; the glide slope antenna must be located to face forward and downward in order to receive signals from the ground during a runway approach. Generally speaking, antennas must be located to prevent signal loss from other structures like landing gear or wing struts. Antennas are often spaced a minimum of 36 in. apart to help prevent signal interference; do not install antennas too close together. The installation documents for a given system will typically include antenna installation instructions as part of the approved data. Certain RF signals can easily be affected by paint containing metallic particles. For example, the thickness of certain paint can affect the signal from a radar antenna; always consult the technical data prior to painting any antenna, or antenna cover panel.

For the most part, an antenna is simply mounted to the outer sheet metal surface of the aircraft; however, a doubler plate is often added to help distribute the physical loads created by wind drag. A gasket is often used to seal out rain and moisture; the gasket is placed between the antenna and the airframe surface. Many aircraft are pressurized in order to fly at higher altitudes; a special sealant may be required at the base of these antennas. Pressurized aircraft also have special structural requirements; never install antennas on pressurized aircraft without proper engineering data. On most installations the antenna base is grounded to the sheet metal skin of the aircraft; this is often called bonding. Typically the inner surface of the sheet metal is cleaned prior to installation, and the mounting hardware of the antenna makes the ground connection between the airframe and the antenna.

Antenna Troubleshooting

During troubleshooting of radio systems, the antenna and related cables must be inspected carefully. If a small leak occurs, moisture can enter the mounting structure or the antenna itself; this can greatly affect radio performance. Also the antenna bonding must remain clean and tight for proper signal transfer. Antenna cables which are not supported correctly may allow excess movement during flight; this may create a loose connection and transmission problems. As seen in Fig. 15-55, there are two common instruments used to test antenna transmission cable; the through line watt meter and the time domain reflectometer (TDR). The through line watt meter measures the amount of power that actually travels through the antenna cable; this instrument can show if the complete signal reaches the antenna and/or if a portion of the signal is reflected back, never reaching the antenna. The TDR is designed to send a pulse into an antenna cable and measure any reflected signal returned to the TDR. Properly used, this instrument will indicate the type of cable fault (open or short) and the approximate location of the problem.

(a)

(b)

FIGURE 15-55 Two common instruments for testing antenna cable: (a) Thruline wattmeter, and (b) time-domain reflectometer.

REVIEW QUESTIONS

1. List the navigation systems commonly found on modern aircraft.
2. What is the frequency range employed for air traffic control communications?
3. Why was ARINC established?
4. What frequency range is utilized for aircraft VHF communication systems?
5. Describe a typical VHF communication transceiver used in light aircraft.
6. What is the difference between the USE and STANDBY displays in a VHF COMM transceiver?
7. What is the function of a Selcal decoder?
8. Describe ACARS.
9. What is the advantage of SATCOM communications?
10. Define the FCC responsibilities.
11. Describe the operational components of an airborne broadband Internet system.
12. Describe the procedure for testing a communications radio for light aircraft.
13. Describe the operation of an automatic direction-finder (ADF) system.
14. Describe a radio magnetic indicator (RMI).
15. Describe the RF signals radiated by a VHF omnirange ground station.
16. What is the maximum transmission range of VOR ground stations?
17. Describe a course-deviation indicator (CDI).
18. What navigational reference is generated by an instrument landing system (ILS)?
19. Briefly describe the operation of a localizer.
20. Compare the glide slope function of an ILS with the function of a localizer.
21. Explain the principle of distance-measuring equipment (DME).
22. What is an important consideration with respect to a DME antenna installation?
23. What is the purpose of a marker-beacon system?
24. What are the indicator lights associated with a marker beacon?
25. Compare the microwave landing system (MLS) with the ILS.
26. Are MLS navigation systems still used in the United States?
27. What is the purpose of a radio tuning system and on what type of aircraft is it typically found?
28. Explain the principle of an area navigation system (RNAV).
29. What are the three basic laws of physics that make an INS operation possible?
30. Describe the function of an accelerometer.
31. What is the purpose of a gimbal platform?
32. Describe the theory of operation of a global positioning system (GPS).
33. What systems are used to improve the accuracy of GPS navigation for aircraft?
34. Explain the wide area augmentation system for GPS.
35. Explain the local area augmentation system for GPS.
36. What is the function of an ATC transponder?
37. What is the value of an encoding altimeter when it is used with an ATC transponder?
38. What is the purpose of an emergency locator transmitter (ELT)?
39. What frequencies are used by an ELT?
40. How can an ELT be tested?
41. What service procedures should be performed on an ELT?
42. What type of aircraft is required to be equipped with a flight data recorder?
43. Describe the operation of a typical flight data recording system.
44. Describe the 406-MHz digital ELT system and how it differs from an analog ELT.
45. On what aircraft are flight data recorders required?
46. Explain the purpose and operation of a cockpit voice recorder.
47. Describe a typical antenna installation on a modern aircraft.

Weather Warning and Other Safety Systems 16

INTRODUCTION

As aircraft are designed to fly higher and faster, there has also been a need to improve safety through the use of electronic warning systems. Some warning systems are used to alert pilots only to an abnormal condition, such as low oil pressure; other warning systems, like weather radar, are designed to provide continuous information. Modern aircraft contain a multitude of systems and sensors designed to monitor a variety of flight conditions, like aircraft altitude, airspeeds, weather conditions, and even search for and identify potential midair collisions. Many of these systems are required for high-speed or commercial aircraft; others are optional and installed to improve flight options.

Since weather conditions along a flight route are critical to passenger safety, means are needed to enable the pilot to "look" ahead to see if dangerous weather exists. One of the principal means for accomplishing this purpose is **radar**. Another system developed to determine weather conditions well ahead of an airplane is called a **weather mapping system**. Weather mapping systems detect the electrical activity caused by storm conditions and display the information on a cathode-ray tube or liquid crystal display screen.

This chapter will present the basic concepts of modern aircraft weather radar, traffic alert and collision avoidance systems (TCASs), ground proximity warning systems, and satellite-based weather systems. The design, architecture, and operational theory of these modern safety systems will be discussed.

RADAR

The word *radar* is derived from the expression **radio detecting and ranging**. Radar equipment was developed to a high level of performance by Great Britain and the United States during World War II for the detection of enemy aircraft and surface vessels. By the mid-1950s radar had found a home in commercial aircraft. The air-carrier industry quickly recognized the advantages of early weather detection using radar. Today, among numerous other functions, radar is used for weather mapping, terrain mapping, and air traffic control.

Radar systems have been developed for all types of aircraft, from single-engine light aircraft to large transport-category aircraft. Early radar systems were heavy and cumbersome and included many separate units. The extensive use of solid-state devices and microelectronics has brought about the development of small, compact systems. Today modern radar systems are highly integrated with other components; radar information is typically presented to the pilots on a multifunction display unit, radar processing circuitry may also be combined with other systems. Of course, certain components are still single-function units such as the radar antenna.

Radar systems operate on an echo principle: "high-energy" radio waves in pulse form are directed in a beam toward a reflecting target. The beam of radar pulses may be thought of as a series of tennis balls thrown consecutively one after the other; each tennis ball represents an energy pulse. If something reflective, like a truck, passes in front of the stream one or more of the balls bounce back. These reflected balls of energy indicate the detection of a solid object; when the reflections stop, the object is no longer in the beam of tennis balls. When a pulse of energy from a radar strikes a target, which may be a mountain, rain clouds, or an airplane, a portion of the pulse is reflected back to the receiving section of the radar system (see Fig. 16-1).

In Fig. 16-1 at *A* a pulse has just been emitted from the airplane's radar antenna. At this point a "pip" appears on the radar display. At *C* the pulse is striking a rain cloud. A portion of the pulse is reflected by the cloud and returns toward the airplane, as shown at *D*. When the reflected pulse reaches the airplane, at *E*, a second, smaller pip appears on the radar screen. The time between the two pips indicates the distance from the airplane to the cloud. In Fig. 16-1 the time between the two pips is shown as 620 microseconds [μs], which represents a distance of approximately 50 mi [80 km]. At *F* another pulse is emitted from the radar antenna. The pulses will continue as long as the radar is active. Airborne weather radar operates on the same basic theory just described; yet in a more refined fashion.

Nature of Radar Signals

A typical radar signal may consist of a carrier wave of 8000 MHz broken into pulses with a duration of 1 μs and

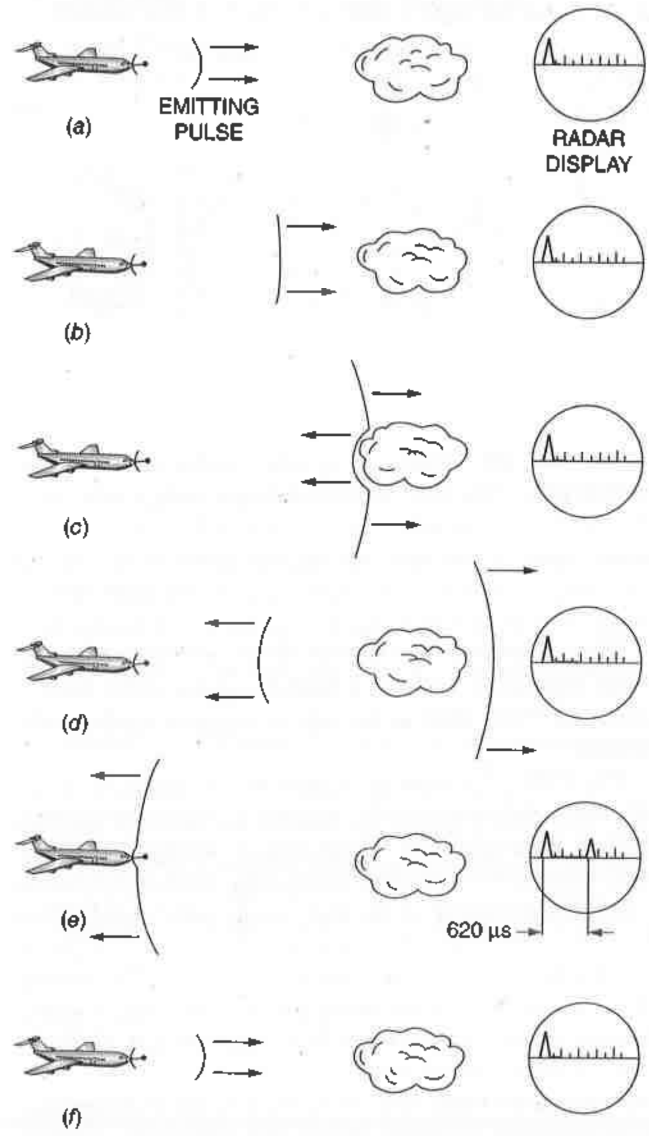


FIGURE 16-1 Radar pulse transmission and reflection.

spaced at intervals of $\frac{1}{400}$ s or 2500 μs. This yields a ratio of roughly 2500:1 for the time of **no signal** to the time of **signal**. It must be pointed out that the ratio of the length of a pulse to the time of no signal varies considerably with the frequency, which ranges from 1000 to 26500 MHz. The various bands are listed in Table 16-1.

The length of the pulses of a radar signal may vary from 0.25 to 50 μs, depending on the requirements of the system. The pulse repetition frequency also varies according to the distance over which the signals must travel. For very long distances, the pulse rate must be slow enough so that the return signal will be received before another pulse is transmitted. If this were not accomplished, it would be difficult to tell whether the pulse shown on the viewing radar display was the one transmitted or the one received.

TABLE 16-1 Various radar bands.

Approximate wavelength	Identification letter	Frequency, MHz
30 cm	L	1000 – 2000
10 cm	S	2000 – 4000
5.6 cm	C	4000 – 8000
3 cm	X	8000 – 12500
1 cm	K	18000 – 265000

The use of a pulse system in radar makes it possible to transmit very powerful pulses. In effect, all the power is concentrated in the very short bursts. If the average power output of a transmitter is 10 W, the pulse power may be as high as 25000 W.

In early types of radar systems, the display on the CRT was a horizontal scale and was called an A scan. The time between the transmitted pulse and the received pulse indicated the distance of the target from the transmitter. With this type of scan, the direction of the target could not be determined except by noting the direction in which the antenna was pointed. To enable the radar to provide direction information, the P scan was developed. The next development in the evolution of radar was an automatic scan by the radar antenna and the processing circuitry to create a picture on the radar screen; originally a cathode ray tube (CRT). This was known as **P scan** because it automatically showed the **position** of the target. The P scan radar system uses a display known as a **plan position indicator (PPI)** because it indicates both direction and distance. Most modern radar systems operate using this scan principle and display the results on an LDC flat panel display. The aviation system is heavily reliant on radar for two main uses; air traffic control which employs ground-based radar to locate aircraft during flight and airborne radar used by pilots to detect dangerous weather.

Operation of the PPI

The operation of a PPI is illustrated in Fig. 16-2. The antenna rotates at 1 revolution per second (rps), more or less, as it searches a 360° area, and the time trace on the scope rotates at precisely the same rate. The time trace is rotated by means of a synchronizer circuit that electronically "rotates" the electron beam that forms the display on the CRT.

Normally, when the PPI radar is installed, the time trace will be vertical from the center of the scope to the top edge when the antenna is pointing due north. When the antenna is turned to the right, the time trace will be to the right, or due east.

Let us assume that the PPI in Fig. 16-2 is installed so the antenna is pointing north. A pulse is transmitted, and a bright spot appears at x. If the length of the trace from the center of the scope to the edge represents a distance of 30 mi [48.3 km], the spot appearing at x indicates that the target (reflecting object) is directly north and at a distance of 20 mi [32.2 km]. Each pulse and each trace will continue to show the object for as long as the transmitted pulses strike it. This will add to the picture, providing an indication of the size of the target as well as its direction.

As the antenna rotates clockwise, the CRT sweep also rotates clockwise. Figure 16-2b shows the electron-beam

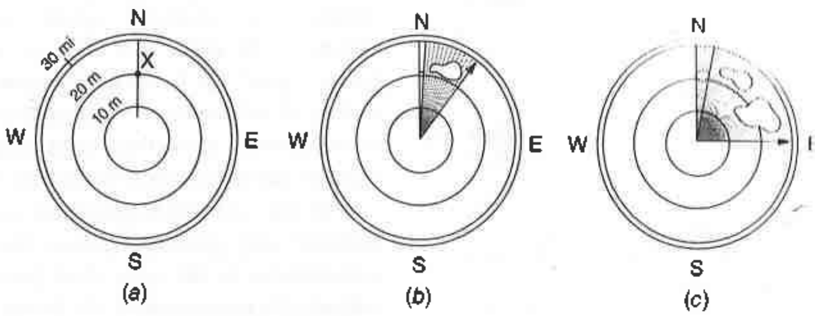


FIGURE 16-2 Operation of a PPI.

sweep as the antenna points slightly to the right of north; Fig. 16-2*c* shows the sweep after the antenna has rotated 90° clockwise. Aircraft weather radar systems are limited in the amount their antennas can rotate. Most airborne systems scan an area approximately 60° to the right and left of the aircraft's flight path.

Principal Units of Analog Radar Systems

Analog radars were the first type of radar system developed for aircraft. Many of these systems are still in use today; however, newer systems operate using the advancements of digital circuits. The operating characteristics of an analog system should be studied to help gain an understanding of basic radar theory. Digital radar systems are discussed later in this chapter.

Figure 16-3 is a simplified block diagram of an analog radar system. This system consists of several principal units, each serving a particular purpose in the system. The **synchronizer** provides the timing for the radar signal and synchronizes the transmitter, receiver, and indicator so that all operate together with correct timing. The timing and synchronizing are accomplished by trigger pulses generated in the synchronizer. These pulses originate in a multivibrator or similar pulse-generating circuit.

The **mixer** stores energy and supplies high-voltage pulses, which are released by the trigger pulse from the synchronizer. During the interval between pulses, a network consisting of inductors and capacitors is charged to a high level. When the trigger pulse releases this energy, a high-voltage pulse is delivered to the **transmitter**.

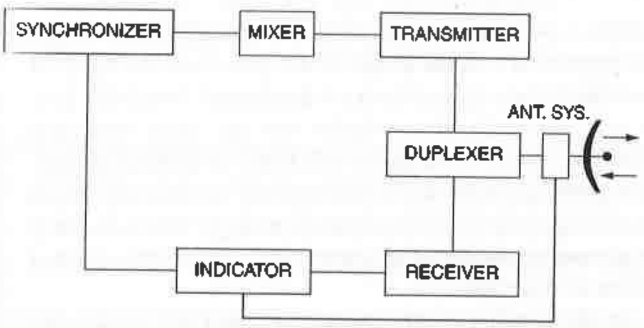


FIGURE 16-3 Block diagram of an analog radar system.

The principal element of a radar transmitter is a **magnetron tube**. This tube receives the high-energy pulse from the mixer and converts it into an extremely high-frequency pulse, which is sent on to the antenna system to be radiated into space. The magnetron makes use of **resonant cavities** to generate the correct frequency for the transmitted pulse.

When a pulse of high-voltage electric energy is delivered to the magnetron cavities, a fixed-frequency radio wave is generated (5400 MHz in the case of a typical weather radar system).

The UHF pulse from the transmitter is carried by means of a waveguide section to the duplexer and from the duplexer through a waveguide to the antenna. A **waveguide** is typically constructed of a hollow rectangular metal tube; it can be considered plumbing for the high-energy radar signal. When the radar pulse leaves the magnetron, it travels through the waveguide as it tries to dissipate or lose energy. The interior of the waveguide is solid metal and the radar signal simply bounces off as it travels toward the radar antenna. Once the signal reaches the antenna, it will be focused into a beam and can safely radiate away from the aircraft. The **duplexer** is an electronic switching device that alternately connects the transmitter and receiver to the antenna. When the pulse is emitted from the transmitter, it is electronically blocked from entering the waveguide to the receiver. As soon as the transmitter pulse ends, the receiver line is opened to receive the reflected pulse. At this time the path to the transmitter is blocked so that the pulse being received cannot go to the magnetron tube.

The **antenna system** can be compared to a search light that rotates to search a particular area with a light beam. There are two common designs for airborne radar antennas; the traditional parabolic shape and the flat panel (array) antenna. Most ground-based radar facilities use parabolic antennas while most modern airborne systems use the flat panel antenna. The parabolic antenna assembly of the radar system, shown in Fig. 16-4, is a rather complex device, largely because of its rotating and tilting mechanisms. The microwave RF signal is transmitted through a variety of waveguide sections and joints from the duplexer to the antenna reflector, and the reflected signal is returned through the same system. In each case the energy must be carried with a minimum of loss.

The upper part of the antenna assembly shown in Fig. 16-4 is attached to the airplane structure and is called the **antenna base assembly**. All the power for rotation and tilt is brought

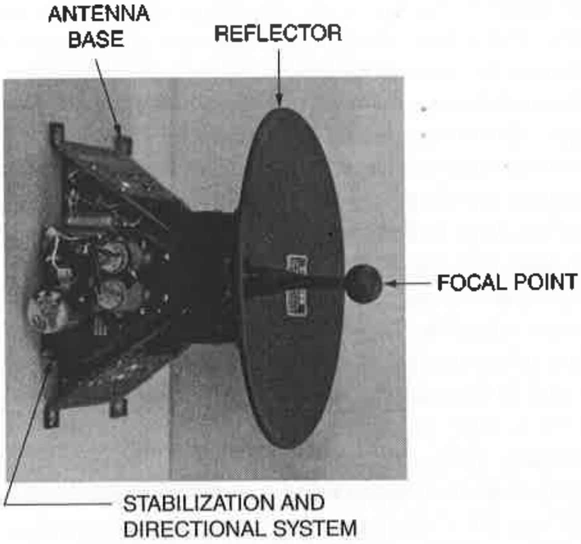


FIGURE 16-4 Parabolic radar antenna.

into the base assembly by means of a plug connector. RF energy enters through the waveguide at the rear and passes down through the antenna frame assembly, which holds the reflector. In the base assembly are the azimuth drive motor and gear train, as well as the control circuitry for synchronization. Electric power is conducted from the stationary base to the rotating antenna by means of slip rings and brushes.

A simplified diagram of the **stabilization system** for the antenna is shown in Fig. 16-5. The purpose of the stabilization system is to enable the radar equipment to scan continuously in the same horizontal plane regardless of the pitch or roll of the airplane. From the diagram it can be seen that the pitch-and-roll signals originate with the flight gyro, which is a part of the automatic-pilot system. These signals are amplified and sent to the azimuth resolver. This resolver is connected through a resistor network to the elevation resolver and the tilt resolver. These resolvers furnish information to a computer system that continuously solves the equation necessary to provide instructions for the elevation drive motor, which performs the work of stabilization. The elevation drive motor actually positions the antenna reflector to provide a continuous horizontal sweep, or rotation, of the antenna beam.

The radar system can be operated either with or without antenna stabilization by means of the STABILIZER switch on the control panel. When the switch is placed in the stabilization position, the antenna becomes stabilized. The tilt on most antenna systems can also be manually adjusted as directed by pilot controls. This becomes a convenient feature which allows the pilot to scan weather above or below the planes current flight path. This may be necessary when a pilot is required to change flight level or wishes to avoid storm activity by changing altitude.

In a radar system the RF energy pulses travel along the waveguide, which terminates in a **feed element**. The feed element reflects the pulses from the transmitter backward to the parabolic reflector of the antenna, which forms the pulses into a beam and radiates them into free space.

A **waveguide** is a hollow metallic tube, typically rectangular in shape, used to direct the UHF radar waves to and from the antenna. Figure 16-6 shows a typical waveguide section. The receiver-transmitter unit connects to the waveguide at the

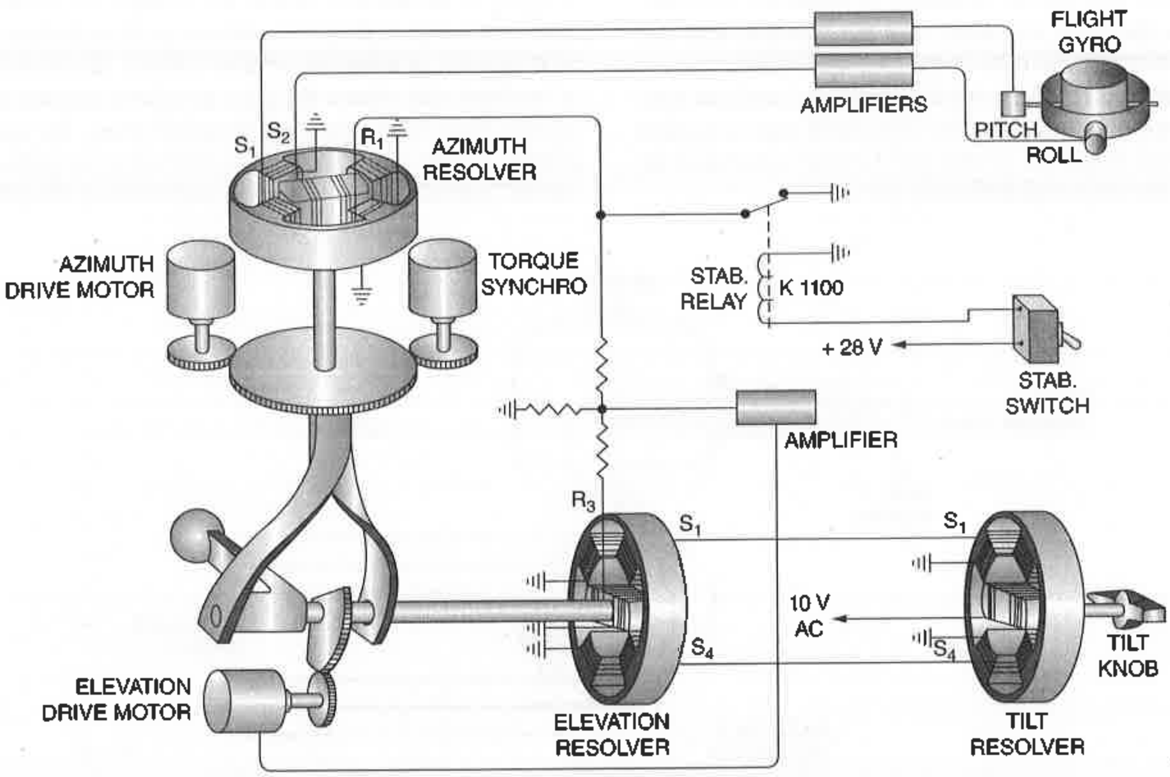


FIGURE 16-5 Antenna stabilization system.

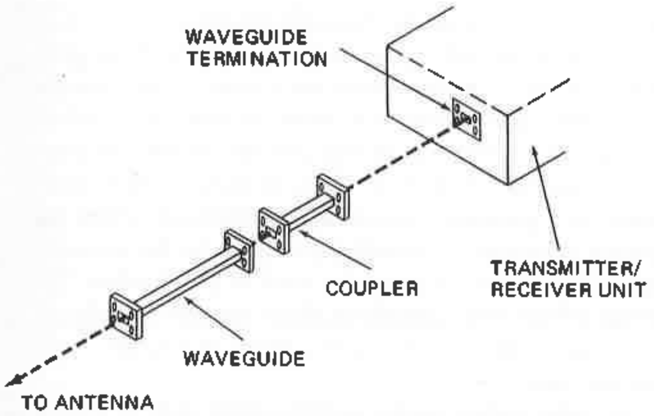


FIGURE 16-6 Typical waveguide.

terminal point. Any transmitted signal travels from the transmitter through the waveguide "plumbing" to the antenna. The UHF signal travels through the waveguide in a manner similar to the way a sound wave travels through a hollow pipe. Since the radar's signals cannot escape through the sides of the waveguide, they simply travel to the end, where they are radiated into the air through the antenna (see Fig. 16-7).

The **receiver** section of the radar system is rather complex in that it must receive the reflected waves and prepare them to give a correct indication at the CRT scope. This involves many electronic operations. The first step is to change the frequency of the incoming signal to a level that can be handled conveniently by a standard electronic system. The change in frequency is accomplished by means of a superheterodyne system, which produces an intermediate frequency.

The incoming radar frequency is typically near 5400 MHz, and the intermediate frequency is approximately 60 MHz. The 60-MHz intermediate frequency is amplified, detected, and sent to the video amplifiers. The signal output from the video amplifiers is sent to the radar CRT indicator.

The **indicator** is a CRT or LCD typically combined with necessary operating circuitry. The video signal must be applied to the vertical deflection circuit, and a sweep signal must be applied to the horizontal deflection circuit.

It is common practice to provide **range markers** on the indicator. These range markers are concentric circles spaced equally from the center of the screen, and they make it possible for the operator to determine accurately the range (distance) of the target from the airplane in which the radar is installed. On most aircraft range of the radar can be adjusted by the pilot; this changes the energy level of the radiated signal and the value of the range markers on the display accordingly.

For radar systems where the installation makes it impossible to rotate the antenna through a complete circle, the antenna is rotated back and forth through a given arc. This situation exists where the antenna is installed in the nose of an aircraft. In this case the antenna may oscillate through an arc of 90 to 240°, depending on the particular installation. This usually gives adequate coverage for weather radar systems because it is necessary to scan the area ahead and to the right and left of the flight path. The diagram of an indicator for this type of installation is shown in Fig. 16-8.

DIGITAL AIRBORNE WEATHER RADAR SYSTEMS

As mentioned earlier in this chapter, the extensive use of solid-state circuitry and microelectronics has led to the development of complete radar systems that weigh but a fraction of early systems. Radar systems of this type began to integrate other functions beyond weather viewing; navigational profiles, terrain mapping, and checklist functions were very common. All that was needed for these additional features was enough for digital memory and processing power. Virtually all radars installed after the early 1990s were fully colored with multiple features. A navigational profile may overlay the weather display, which allows the pilot to determine if the plotted course will intersect or avoid the weather activity. Terrain mapping is available that allows the pilot to receive detailed ground profiles when adjusted to the appropriate mode. The checklist display feature allows the pilot to store up to 16 pages of the aircraft's checklist within the radar unit memory. The pilot can

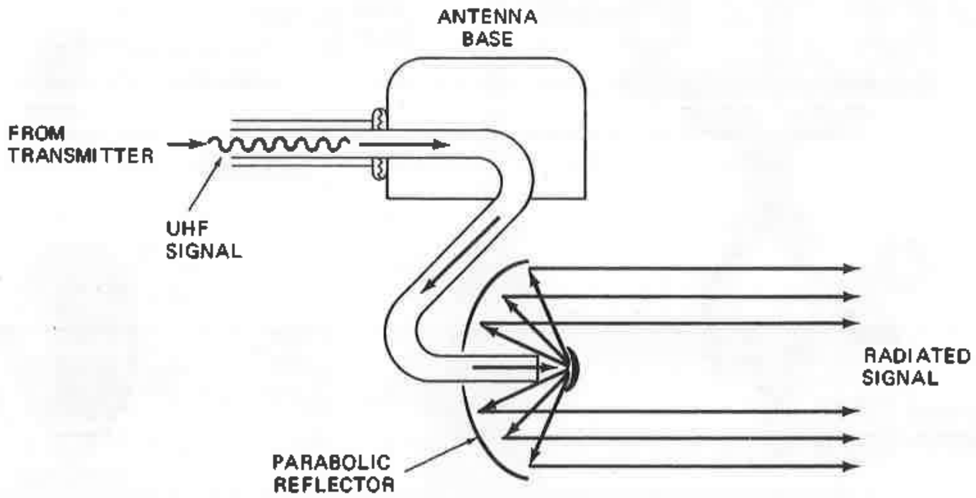
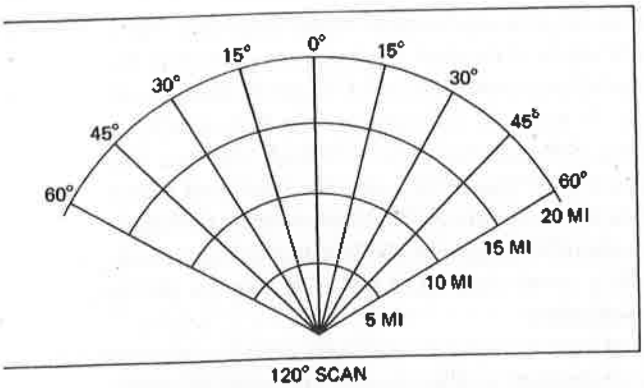


FIGURE 16-7 Radiation of a UHF signal from a parabolic radar antenna.



IGURE 16-8 PPI for an oscillating radar antenna.

etrieve the checklist whenever needed, thus eliminating the ieed for a less convenient paper checklist.

As radar continued to evolve and more aircraft were lesigned with electronic display systems, often called elecronic flight instrument systems (EFISs), dedicated weather lisplays were no longer needed. Weather information was simply displayed on one or more of the electronic flight displays. This saved weight and created a more efficient instrument panel. This concept of integration continued to evolve and virtually no modern aircraft contains a "radar display"; today, all weather information is presented on **multifunction** or **navigational** displays.

Color Weather Radar

Color added to weather radar displays enhances the storm activity image and provides a more effective means to detect severe weather. A green color indicates level 1 storm activity; yellow indicates moderate rain as in level 2; and red indicates level 3, or heavy rain (see Fig. 16-9). Some color radar equipment also use the color magenta (purplish-red) to display turbulence or very heavy rain fall or ICE.

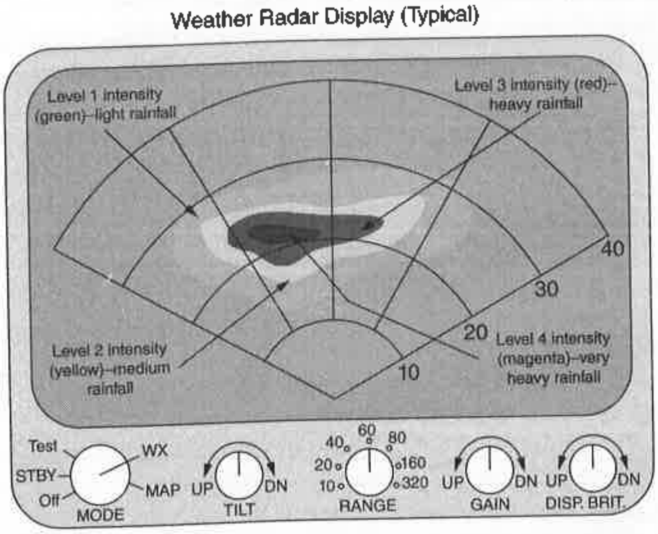


FIGURE 16-9 A typical color radar display. The range markings are typically white or blue. Level 1 storm activity (light rain), green; Level 2 storm activity (moderate rain), yellow; Level 3 storm activity (heavy rain), red; turbulence (extreme storm activity), magenta. See also color insert.

Color radar equipment enables the pilot to more effectively identify the intensity of a storm. It is this sole advantage that has made color radar the standard of the industry. Black-and-white radar systems are still found in limited use on some older aircraft. Virtually every modern corporate or transport-category aircraft currently employs a color radar system.

Weather Radar Frequencies

Weather radar systems are designed to detect the presence of rain, thunderstorms, and violent air turbulence. This is accomplished by utilizing frequencies that reflect most easily from these conditions. Weather radar should *not* be used as a proximity warning device for other aircraft or for collision avoidance. The frequencies used to detect rain are not useful at detecting aircraft. For these purposes, a different type of design is required for dependable results.

Airborne weather radar typically operates at one of two frequencies, **C-band** or **X-band**. The C-band range is from 4000 to 8000 MHz, and the X-band range is from 8000 to 12000 MHz. The C-band radars are typically used in situations where the pilot needs to fly through narrow passages between thunderstorms. C-band frequencies tend to pass through some of the precipitation that would reflect X-band energy. Since the C-band frequencies do not easily reflect, they cannot "see" some storm activity. The resolution of C-band radar is therefore poor compared with that of X-band units. However, this characteristic allows the C-band to penetrate precipitation and identify targets (storms) behind the initial rainfall. This allows the pilot to determine if passing through the initial rain will bring clear skies or more storms. The **resolution** of a radar system defines its ability to accurately display the various levels of storm activity scanned by the radar.

X-band radars have good resolution; however, X-band will not provide reliable coverage behind precipitation. This is because very little of the X-band energy will pass through the precipitation first encountered by the transmitted wave. X-band radars are typically used by pilots who use radar as a weather avoidance tool. Some advanced radar systems have overcome the limitations of single-band equipment; these are hybrid systems that can vary the strength of the emitted radar pulse and/or choose between C- or X-band frequencies as needed. Using powerful microprocessor circuitry, the most advanced systems can automatically map all facets of a storm's activity with minimal need for pilot adjustments to the radar controls.

Figure 16-10 illustrates the difference between the transmitted signals of typical X- and C-band radars. Here it is easy to see that the X-band wave propagation pattern is more concentrated than that of the C-band. This characteristic helps to determine the type of reflected signal and use of the radar systems.

A typical airborne weather radar system consists of a receiver-transmitter, one or two indicators, a control panel, and an antenna system (Fig. 16-11). This type of system is commonly found in corporate and commuter aircraft.

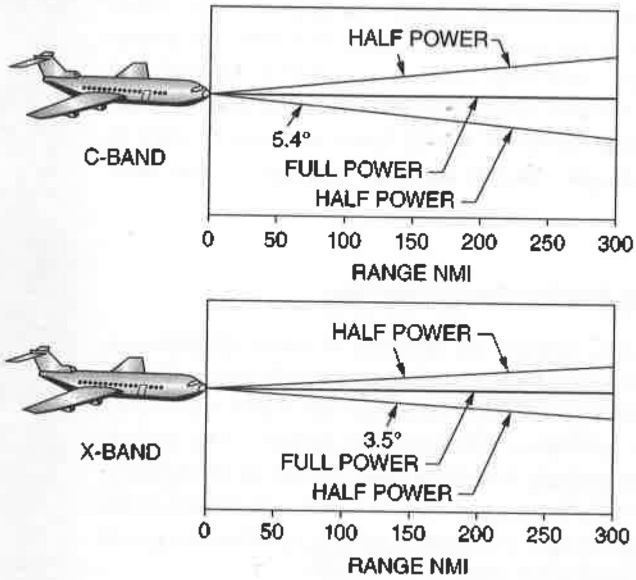


FIGURE 16-10 Radar C- and X-band radar transmission characteristics. (*Rockwell Collins.*)

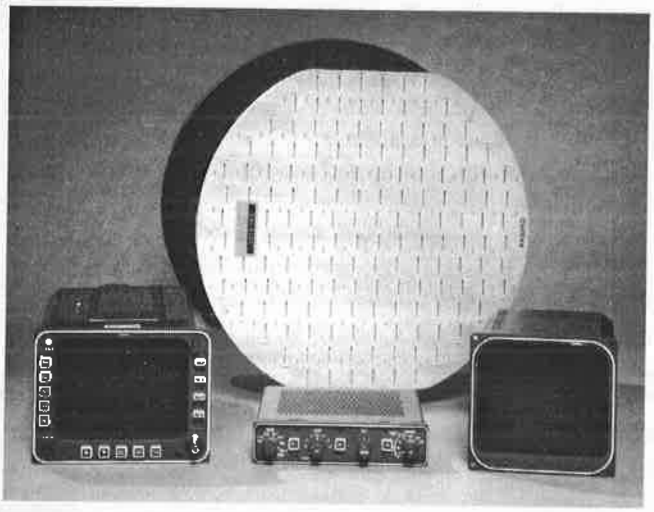


FIGURE 16-11 Typical components of an aircraft weather radar. (*Rockwell Collins.*)

The Receiver-Transmitter

A **receiver-transmitter (r-t)** for a typical airborne weather radar system is divided into three basic sections: the receiver, the transmitter, and the data processor. The transmitter section is designed to produce pulses at C- or X-band frequencies and transmit that energy to the antenna section at the correct time. Most modern radars use a completely solid-state digital interface for communication between the various sections of the radar system. Radar indicators can be stand-alone displays used for radar information only; or the indicator will be incorporated into a multifunction display (MFD) or navigational display (ND). The MFD and ND units are installed as part of an electronic instrument system and can easily be adapted to show weather information. This concept of display integration saves valuable weight, space on the instrument panel, and improves pilot awareness. There are two basic types of displays used on modern aircraft; the CRT and the liquid crystal display (LCD). Both displays can easily show a variety of information with high-resolution color images; however, the LCD is lighter and uses less power than the CRT. The LCD is now the display of choice and found on the latest aircraft; however, there are thousands of aircraft currently equipped with CRT displays and a technician is likely so see both LCD and CRT displays during aircraft maintenance.

The signal from the radar receiver-processor is converted to a format compatible with the display; this could be a digital or analog signal depending on the system design. The display will then decode and process the information as needed to create a weather picture for the pilot. Some dedicated weather display units and some multifunction displays will contain push-buttons or other controls for radar functions. Most radar systems also have a dedicated panel specifically for control of radar functions. A block diagram of a typical transport-category aircraft weather radar system is shown in Fig. 16-12.

The **transmitter** generates a stable intermediate frequency (IF) using a crystal-controlled oscillator. The IF is translated up to the X- or C-band through a varactor multiplexer. Several steps may be required to increase the signal to the correct frequency for transmission. Another type of system uses a special diode circuit that generates the transmit frequency immediately. In either case the transmit signal is modulated, and the pulse timing is controlled by a synchronizer circuit.

The **pulse width** of the transmitted signal determines the radar's ability to resolve targets at various distances. To understand this phenomenon, consider that the transmitted signal is a burst of energy followed by a relatively long period of no energy, followed by another burst. As shown in Fig. 16-13, this cycle repeats for as long as the radar is transmitting. Assuming that an energy burst lasts for 3.9 μs, this would make the burst of energy (pulse width) 1917 ft long traveling through the air. At this pulse width, it would be impossible for the radar to distinguish storm targets that are separated by 1917 ft or less.

Many modern transmitters vary the pulse width according to the range selected by the pilot. A short pulse width is used for short-distance radar scans. A long pulse width is used for long-distance weather observation.

The **receiver** section of the r-t unit receives the reflected radar signal through the antenna and duplexer. This signal is received only during the listening time, which occurs between bursts of transmitted energy. The first step is to amplify the received signal to eliminate the loss of any resolution. The amplified signal is sent to the mixer, which produces a lower-frequency IF. Using a lower-frequency IF allows for less complicated circuitry than if the radar frequency was used.

The IF is then amplified, decoded, and filtered by the **data processor** section of the r-t unit. A range filter is used to determine the distance between the storm activity and the aircraft. The data processor analyzes the IF and performs the

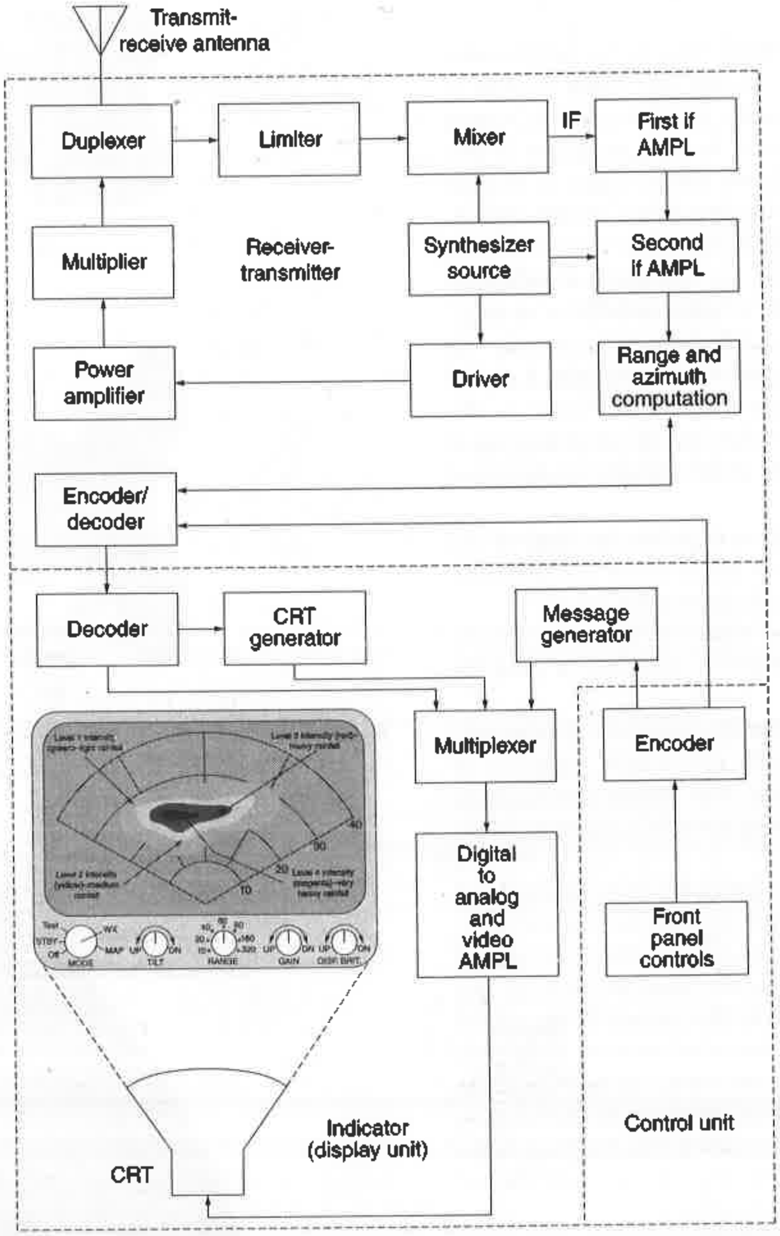


FIGURE 16-12 Block diagram of typical weather radar. (*Rockwell Collins.*)

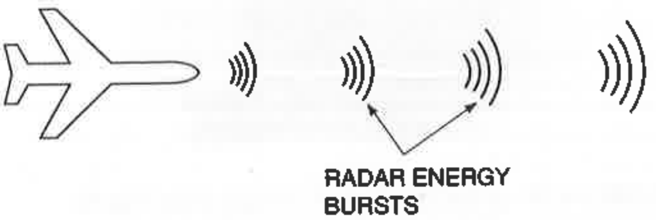


FIGURE 16-13 Bursts of radar energy.

calculations needed to determine the intensity of the storm activity. The range and intensity information is then digitized and stored in data bins. The data are then sent to an azimuth filter, where the information for one azimuth bearing is averaged. The results are sent to the indicator unit via a digital data bus for display.

The Indicator

Using advanced high-energy, high-frequency circuit design, many of the latest radar transmitters have eliminated the need for a magnetron tube. Elimination of the magnetron helps to create a more efficient and compact system which also has improved reliability because the tube is a relatively delicate component prone to failure. Many of these same advanced radar systems employ miniaturized circuitry and combine the r-t unit, waveguide, and antenna in one unit. This all-in-one radar is then mounted in the nose of the aircraft behind the radome; this eliminates the need for a long waveguide, saves weight, and reduces signal loss. This type of radar system consists of three basic units: (1) the r-t unit antenna assembly, (2) the control panel mounted on the flight deck, and (3) the display which may be combined with other electronic CRT or LCD instruments available to the pilot.

The Control Panel

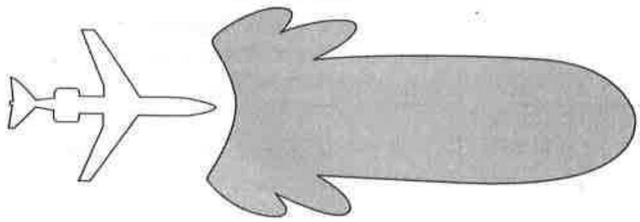
The weather radar **control panel** must be located for easy access by the flight crew. If only one radar system is installed in an aircraft, the control panel is typically located in the center console for access by both the pilots. If two radar systems are installed, one control panel is located for access by the pilot and one for access by the copilot. The operating controls include the power switch, display brightness, stabilization, gain, the brightness of reference marks, mode of operation (test, weather, turbulence, or map), selection of operating range, and antenna tilt controls. On a digital radar system, the control unit transmits a digital signal (representing the control switch positions) to the r-t unit in a serial format. On older systems an analog signal is sent. The functions of some of the controls are described below.

The **range control** is used to establish the range of the indicator. This control alters the transmission characteristics of the r-t unit to coordinate with the selected range.

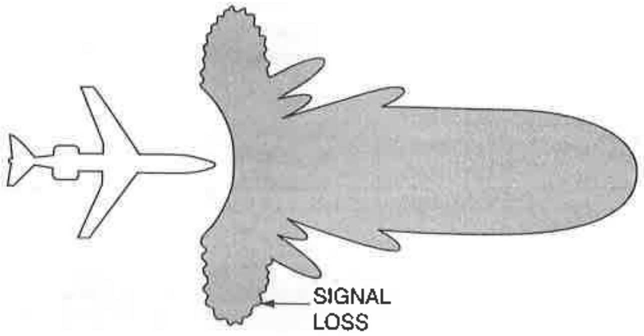
The **gain control** is used to adjust the IF receiver gain to the proper operating point to assure reception of even the weakest reflected signals.

When the **stabilization control** is turned on, the transmitted radar signal will scan parallel to the earth, regardless of the pitch and roll of the aircraft. This system is particularly useful when the airplane is flying through areas of excessive turbulence.

The **tilt control** is used to change the angle in which the antenna is scanning. In the ZERO position the antenna beam is always parallel to the surface of the earth. If the control is turned toward the UP position, the beam will scan an area above the level of the airplane. In like manner, if the control is turned to a DOWN angle, the beam will scan an area below the level of the airplane. Thus the radar can provide better coverage during climb or descent and/or can be used to scan the areas above or below the aircraft in search of less storm activity.



(*a*)



(*b*)

FIGURE 16-14 Radar signal transmission patterns. (*a*) A flat-plate antenna's signal; (*b*) a parabolic antenna's signal.

Flat-Plate Antenna System

Most modern weather radar systems employ a **flat-plate** radar antenna. A flat-plate antenna utilizes a waveguide system that radiates the radar pulse from the rear of the antenna. This type of antenna is often called a **phased-array** antenna. Flat-plate antennas have approximately twice the efficiency of conventional parabolic antennas. This is due to the accurate signal transmission pattern of the flat-plate antenna (see Fig. 16-14). As illustrated, with the flat-plate antenna (Fig. 16-14*a*), there is less signal loss to the sides of the antenna. This more efficient antenna extends the range and resolution of any given radar transmitter. Or a less powerful transmitter can be used to achieve a radar system with comparable range and resolution.

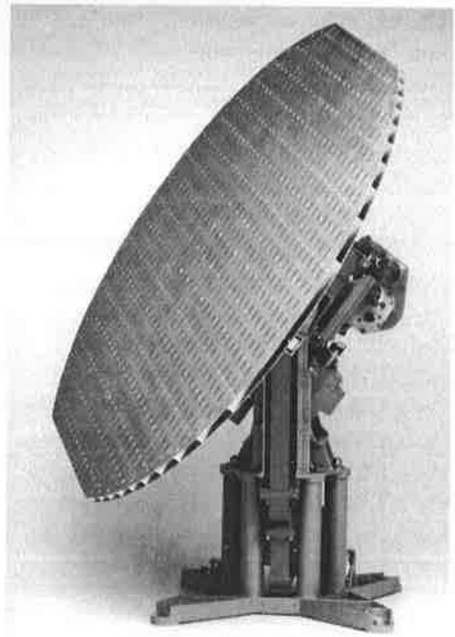


FIGURE 16-15 A flat-plate antenna for use in commercial transport planes. (*Bendix King by Honeywell.*)

Figure 16-15 shows a typical flat-plate antenna. As illustrated in Fig. 16-16, the waveguide from the receiver-transmitter connects to the rear of the antenna. The antenna contains several rows of horizontal and vertical waveguides. During transmission, the radar signals travel into the horizontal and vertical waveguides and "escapes" through the slots in the front of the antenna. From here they radiate outward from the antenna in a relatively straight line. During reception, any radar wave that returns to the antenna enters the slots and travels through the waveguides and eventually into the receiver. Most flat-plate antennas are 10 to 30 in. in diameter.

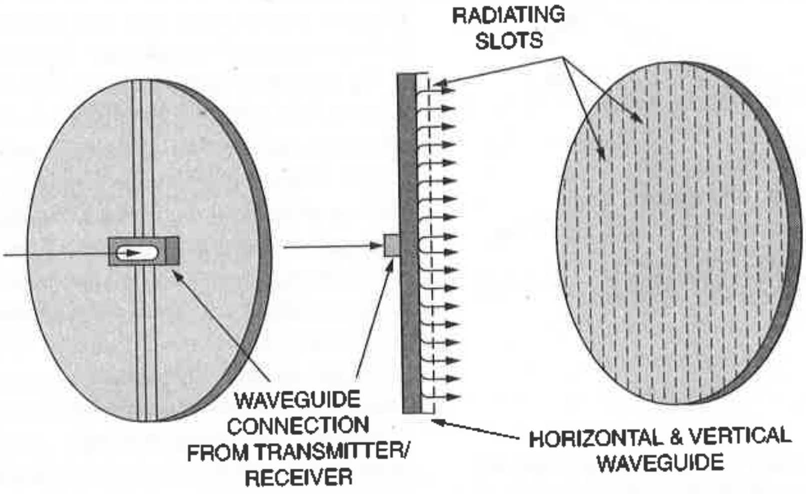


FIGURE 16-16 The operation of a flat-plate antenna.

Waveguides

As discussed under analog radar theory, a **waveguide** is used to connect an antenna to an r-t unit. A waveguide must be used for this connection, since the radar frequency is too high to be transmitted through conventional wiring. To improve efficiencies in the system, a waveguide should be as short as possible. Therefore, on some systems the r-t unit is mounted directly to the base of the antenna. This eliminates the need for any waveguide outside of the antenna or r-t unit. Ideally, all r-t units should be mounted to the antenna base; however, in many aircraft the space limitations do not allow this type of arrangement. Whenever an r-t is remotely located from the antenna, a waveguide must be installed.

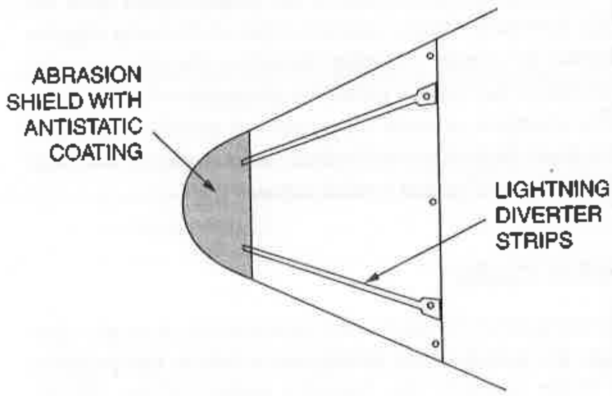


FIGURE 16-17 Typical radome installation.

Radomes

A radar antenna is typically mounted in the nose section of an airplane and is protected by a nonmetallic streamlined cover called a **radome**. The radome is necessary to protect the antenna assembly and still allow the transmitted signals to be radiated into space. A metal cover would reflect the waves back; hence there would be no way to detect storm activity.

A radome is designed to protect the radar antenna from the elements and yet remain "clear" to the transmitted radar signals. It must be constructed of a material that will not interfere with or reflect the RF pulses emanating from the antenna. The material may be fiberglass laminate, plastic, or some other material that will not adversely affect the radar signals.

A radome may or may not be equipped with an **abrasion shield**. Such a shield is usually made of neoprene or some other synthetic rubber or plastic (Fig. 16-17). In any event, the shield has a resilient surface that resists abrasion caused by sand, rain, rocks, or other objects.

Static electrical buildup is often a problem with radomes. Since radomes are made of a nonconductive material, static cannot easily dissipate from the radome to the airframe. If too much static charge accumulates on a radome, it will arc to the metal airframe and cause radio interference. If this arcing continues, the radome will most likely become damaged. To help eliminate static discharge on radomes, an antistatic protective coating is applied to the radome surface. Often this coating is incorporated in the abrasion shield.

Lightning diverter strips may also be used to help discharge any static accumulation on a radome. Lightning diverters are simply thin metallic foil strips adhered to the surface of the radome (Fig. 16-17). The foil strips are electrically bonded to the airframe when the radome is mounted to the aircraft. The lightning diverters provide an electrical path to discharge any static charge.

The paint or other coating applied to a radome must be of a type that will not affect the radar signals. Many paints contain metallic pigments such as titanium, aluminum, or lead. Paints of these types must not be applied to a radome. The manufacturer usually specifies the types of paints and thickness of application that are satisfactory for repainting or touch-up.

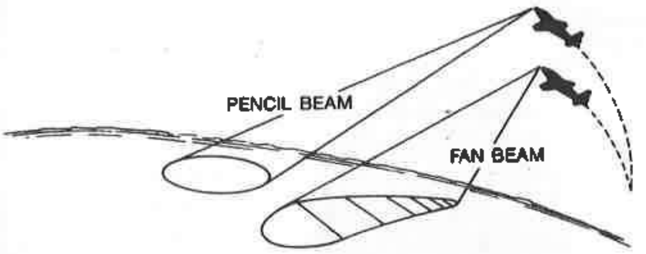


FIGURE 16-18 Fan beam used for terrain mapping. (*Rockwell Collins.*)

Terrain Mapping

Some weather radar systems offer a **terrain map** mode of operation. The primary function of weather radar is to detect thunderstorm activity; however, the radar system can be used as an alternative navigation system via terrain mapping. Some systems provide a wide **fan beam** for use in mapping. As seen in Fig. 16-18, the fan beam provides a wider coverage area than that provided by the **pencil beam** used for weather detection. Proper interpretation of the radar display is essential for terrain mapping; therefore, the pilot must be well versed in the various reflective properties of ground targets. For example, smooth water will not provide much of a return signal; large cities will reflect the majority of the radar signal; forests will return a weak signal.

Doppler Radar

Traditional aircraft weather radar systems measure only rainfall rate; the actual storm turbulence is left to the interpretation of the operator. The **Doppler radar** system actually measures storm turbulence and indicates its presence by the color magenta on the radar display. The Doppler radar also displays the weather information produced by typical color radars. This combination allows the flight crew to provide a safer and more comfortable flight in heavy storm activity. The system's limitations include the fact that moisture (rain) must be present in order to detect wind shear turbulence. No clear-air turbulence can be detected by Doppler radar. The Doppler radar system is by far the most informative radar yet; it has therefore been selected for new installations on transport-category aircraft.

The Doppler radar system is virtually identical with the conventional radar described earlier. The r-t unit incorporates different circuitry; however, this would be less than evident to the casual observer. The Doppler radar system, as the name implies, works on the Doppler shift principle. A sophisticated Doppler signal processor monitors the transmitted and received radar signal frequencies. If the returning frequency is out of phase with the transmitted frequency, the wind shear component (turbulence) of the storm is high. If the frequencies are in phase, there is no wind shear. A frequency shift is caused by the rain within a storm moving violently owing to an excessive wind shear. Since the transmitted signal reflects off of moving raindrops, the signal returns to the receiver at a different frequency. Of course, the Doppler system must take into consideration the aircraft's forward speed and compensate accordingly.

To accurately measure a frequency shift caused by turbulence, the radar's transmitter must be extremely stable. Likewise, the receiver must be capable of processing any returns without affecting the frequency. The Doppler system takes an average of the returned signals to ensure reliability. To acquire enough data in a short time period, the pulse repetition frequency (number of pulses per second) is increased to approximately 10 times that of standard weather radar. In other words, the r-t will transmit 10 times as many energy bursts per second. This increases accuracy but reduces the range of the turbulence detection to approximately 60 mi.

Doppler turbulence detection reveals new information about storm cells that cannot be identified by non-doppler weather radar and have now become the standard for all modern aircraft.

RADAR MAINTENANCE

The maintenance and repair of radar systems and components should be carried out in accordance with the manufacturer's instructions. There are, however, certain generally accepted practices, particularly with respect to radomes and radar safety.

Radomes

The efficiency of any radar system can be greatly reduced by improper radome maintenance. In general, the radome must remain transparent to the radar signal and yet protect the radar antenna from the elements. This task sounds simple, but the radome must remain nearly perfect; otherwise, the radar efficiency will suffer. One of the most common problems occurs when the radome develops a small crack. This crack will then allow moisture to enter the radome material. The moisture itself will reflect some of the transmitted radar energy, thus affecting efficiency. The moisture may also freeze, causing a delamination of the radome. This, too, can degrade radar performance, as well as create structural problems for the radome.

A radome should be inspected frequently for abrasion, cracks, delamination, the condition of lightning diverter strips, dents, and any other visible damage. The attachment of the radome to the aircraft should be examined for security to assure that water cannot enter the antenna space. The seal around the edges should be checked for cracks, separations, or any other type of fissure that would admit moisture. If the radome is equipped with an abrasion shield, the shield should first be checked for damage such as cuts or cracks. Since the shield can conceal damage to the radome, the radome should be checked for damage on the inside.

The repair of cracks and cuts in a radome is important because such defects may allow water to enter the antenna space or seep between layers in a radome lamination. As noted above, if water is trapped in the radome material, it will affect the radar signal, or it may freeze and cause further damage. The thickness of the radome is critical to system performance. Cracks should be repaired as specified by the manufacturer. Any radome with a multitude of repairs is most likely affecting radar performance by as much as 50 percent and should be replaced.

The radome should also be inspected carefully for signs of static discharge. This is especially important for high-speed aircraft. Static discharge damage appears as small carbon traces, burns, or pits on the radome surface. The damaged material must be removed and the radome repaired. If the radome is equipped with lightning arresters, be sure that they are attached securely to the radome and the aircraft. A continuity check of the lightning arresters to the airframe is also recommended.

Components of a radar system are inspected in a manner similar to that employed for other electric and electronic equipment. Items should be checked for security of mounting or attachment, security of connector plugs, the condition of shock-absorbing units, cleanliness, and freedom from corrosion and any other unsatisfactory condition. Cleaning is very important to enhance system cooling. Be sure all vent holes are clean so that air can easily flow through the unit. Some units employ forced-air cooling; be sure this system is clean and operable. Testing of the entire radar system should be done according to the instructions provided by the manufacturer.

Radar Safety

It must be remembered that when a radar system is turned on, the antenna is emitting millions of high-energy electromagnetic pulses. These can cause physical injury to the body, as well as ignition of flammable materials in the vicinity. For these reasons, the radar should not be turned on when the aircraft is on the ground except under carefully controlled conditions. The safety of personnel is increased by the observance of the established maximum permissible exposure level (MPEL) boundary for the equipment being tested. This boundary is illustrated in Fig. 16-19 for a wing-installed antenna.

Radar should not be turned on when an aircraft is being defueled or fueled. This applies not only to the aircraft in which it is installed but also to other nearby aircraft. The radar should not be turned on in a hangar unless appropriate shielding and wave-absorbing equipment is in place in front of the antenna. In order to ensure that radar equipment does not transmit dangerous RF while on the ground, virtually all modern aircraft incorporate automated controls to deactivate the radar transmitter. These systems consist of a simple circuit which contains an aircraft **weight on wheels** switch, or sensor. Often called a **squat switch**, the weight on wheels sensor will be used to turn off the radar transmitter whenever the aircraft is on the ground; or has "weight on wheels." Since this is a critical safety feature, there are usually redundant circuits used to deactivate the radar.

Radar can usually be tested safely on the ground by placing the aircraft in an open area with the antenna tilted upward so the beam cannot strike any object on the ground.

Any person operating an aircraft is responsible for damage caused by that aircraft, including the aircraft's weather radar. Always make sure the radar is turned off before turning on any aircraft battery master switch. If the last person to operate the radar accidentally left the radar on, you may inadvertently operate the radar simply by energizing the aircraft bus. This can cause severe bodily injury or property damage; therefore, double-check that the radar is off.

Additional recommended safety precautions for airborne radar are set forth in FAA publication AC 20-60B.

Three-Dimensional Weather Radar

The latest technology to enter the field of airborne weather radar has been developed by Honeywell Corporation and uses a system which scans the entire sky in front of the aircraft from the ground level to 60 000 ft. The system is designed so the pilot's weather display will only show relevant storm activity; that is, 4000 ft above and 4000 ft below the aircraft. Weather which will not be encountered on the current flight path is displayed as a transparent and cross-hatched image (see Fig. 16-20). This system helps to improve safety by using advanced computer technologies to paint a detailed three-dimensional picture of the weather ahead of the aircraft; the system even predicts, with approximately 90 percent accuracy, where within a storm system lightning or hail may be hidden. Honeywell calls this system

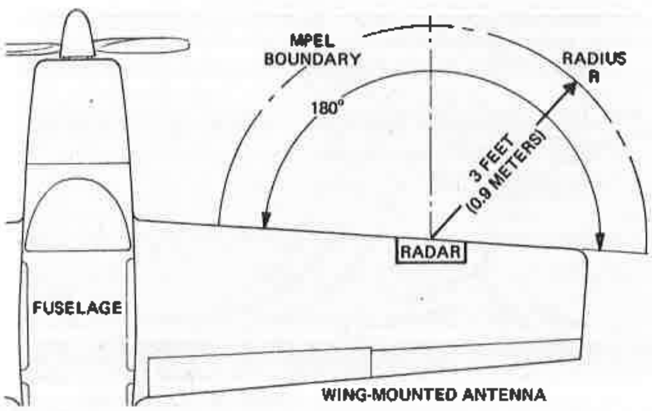


FIGURE 16-19 A typical MPEL boundary for radar. (*RCA*.)

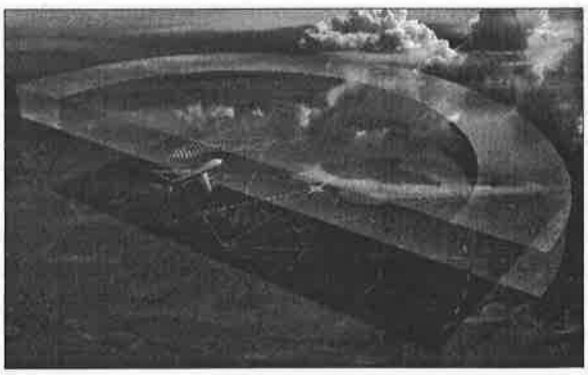


FIGURE 16-20 3-D aircraft weather radar. See also color insert. (*Honeywell*.)

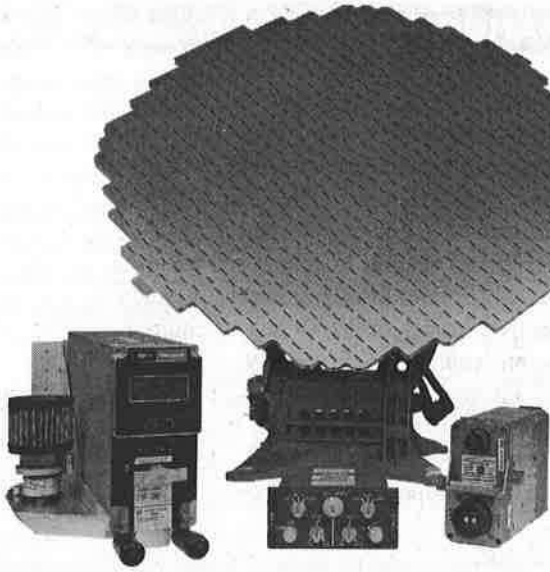


FIGURE 16-21 The RDT-4000 IntuVue 3-D radar system for a Boeing 737. See also color insert. *(Honeywell.)*

IntuVue because it has been designed for simple and intuitive operation.

The 3-D weather radar employs a sophisticated processor with a self-contained cooling fan, a large flat-panel antenna and r-t unit mounted in the nose of the aircraft, and the radar control panel (as seen in Fig. 16-21). The radar display is hosted on one or more of the integrated electronic flat panel instruments. The system is designed to rapidly scan the area in front of the aircraft with both a horizontal and a vertical movement. The data received from the r-t unit is stored by complex processor circuitry which then creates the 3-D image of all reflective material in the sky. The radar range is 320 mi in front of the aircraft. Traditional radar systems transmit a narrow beam and only scan a narrow path to create a 2-D image. The IntuVue system also employs a large database to store topographical data; this information is used to remove any signal noise generated by radar bouncing off the ground and helps improve image quality. Using high-speed digital circuits, the radar system can refresh the weather image within every couple of seconds. The IntuVue system captures the density of the clouds using a radar signal with a relatively long wavelength (low frequency). Doppler radar techniques are used to determine the movement of moisture or turbulence within a cloud. The system processors then use complex algorithms to predict what might be hiding behind the radar signal as well as hail and lightning. All this information is presented to the pilot in an easy-to-understand format on a conventional multifunction or navigational display. Conventional radar colors are used to show storm activity (green through red); and the extreme hazards as presented with magenta indicating turbulence, small "lightning bolt" symbols to indicate the presence of lightning, and hail displayed as small balls with short tails. The Honeywell RDR-4000 3-D radar is currently only available for transport-category aircraft, such as the A-320 or B-777; however, as technologies advance 3-D radar will likely be developed for more aircraft in the future.

LIGHTNING DETECTION

A **weather mapping system** is basically a radio receiver designed to detect thunderstorm activity and display a map of that activity on a CRT or a liquid crystal display. Weather mapping systems were originally developed as a low-cost alternative to weather radar systems. Although most weather mapping systems cost less than radar, in many cases weather mapping systems are used in conjunction with weather radar. Many modern systems have merged weather mapping with Doppler radar; this creates radar that can also "see" lightning. These systems will have a conventional radar display with a dedicated symbol used to identify lightning and/or hail. This is mainly due to the reliability of weather mapping units and their ability to consistently detect thunderstorms that are located behind other storms.

In any storm system, there are areas of convective shear air currents. These conditions are caused by the rising and falling air currents near each other as shown in Fig. 16-22. For example, as a cold front moves across the country, the cold air in the advancing front flows under the warmer air and causes the warmer air to rise. At the same time, the colder air in the front flows downward, and convective shear takes place between the rising and falling columns of air.

The convective wind shear creates static electric charges that must discharge when they reach a certain voltage level. If a large number of static discharges occur simultaneously, visible lightning will result. Any discharge, with or without lightning, will emit an RF signal. A weather mapping system detects this signal and displays the discharge activity on an LCD or CRT display unit.

There is always an abundance of static discharge activity within any storm. Since the number of static discharges increases with the severity of the storm, a weather mapping system can "count" the discharges to determine the storm's intensity. A relatively intense storm will have a large number of static discharges per minute. A weak storm will have fewer discharges per minute.

A weather mapping system is a receiver only; however, it has the capability of determining the direction from which the electric signals from a thunderstorm are coming.

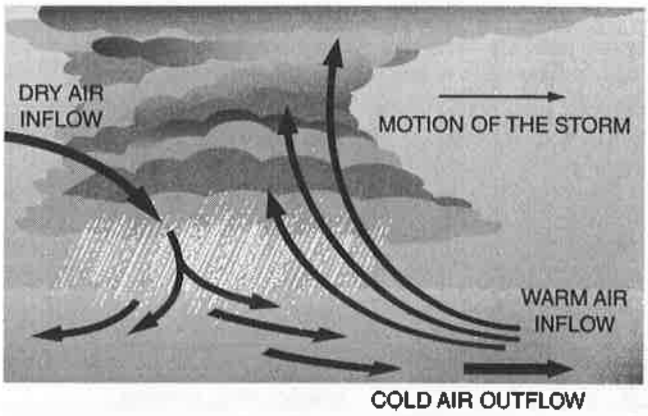


FIGURE 16-22 Air currents in a storm front.

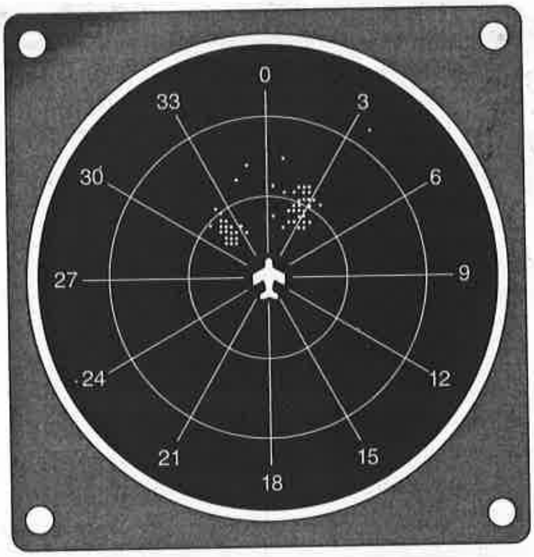


FIGURE 16-23 Weather mapping system displays.

This is accomplished by employing a loop antenna and a sense antenna in a manner similar to the way they are used for an automatic direction finder (ADF). Both antennas are typically contained in one streamlined unit that employs no moving parts. The loop antenna is electronically (not physically) rotated. The distance to the storm activity is determined by measuring the strength of the electromagnetic RF signal created by the static discharge.

Typical weather displays are shown in Fig. 16-23. Another type of weather mapping display uses a liquid crystal to show the location of the storm activity. With this display the screen is divided into quadrants, and each quadrant shows the color green, yellow, or red to identify the level of storm activity in that area. The computer/processor, display unit, and antenna of a typical weather mapping system are shown in Fig. 16-24. The controls of this weather mapping system are mounted on the front of the display unit.

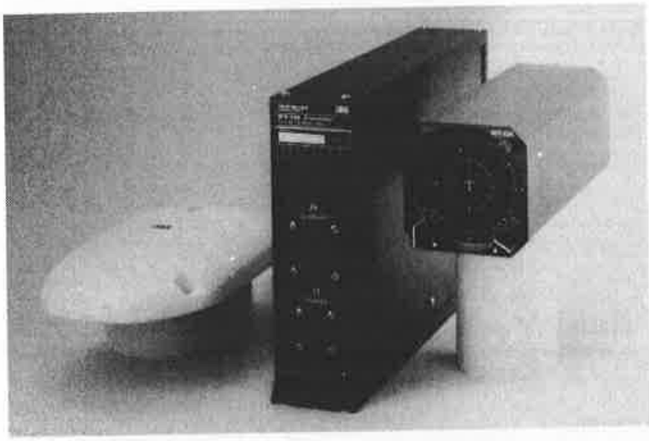


FIGURE 16-24 Lightning detection system display.

AVIATION SATELLITE WEATHER

Today, pilots flying all types of aircraft have an alternative to onboard weather radar systems. XM Satellite Radio (XM) provides subscription-based weather radio service commonly used on aircraft. The XM WX weather service (as it is known) has become extremely valuable to the aviation community because it requires a minimal amount of airborne equipment. Simple controls, a satellite antenna, and a receiver/processor are all that is required; the weather information would then be displayed on the MFD or ND currently installed on the aircraft. The versatility and relatively low cost of the XM satellite weather service coupled with the multitude of hand-held and onboard display options has made this weather system extremely popular with many pilots as well as sailors and the general public.

The airborne XM WX service does not actually monitor weather itself; instead the system receives National Aviation Weather Radar (NEXRAD) through the satellite downloads using simple RF signals similar to the XM audio broadcasts. The systems do respond a bit slower than onboard radar; however, since most light aircraft travel at relatively slow speeds, the slow refresh rate is perfectly acceptable. The cost of XM WX equipment and monthly service is minimal compared to the cost of onboard weather radar; not to mention that radar systems cannot easily be installed on light single-engine aircraft. This makes satellite weather a perfect choice for many pilots.

The ground-based XM WX weather facilities simply analyze, synthesize, and transmit NEXRAD Doppler radar information to a series of satellites above the United States; these satellites then relay the information back toward earth. If the aircraft is properly equipped, the MX signal enters a top-mounted antenna, the information is processed by the XM receiver, and the information is converted to a traditional radar image and presented on the display.

The XM weather shows seven levels of precipitation across the country, revealing nested storms, and widespread, fast-changing convective activity. Unlike airborne radar, which scans a limited range, NEXRAD shows a big picture which provides a valuable tool for pilot decision making. XM WX can even be activated on the ground so the pilot can get the latest weather information before the flight even begins. Of course, the airborne XM weather equipment allows the pilot to zoom in/out as desired. The XM system also provides the ability to "look through" large storm activity; this is a limitation of most airborne weather radar. The system also delivers lightning patterns showing strikes over a 5-minute time period.

GROUND PROXIMITY WARNING SYSTEMS

Through an extensive study conducted in the 1960s, it became apparent that many aircraft accidents were caused by controlled flight into terrain (CFIT). This occurs when the aircraft has no malfunctions, and the pilot is totally capable of avoiding a crash; however, the plane literally "flies into the ground." It was determined that in most cases the pilot was simply unaware of the dangerously low altitude. The FAA concluded that CFIT could be minimized through use of a terrain awareness warning system (TAWS). Today there are basically two variations of TAWSs; the **ground proximity warning system (GPWS)** and a more advanced version known as enhanced ground proximity warning system (EGPWS).

Early ground warning systems were found only on commercial aircraft; however in most countries today, some form of TAWS is required on all turbine-powered aircraft containing six or more passenger seats. The GPWS is a simple system consisting of an antenna, processor, and display unit. The system requires no control panel because it is always active during flight. The display can be a dedicated GPWS unit or integrated into one or more electronic flight instruments. The GPWS r-t unit creates a short RF pulse, which is transmitted toward the ground by the downward-facing directional antenna. The processor unit then waits for a return of the RF as it is reflected off the ground back toward the aircraft. The antenna receives the reflected portion of the signal; the r-t unit simply uses time calculations to determine aircraft altitude. This process repeats many times a second to update altitude data. Most systems operate up to approximately 2500 ft above ground level (AGL); above this altitude there is little possibility of a ground strike. The GPWS often works in conjunction with the aircraft's radar altimeter; these systems will be described in the next section.

The **EGPWS** employs advanced processing circuitry to constantly predict the aircraft's risk of ground impact. The EGPWS must therefore know aircraft altitude, airspeed, and what ground level lies ahead (see Fig. 16-25). To perform these predictions, the EGPWS processor must receive information on (1) the aircraft altitude above the ground, (2) the airspeed of the aircraft, (3) the specific position of the aircraft on the earth's surface, and (4) the local terrain around the aircraft. The EGPWS is truly an integrated system; the processor receives input from a variety of aircraft systems and sensors, employs an extensive database of local terrain, and outputs all warnings through a central display and warning system (see Fig. 16-26). In the event the EGPWS determines a potential ground impact, the system creates both an audio and visual warning on the flight deck. In most cases, EGPWS will provide an audio message related to the impending danger of the situation. For example, if the computer detects a potential ground strike, an automatic audio message "TERRAIN PULL UP" will be repeated until the condition is corrected. These warnings are of very high priority and in almost all cases the pilot must follow the recommendations of the EGPWS.

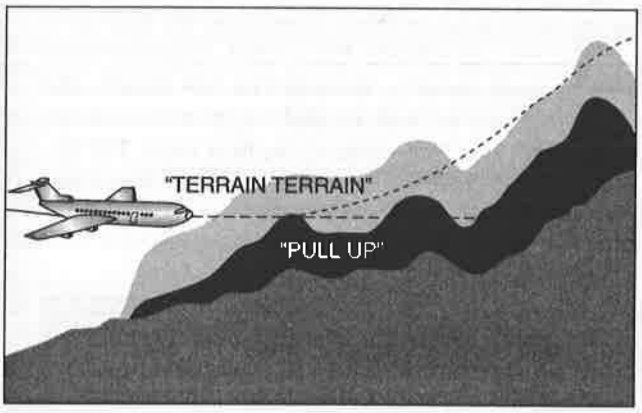


FIGURE 16-25 Enhanced ground proximity warning systems know the terrain in front of the aircraft and provide warnings as needed.

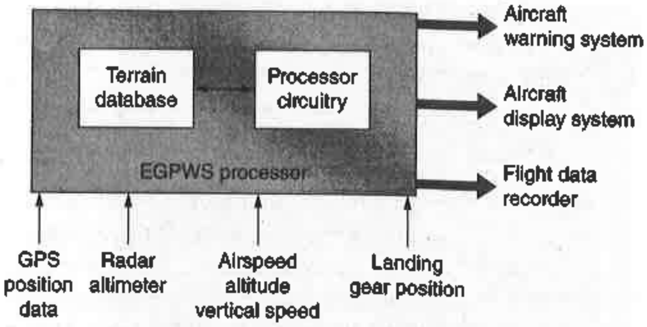


FIGURE 16-26 Major elements of an enhanced ground proximity warning system (EGPWS).

Radar Altimeters

Radar altimeters were developed to give an accurate indication of aircraft altitude above ground level (AGL). These altimeters provide the AGL accuracy not found in conventional pressure-sensitive altimeters. The radar altimeter shown in Fig. 16-27 contains three units: the antenna, the receiver-transmitter, and the altitude indicator.

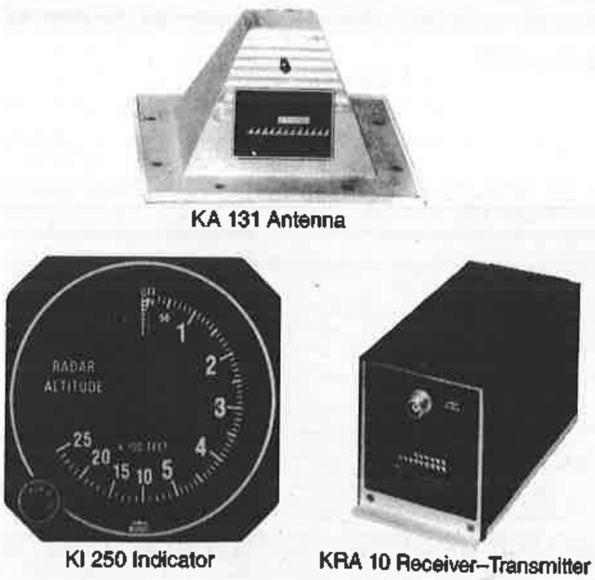


FIGURE 16-27 Components of a radar altimeter. (*Bendix King by Honeywell.*)

Radar altimeters obtain their accuracy by constantly measuring the aircraft's height above the ground. By transmitting a VHF signal downward from the aircraft and receiving the reflected signal, a radar altimeter can determine the aircraft's AGL altitude. The time required for the transmitted signal to reach the ground and return to the aircraft is measured by the receiver-transmitter unit. The unit performs the calculations needed to send the corresponding signal to the altitude indicator, located on the instrument panel. The indicator is typically calibrated in feet from 0 to 2500. A decision height (DH) light is often incorporated on the altitude indicator to aid the pilot during an instrument approach. If the decision height is properly set, then when the DH light illuminates, the pilot must decide either to proceed with the landing or to execute a missed approach.

TRAFFIC COLLISION AVOIDANCE SYSTEM (TCAS)

The system designed to help prevent midair collisions is called the traffic alert and collision avoidance system; although it is more commonly known by the acronym **TCAS** (pronounced T-KAS). This fully independent and automated system monitors the airspace around an aircraft for other traffic; if a potential threat occurs, the system creates an audio and visual flight deck warning of a potential midair collision (see Fig. 16-28). TCAS relies on the installation of an ATC transponder in order to monitor nearby aircraft. As discussed earlier, a transponder is a receiver-transmitter unit that continually broadcasts altitude, airspeed, and other critical information about that aircraft. Only transponder-equipped aircraft will be detected by TCAS; therefore, the FAA requires a working transponder on all high-speed aircraft and all aircraft operating in crowded airspace such as near major airports. In the United States and most other countries, TCAS is required for all civilian aircraft which carry 19 or more passengers.

There are two basic levels of TCAS equipment, **TCAS I**, typically used by general aviation aircraft and **TCAS II** used by larger aircraft. TCAS I monitors the approximately 40 mi of airspace around the aircraft and provides a synthesized audio voice, "TRAFFIC, TRAFFIC," if the system determines a hazard. The pilot must then establish a connection with any threat and take evasive maneuver as needed. TCAS II is a more elaborate system and provides more information

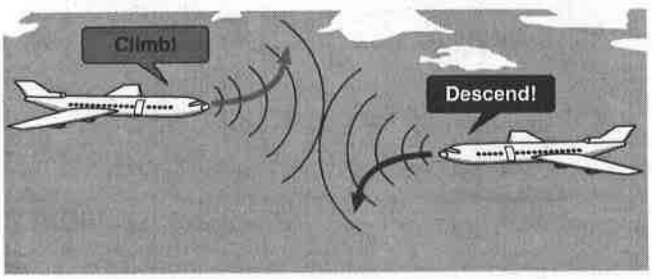


FIGURE 16-28 The basic concepts of TCAS.

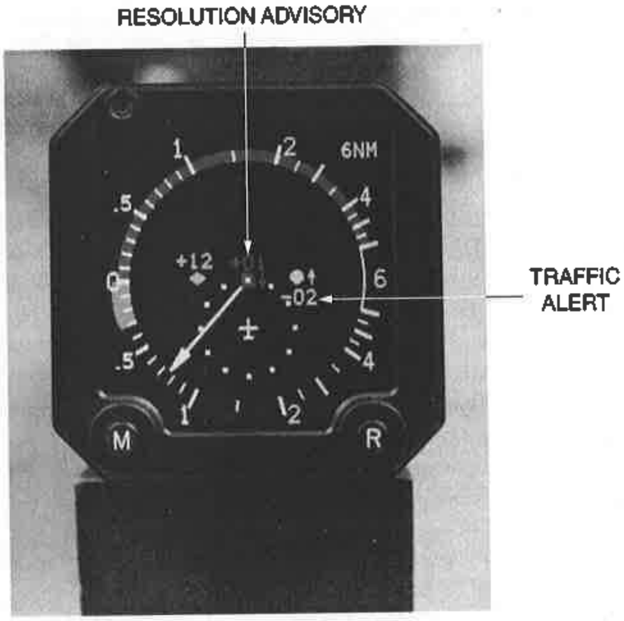


FIGURE 16-29 TCAS display.

to the pilot; both systems operate on the same basic principle. Version 7.0 is the newest update to TCAS II and is required in certain types of airspace. TCAS II 7.0 provides vocalized instructions to avoid danger, known as a "Resolution Advisory" (RA). Audio warnings include: "DESCEND DESCEND," "CLIMB CLIMB," or "ADJUST VERTICAL SPEED ADJUST" (meaning reduce vertical speed). Early TCAS employed a stand-alone display as seen in Fig. 16-29. On many aircraft, the stand-alone TCAS display is eliminated and visual warnings are shown on the integrated display system.

The operation of TCAS involves communication between all aircraft within a certain area, or "envelope," as seen in Fig. 16-30; please refer to this diagram during the following discussion. For the purpose of simplicity the illustration shows only two aircraft, called the **target** and the **intruder**. Both aircraft must be transponder-equipped; these transponders send an interrogation/response several times each second in order to identify aircraft positions and predict a potential hazard. The onboard transponders must be capable of mode C which provides altitude information and/or mode S which transmits a unique 24-bit identifier assigned to each aircraft. In effect, the TCAS equipment on each aircraft "talks" to each other and determines if a potential collision might occur. If a threat is identified, the equipment automatically negotiates avoidance maneuvers between all conflicting aircraft. The TCAS software processor uses complex formulas which are based on aircraft altitude, speed, and the flight path of all aircraft within the TCAS protection envelope.

In the example, Fig. 16-30, the operation of TCAS will be presented from the perspective of the target aircraft. At position A, the intruder is less than 4 miles ahead of the target aircraft and flying at the same altitude. Since position A is within the surveillance area of the target aircraft's TCAS, the intruder will be presented on the TCAS display, but no warning will be issued. If the intruder progresses to

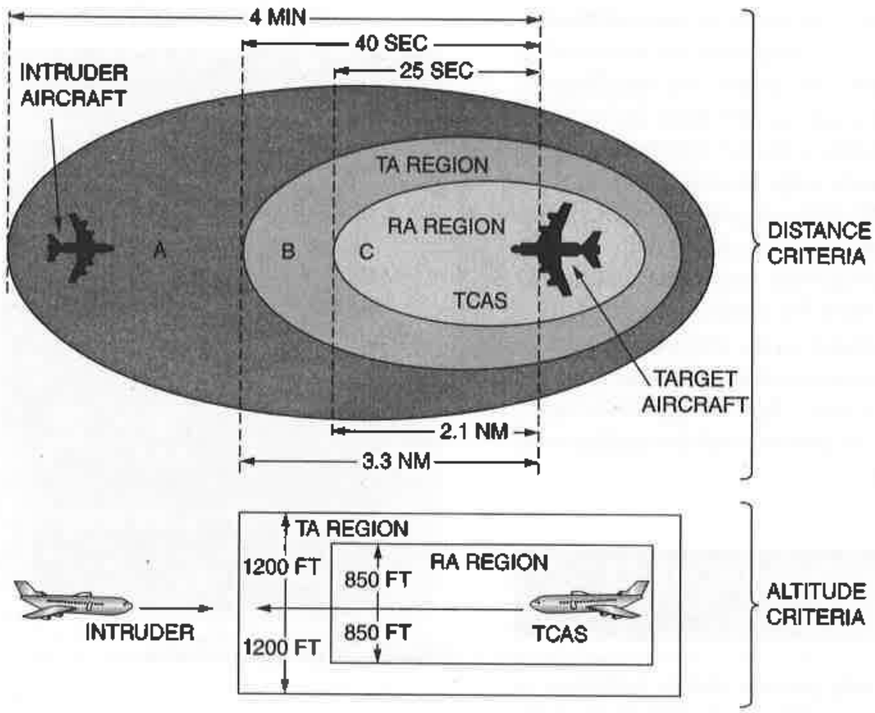


FIGURE 16-30 TCAS surveillance envelope.

point B, it is now in the **traffic advisory (TA)** region of the target aircraft. The TA is the first level of alert and presented to the pilot in form of the word **TRAFFIC** displayed in yellow on the TCAS display, ND, or MFD, and the aural voice annunciation "TRAFFIC TRAFFIC." If the intruder moves to position C on the diagram, less than 25 sec to a collision with the target aircraft, the intruder has moved into the **resolution advisory (RA)** region. The RA is the highest level of TCAS alert. Its purpose is to resolve a conflict by providing the pilot with aural and visual pitch commands. A typical RA will include an audio alarm "DESCEND DESCEND" and TCAS will show TRAFFIC in red on the display. This has been a simplified explanation of the parameters which cause TCAS alerts; the actual algorithms calculated by the TCAS processor take into consideration additional information; for example, the TA and RA regions for any situation may change with aircraft speed and aircraft altitude. According to flight regulations, a pilot must follow the instructions of any TCAS message; even if TCAS causes the pilot to deviate from air traffic control instructions. There are only two higher priorities than TCAS when it comes to pilot instructions; they are a stall warning and ground proximity warning.

REVIEW QUESTIONS

1. What is meant by the word *radar*?

2. Explain how a radar signal can be used to detect storm activity.

3. Why must a radar pulse rate be slow enough so that the return signal is received before the next pulse is emitted?

4. How may the distance of an object from an aircraft be determined by radar?

5. Compare the power of an individual radar pulse with the average power of the system.

6. Name the principal units of a typical radar system.

7. Describe the functions of a synchronizer, mixer, magnetron tube, and duplexer.

8. What devices commonly serve as the indicators for a radar system?

9. Why is a waveguide system required in a radar receiver-transmitter unit?

10. What is the purpose of the antenna stabilization system?

11. What is the value of a tilt control?

12. What technology has made it possible to develop very lightweight radar systems?

13. What two types of antennas are available for radar systems?

14. What are the advantages of a flat-plate antenna?

15. Describe the function of the parabolic and flat-plate antenna system.

16. What colors are used to indicate the levels of storm activity on a color radar indicator?

17. What is wind shear?

18. What type of radar systems are capable of detecting wind shear?

19. Describe the operation of a Doppler radar system.

20. List inspections that should be made regularly on a radome.

21. What are common materials used in the construction of radomes?

22. What precaution must be taken with respect to painting a radome?

23. What may happen if water is trapped between lamination of the radome structure?

24. Describe safety precautions that must be observed in the operation of radar on the ground.

25. Why is it important to make sure the radar is off before supplying power to the aircraft bus?

26. Describe the principle of operation for a lightning detection system.

27. Describe the 3-D weather radar called *IntuVue*.

28. How are satellite weather systems made available to aircraft?

29. Describe the operation of TCAS.

30. Describe what occurs when the airborne TCAS equipment detects a threat aircraft.

31. What function does a radar altimeter perform?

32. Explain the advantages of a radar altimeter.

33. What is the purpose of a ground proximity warning system?

34. Define a *TCAS resolution advisory* and *traffic advisory*.

Instruments and Autoflight Systems 17

INTRODUCTION

Instruments of one sort of another have been used on aircraft for over a century. Today's instruments rely on electromagnets, electronic control circuits, and even computer processors for operation; a major change from the early days of aviation. The first aircraft were designed without electrical systems; these planes used only mechanical instruments. Eventually planes carried batteries and used generators for power; at this time newer electrical instruments were designed to replace the heavier, less reliable mechanical systems. Today the most modern aircraft employ digital technologies and LCD flat panels for the display instrumentation. The "electronics revolution" has truly transformed aircraft instruments into highly reliable and more versatile systems that also improve pilot efficiencies and reduce the aircraft's overall weight.

Today even the simplest aircraft must contain a variety of instruments; larger complex aircraft monitor hundreds of systems and use high-tech displays. The use of computerized instrument systems allows information to be displayed "as-needed"; this concept helps to simplify the flight deck and improve pilot awareness when a system fault occurs.

Instruments are needed to measure pressures, temperature, altitudes, velocity, current, voltage, and numerous other conditions or parameters affecting the flight and operation of aircraft. Human beings are unable to react rapidly and accurately to the many variable conditions that affect the flight of an airplane unless they have accurate and reliable instruments.

On modern aircraft the entire autoflight system relies on electronic signals from a variety of flight instruments for proper operation. The use of electric instruments provides a commonality between the instrumentation system and the automatic flight control systems (autopilots). Modern autoflight systems monitor hundreds of navigation, engine, and airframe parameters. This is made possible through the use of onboard computer systems and electronic instrumentation.

It is the purpose of this chapter to present the basic principles of electrically operated instruments and automatic flight control systems. The principles discussed in this chapter will provide a framework upon which a technician can build an understanding of any instrument or autoflight system.

RPM-MEASURING INSTRUMENTS

An rpm indicator, or **tachometer**, is a most essential instrument in all aircraft. It is used to show the rpm of reciprocating engines, the percentage of power for turbine engines, the rpm of helicopter rotors, and the rotational speed of any other device where this information is critical. A typical tachometer for a reciprocating engine is shown in Fig. 17-1.

Since a tachometer registers engine rpm, it is a primary indicator of engine performance. An electric tachometer gives the same indications that are given by a mechanical tachometer, but the method for actuating the indicating unit is entirely different.

FIGURE 17-1 Tachometer for a reciprocating engine.

AC Tachometer

The ac tachometer system in most common use consists of a three-phase ac generator (alternator) and the tachometer indicator, which is driven by the alternator. The indicating mechanism consists of a mechanical tachometer driven by a three-phase synchronous motor.

The alternator, or transmitter, is directly coupled to the engine in order to measure rpm; the unit consists of a four-pole permanent magnet that rotates inside a three-phase stator. The stator of the alternator is connected by three wires to a similar stator in the synchronous motor, which operates the indicator. As the alternator is driven by the engine, the rotation of the permanent magnet induces a three-phase current in the stator. This current flows through the stator of the synchronous motor in the indicator and produces a rotating field that turns at the same rate as the alternator rotor. The permanent-magnet rotor of the indicator keeps itself aligned with the rotating field and hence must also turn at the rate of the alternator rotor.

The synchronous motor in the indicator is directly coupled to a cylindrical permanent magnet that rotates inside a drag cup, as shown in Fig. 17-2. As this magnet turns, it causes magnetic lines of force to drag through the metal cup and induce eddy currents in the metal. These eddy currents produce magnetic fields that oppose the field of the rotating magnet. The result is that as the speed of the rotating magnet increases, the drag or torque on the drag cup increases. The torque on the drag cup causes it to rotate against the force of the balancing hairspring and turn the pointer on the indicating dial. The distance through which the drag cup rotates is proportional to the speed of the synchronous motor; hence it is also proportional to the engine speed.

Modern electronic tachometers may use a frequency counter circuit to determine engine rpm as shown in Fig. 17-3. The rpm sensor in this circuit is a single-phase ac generator which produces a variable frequency ac output. The frequency is a function of engine rpm; the faster the engine turns, the higher the frequency. The variable frequency alternating current is sent to a frequency counter circuit that literally "counts" each ac pulse and converts the information into a digital signal. The digitized rpm data is then sent to an electronic display processor or directly to the display itself. In this system there is no dedicated rpm gauge; the information can be shown as a traditional "round dial" of digital format on a multifunction display. There are also some modern tachometer sensors which connect to the magneto of a piston engine and send an output signal to an engine control processor. The output of the processor is used to create the rpm display on an LCD instrument panel.

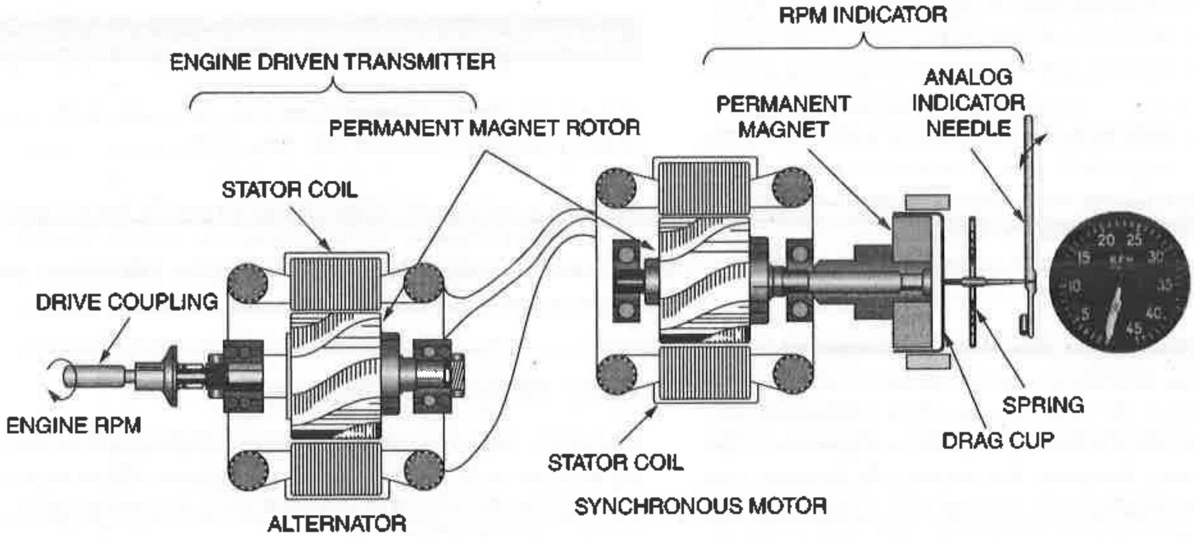


FIGURE 17-2 Three-phase tachometer system.

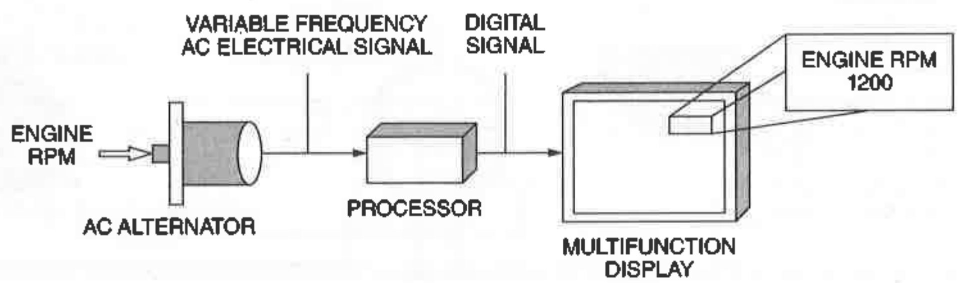


FIGURE 17-3 A frequency counter tachometer.

TEMPERATURE INDICATORS

Thermocouple Temperature Indicators

Thermocouple temperature indicators are used most frequently when it is necessary to measure comparatively high temperatures. They are used to measure cylinder head temperature in aircraft with reciprocating engines and tailpipe or exhaust temperature in aircraft with jet engines. The readings of these instruments provide information for the pilot or an engine control computer that operates the engine at its most efficient temperature. As explained in Chaps. 1 and 8, a thermocouple temperature indicator operates on the thermoelectric effect. A thermocouple consists of two dissimilar metal wires joined together at one end as seen in Fig. 17-4. This junction is called a **sensing** or **hot junction.** The two wires are terminated at the other end, called a **reference** or **cold junction.** The cold junction is maintained at a known constant reference temperature. When a temperature difference exists between the sensing and reference junction, a voltage is produced and current will flow in the circuit. When a meter or other instrument is connected to the reference junction, the meter indication will be proportional to the temperature difference between the hot and reference junctions. The magnitude of the voltage produced depends on the wire material used and also on the temperature difference between the junctions.

For long life, thermocouple is typically placed in a protecting tube. In most cases, the protective tube is both chemically inert and vacuum tight to prevent chemical reactions or deterioration from moisture. All connections to a thermocouple must be made using special wires of a specific length, called compensating wires. The measurement is very accurate when compensating wires are of the same materials as those used to produce the thermocouple.

Thermocouple Leads

In accordance with Ohm's law, the emf generated in a thermocouple circuit produces a current inversely proportional to the resistance of the circuit at any given temperature difference between the hot junction and the cold junction. That is, if the resistance increases, the current will decrease; and if the resistance decreases, the current will increase. For this reason all thermocouple leads must be made with a specific resistance.

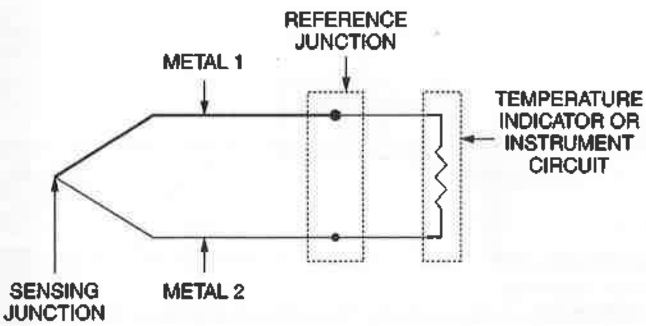


FIGURE 17-4 Diagram of a thermocoupler circuit.

Thermocouple leads are usually made of either constantan and iron or constantan and copper. Constantan is a copper-nickel alloy that shows practically no change in resistance with considerable changes in temperature. Thermocouples that are designed to measure high temperatures are composed of Chromel and Alumel, which are special high-temperature alloys. Typically, thermocouple leads are made of the same alloy as the thermocouple hot junction.

When a thermocouple instrument is installed, it is essential that the correct leads be used. Standard thermocouple leads have resistances of 2 and 8 Ω, and the instrument must be provided with the type for which it is designed. Because of the very small amount of electric energy produced by a thermocouple, the electrical connections must be clean and tight. Furthermore, it is absolutely essential that the leads not be crossed during installation. Iron must be connected to iron, constantan to constantan, copper to copper, Chromel to Chromel, Alumel to Alumel, etc. Usually, thermocouple leads are provided with connectors that make it impossible to connect them in reverse; however, it is always wise to examine the leads closely to make sure that the connections have been correctly made.

Since thermocouple leads are made with a specific resistance, they must never be cut or spliced. If there is extra length in the leads, they should be coiled up to take up the slack and secured.

SYNCHRO SYSTEMS

A synchro system is designed to measure an angular deflection at one point and reproduce this same deflection at a remote point. Synchro systems have been designed to employ both alternating current and direct current for power, but the present trend is to employ 400-Hz alternating current. Synchros are used as position indicators, for remote indications, for autopilots and other remote-control and automated systems.

Early DC Synchro Systems

One of the early dc synchro systems was often used to show the position of the wing flaps and landing gear. The dc instrument system consists of an indicator and a transmitter operating in synchronization.

A schematic diagram of a dc synchro system is shown in Fig. 17-5. The transmitter is merely a winding of fine resistance

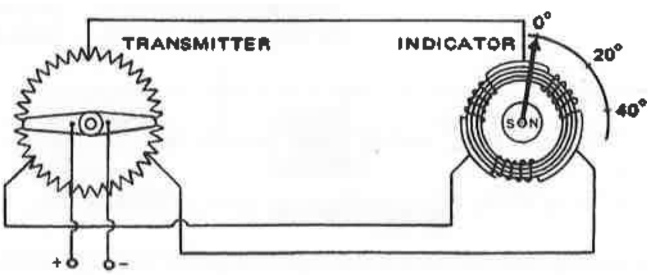


FIGURE 17-5 Schematic diagram of a dc Selsyn circuit.

wire on a circular form with connections located at three equally spaced points around the winding. DC power is fed to the ring winding at points 180° apart by means of wiper arms (see Fig. 17-5). This arrangement is actually a special type of potentiometer, and when the wiper arms are rotated, the voltages appearing at the three connections will change with respect to one another. As shown in the diagram, the three connections to the transmitter are connected to three similar connections at the indicator. The indicator unit consists of a laminated ring of ferromagnetic material on which three windings are equally spaced in a delta connection. When this unit is connected to the transmitter by means of three conductors as shown in the diagram, rotation of the wiper arms in the transmitter will vary the currents in the coils of the indicator in such a manner that the magnetic field of these coils will rotate also. The rotating element of the indicator is a permanent-magnet armature mounted on bearings so that it is free to turn with the rotation of the field. Thus the indicating needle attached to the rotor shaft will follow the movement of the wiper arms at the transmitter. When the transmitter is linked to the flap-actuating mechanism, it will produce a signal that causes the indicator to show the position of the flaps. In like manner, it can be used to show the position of the landing gear or any other unit that moves through a range of positions. This type of synchro system is very prone to errors and malfunctions due to the delicate moving contacts found on the transmitter. DC synchros will only be found on older aircraft.

AC Synchro Systems

On aircraft that have ac electrical systems, an ac synchro could be used; these systems contained no moving contacts as in the dc synchro and are therefore more reliable. The system employed a transmitter, connected to the moving component to be monitored, and a receiver unit or indicator on the flight deck. These systems can be used to determine the position of various moving components, such as flaps, landing gear, and autopilot servo motors. The transmitter will send an output signal to a dedicated instrument or to a processor such as an autoflight computer. The autoflight computer can then use the information to position flight controls as well as send an output to one or more flight deck displays.

When used for the purpose of moving a dedicated analog indicator (meter), the operation is similar to a low-current ac motor, see Fig. 17-6.

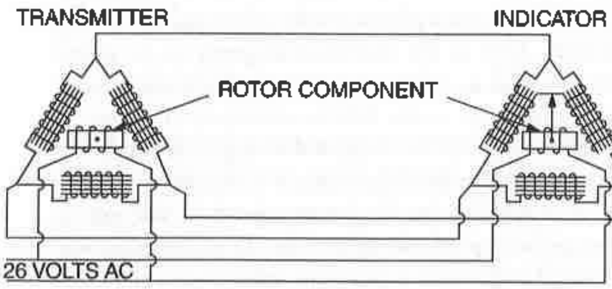


FIGURE 17-6 Schematic diagram of an Autosyn synchro system.

The system is basically an adaptation of the self-synchronous motor principle, whereby two motors operate in exact synchronism; that is, the rotor of one motor spins at the same speed as the rotor of the other. When this principle is applied to this system, however, the rotors neither spin nor produce power. Instead, the rotors of the two connected units come into coincidence when they are energized by an alternating current, and thereafter the rotor of the first indicator moves only the distance necessary to match any rotation of the transmitter, no matter how slight that movement may be.

It must be understood that the transmitter and indicator of this system are essentially alike, both in electrical characteristics and in construction. Each has a rotor and a stator. When ac power is applied and a rotor is energized, the transformer action between the rotor and stator causes three distinct voltages to be induced in the rotor relative to the stator. For each tiny change in the position of the rotor, a new and completely different combination of three voltages is induced.

When two units are connected as shown in Fig. 17-6 and the rotors of both occupy exactly the same positions relative to their respective stators, both sets of induced voltages are equal and opposite. For this reason no current flows in the interconnected leads, with the result that both rotors remain stationary. On the other hand, when the two rotors do not coincide in position, the combination of voltages of one rotor is not like that of the other, and rotation takes place, continuing until the rotors are in identical positions. The induced voltages are then equal and opposite, and so there is no current flow in any of the three conductors; hence the rotors will be in stationary and identical positions. Since the rotor of the transmitter unit is directly connected to a moving component, such as the wing flaps, the transmitter unit tends to "drive" the indicator into the correct position. The indicator is designed to move easily and precisely according to the position of the transmitter rotor.

Modern AC Synchros

Another version of the ac synchro just discussed is commonly used to provide a positioning feedback signal for modern autoflight systems. This unit employs a stationary primary winding and pivoting secondary winding to measure angular displacement. Figure 17-7 shows the primary winding on the top row of the diagram; this coil receives an input voltage of 26 V 400 Hz ac. As with all transformers, an ac voltage is induced into the secondary, shown on the bottom row of the diagram. The output voltage of the secondary is a function of the angular position of the secondary winding. In position A (Fig. 17-7), the output voltage is equal to the input voltage due to the alignment of the two coils. (*Note*: This example assumes 100 percent efficiency of the electromagnetic induction process.) As the secondary is rotated by the device being measured, the value of the output voltage changes; position B = 20 V ac, position C = 6 V ac, and eventually there is no voltage produced in the secondary winding. When the secondary produces no voltage, it is called the **null position**.

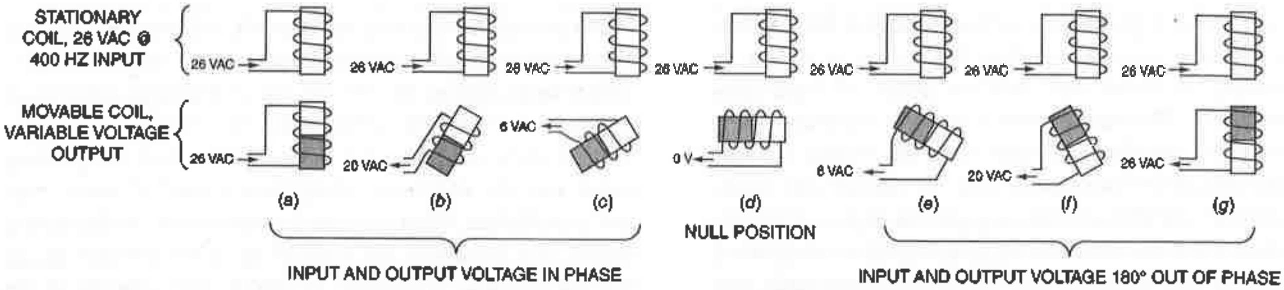


FIGURE 17-7 Operation of a typical feedback synchro.

As the secondary passes through the null position, there is a shift in the phase relationship between the ac input voltage and the ac output voltage. As the diagram illustrates, in positions A to C the input and output are in phase, at position D there is no output voltage, and at positions E to G the input and output are 180° out of phase. Due to this phase shift, the null becomes the most sensitive position for the synchro device; therefore, any rotational movement from the null provides the most accurate output signal.

AC synchros provide excellent feedback for much of the autopilot system. The phase-shift principle, discussed above, allows for accurate measurements of even small control surface movement. When placed in the null position, any movement clockwise or counterclockwise is easy to measure due to the phase shift and voltage change. On most systems, the secondary coil contained within the synchro rotor is connected to the moving component through a mechanical linkage; the synchro output signal therefore is directly related to any component movement.

Most synchro sensors are very reliable because they are simply wire coils and seldom fail. Items which typically cause problems are the moving components; secondary pivot bearings can fail or become worn. Also any mechanical linkage used to connect the synchro can fail, bind, or become misadjusted creating inaccurate output signals. On many systems, adjustment of the synchro to the null position is critical for proper operation. Many autopilot servos drive the synchro to the null position prior to activating the autoflight system. This can easily be done through the use of an electric clutch to engage/disengage the synchro as needed for positioning. This alignment procedure ensures that the synchro begins in the null position each time the autopilot is engaged.

Instrument Sensors

Modern aircraft are designed to collect large quantities of data; in some cases, this data is processed and converted into information shown on a flight deck display. In other cases, the data is shared between various computers and used for aircraft or systems control. There are two common sensors found on modern aircraft that have been developed for use with computerized systems; proximity sensors and differential transducers. The **proximity sensor** is a solid-state switching device that is used to determine the position of moving components, such as flaps, cargo doors, and landing gear.

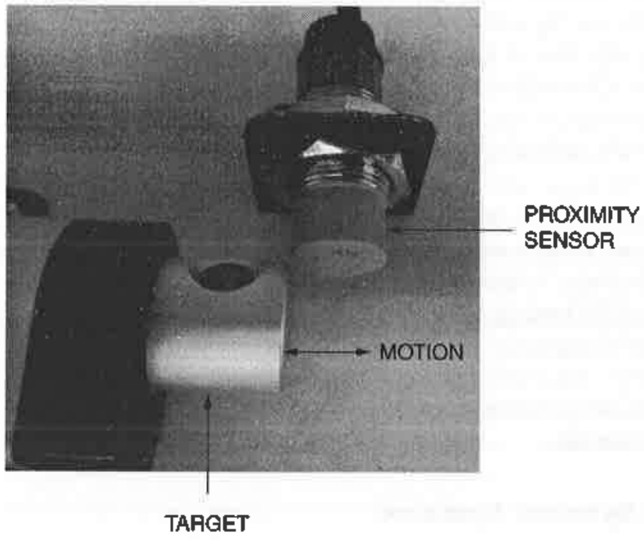


FIGURE 17-8 A typical proximity sensor.

Proximity sensors must perform two main functions: (1) emit an electromagnetic field or a beam of electromagnetic radiation and (2) measure any changes in the emitted field, or return signal, caused by the close proximity of a moving part. Figure 17-8 shows a typical proximity sensor used to detect the position of a common servo actuator. The object being sensed is often referred to as the proximity sensor's **target**; targets made of different materials may require different sensors. For example, a capacitive photoelectric sensor might be suitable for a plastic target; an inductive proximity sensor requires a metal target.

Proximity sensors can have a high reliability and long functional life because of the absence of mechanical parts and lack of physical contact between the sensor and the sensed object. Figure 17-9 is the electrical diagram of a typical proximity sensor. A dc voltage must be applied to the sensor as an input signal; the brown wire is connected to a positive voltage and the blue wire is connected to negative. Inside the sensor, represented by the dotted line, is a switching transistor which is controlled by the sensor circuit. If the sensor detects the proximity of the target, the transistor becomes forward-biased and sends a negative voltage signal to the black output connection. The load is connected between the brown and black connections and therefore controlled

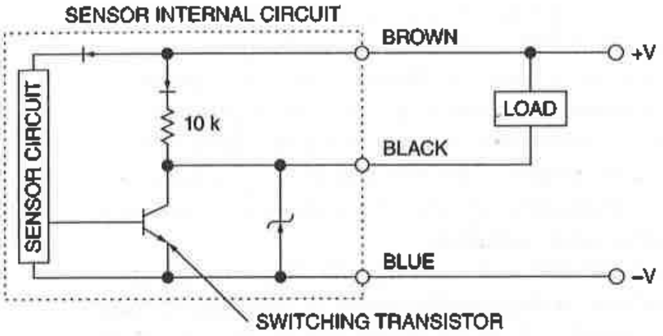


FIGURE 17-9 Proximity sensor circuit.

by the sensor circuit through the switching transistor. The load could be any low-current DC circuit like an input to a landing-gear control computer or motor control relay. More information on proximity sensors can be found in Chap. 13 of this text.

The **linear variable differential transducer (LVDT)** is another common sensor found on modern aircraft; a typical design has three inductor coils placed end-to-end around a tube. The center coil acts as the transformer primary winding, and the two outer coils create the transformer secondary windings. The transformer core is constructed of a ferrous metal and connected to the moving component whose position is to be monitored.

Figure 17-10 shows the operational circuit and physical components of an LVDT. An alternating current is applied to the primary and causes a voltage to be induced in each secondary proportional to the position of the movable core.

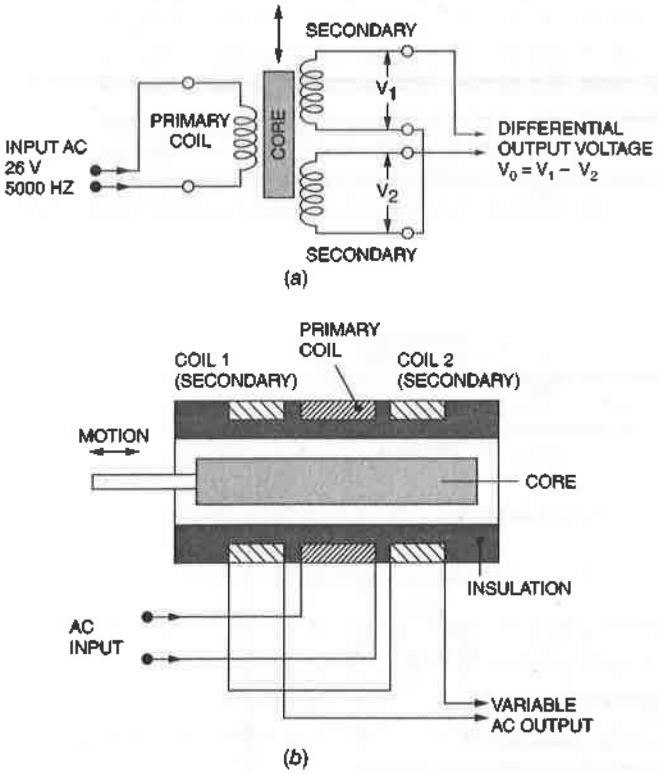


FIGURE 17-10 Linear variable differential transducer (LVDT): (*a*) operational circuit and (*b*) structure.

The ac voltage connected to input of the primary coil is typically a high frequency; approximately 1 to 10 kHz. As the core moves, the magnetic linkage to the two secondary coils changes and causes the induced voltages to change. The coils are connected so that the output voltage is the difference (hence "differential") between the two secondary coils; hence $V_{output} = V_1 - V_2$.

The phase relationship between the ac input and output voltages also changes when the core moves from the center "null" position. At the null position the output voltage is zero. If the core is displaced outward from the null, the resulting output voltage increases from zero and stays in phase with the input. When the core moves in the other direction, inward from the null position, the output voltage also increases from zero, but its phase is opposite to that of the primary. The phase of the output voltage is determined by the direction of the movement (in or out); the amplitude of the output is determined by the amount of movement. The output of an LVDT must be connected to a processor circuit, which can then create a display signal or use the LVDT data for other purposes, such as control of the autoflight system.

Another common transducer used with modern computerized aircraft is known as the **rotary variable differential transducer (RVDT)**. The LVDT and RVDT both operate using the same principles of electromagnetic induction; however, they are used for slightly different applications. The RVDT, as the name implies, is used to monitor the movement of components that rotate. The LVDT detects motion in linear components.

FUEL-QUANTITY INDICATORS

Fuel-quantity indicators for most light aircraft and all large commercial aircraft are either electrically or electronically operated. The electrically operated indicating systems are usually of the variable-resistor type, and the electronically operated systems are of the capacitor type.

Electric fuel-quantity indicators utilize a variable resistor in the tank unit or sensor. The resistor is in the form of a rheostat or potentiometer, depending on the method of indication. The fuel-quantity signal provided as a float arm in the tank changes the resistance of the sensor as the fuel level changes. A schematic diagram of a fuel-quantity-indicating system with a rheostat-type sensor is shown in Fig. 17-11. The variable resistor of the tank unit is connected in a bridge circuit with reference resistors in the indicator case.

In order to ensure the accuracy of fuel-quantity instruments, many fuel-quantity circuits contain **compensator potentiometers**. The compensators are used to make fine adjustments to the fuel gauge when the tank is full and/or empty. The compensation procedure is typically a matter of testing the accuracy of the gauge with a full fuel tank; the potentiometer is adjusted as needed to change the indicated fuel quantity. This test is often performed as part of the aircraft inspection process. Also one more common test during inspections is a resistance test of the fuel-quantity sensor circuit. Since accurate fuel-quantity indications are important to flight safety, these

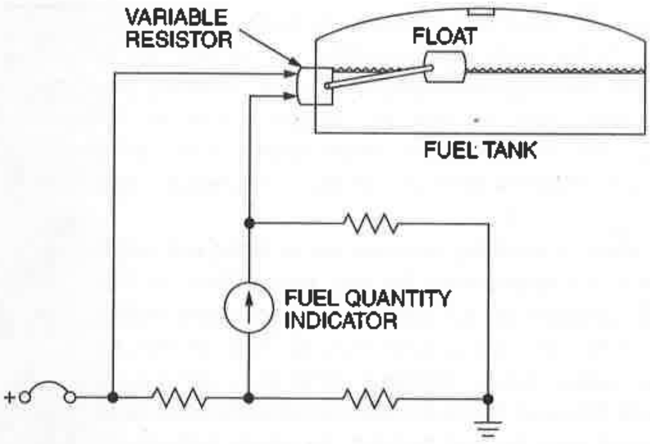


FIGURE 17-11 Schematic diagram of a float-type fuel-level indicator with a variable resistor.

systems are often tested during 100-h, annual, and periodic inspections.

Electronic, or capacitor-type, fuel indicators utilize a variable capacitor as the sensor unit in the fuel tank. The capacitance of the sensor in the tank is changed as fuel rises and falls between the two electrodes (plates) in the tank unit. The change of capacitance is due to the difference between the dielectric strength of the fuel and that of air. Since fuel has a dielectric strength more than twice that of air, the capacitance of the sensor increases in accordance with the amount of fuel in the tank. The change in capacitance of the sensor unit can be sent directly to a fuel-quantity indicator, or sent to a digital circuit for additional processing. A schematic diagram to illustrate the operation of a capacitor-type fuel-quantity-indicating system is shown in Fig. 17-12.

In an actual system in an aircraft, the fuel-quantity-indicating instrument may contain the amplifier or signal conditioner, thus eliminating the necessity for a separate unit installation. The indicating unit for fuel quantity may vary considerably from aircraft to aircraft. Formerly the majority of indicating units utilized a needle-and-scale type of indicator; however, with the availability of solid-state devices, many indicators are now of the digital type. The indication may be in pounds of fuel or in gallons or in both. Capacitor-type systems measure fuel quantity by weight (mass) rather than volume because the dielectric strength of the fuel changes in accordance with density. Compensators are often employed with the probes to assure an accurate indication.

Capacitance fuel probes are typically very accurate; therefore, this type of fuel-quantity sensor is employed on many modern aircraft. On larger aircraft due to the size of the fuel tank, several sensors are located in each tank. The output of each sensor is monitored and an averaged fuel level is determined by the fuel-quantity processor circuitry. In many aircraft, the fuel-quantity calculations are performed by a processor unit which is responsible for multiple functions. The processor uses digital technologies to create the display of fuel-quantity data; typically on a flat panel or CRT display.

ELECTROMECHANICAL FLIGHT INSTRUMENTS

During the last decade, there has been an electronics revolution in the aviation industry. This revolution has had a great impact on the design and operation of the instrument systems found on modern aircraft. Instruments that are mechanically driven with pitot and/or static pressure inputs are still used on many aircraft. For example, most light aircraft still operate using the traditional mechanical instruments. On the other hand, large transport-category aircraft require so much instrumentation that it has become almost impossible to fit all the necessary mechanical instruments in view of the pilot. Also, the newest light aircraft take advantage of digital technologies to save weight and improve flight safety. To simplify the instrument panel, many modern corporate and transport-category aircraft employ electronic instruments

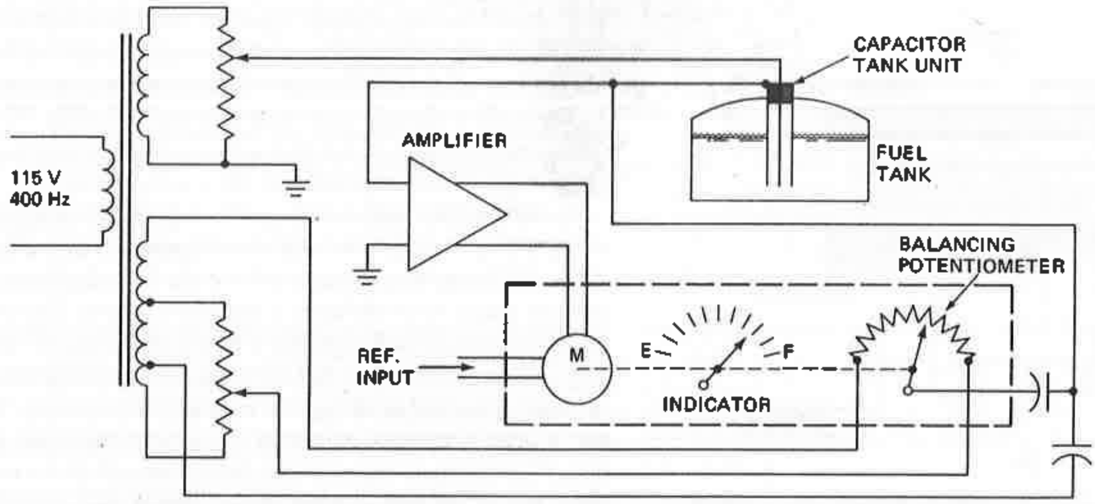


FIGURE 17-12 Schematic diagram of a capacitor-type fuel-quantity-indicating system.

of one type or another. To better understand the electronic instruments, we should review some basic instrument theory.

There are two common electromechanical instruments found on high-performance aircraft that were replicated when the state-of-the-art electronic systems were designed. The **attitude-director indicator** (ADI) and the **horizontal-situation indicator** (HSI) are both hybrid electromechanical components that combine several basic flight instruments. The ADI is used to display the attitude information necessary for flight. The ADI typically includes the attitude indicator, the turn-and-slip indicator, pitch-and-bank steering bars, the glide slope indicator, and a variety of warning flags. Some ADIs incorporate indicators known as **command bars** (Fig. 17-13). The command bars display information from several different attitude and navigational inputs. This system allows the pilot to fly the aircraft using the command bars as the main reference.

The HSI is an instrument that displays information concerning the aircraft's position in the horizontal plane of reference. This instrument combines a variety of conventional components, such as the heading indicator (gyro compass), the course-deviation indicator, and a DME distance indicator.

Typically, the ADI and HSI work in conjunction with the **flight director** system. The flight director system typically consists of an electronic control unit that receives inputs from various navigational systems, attitude gyros,

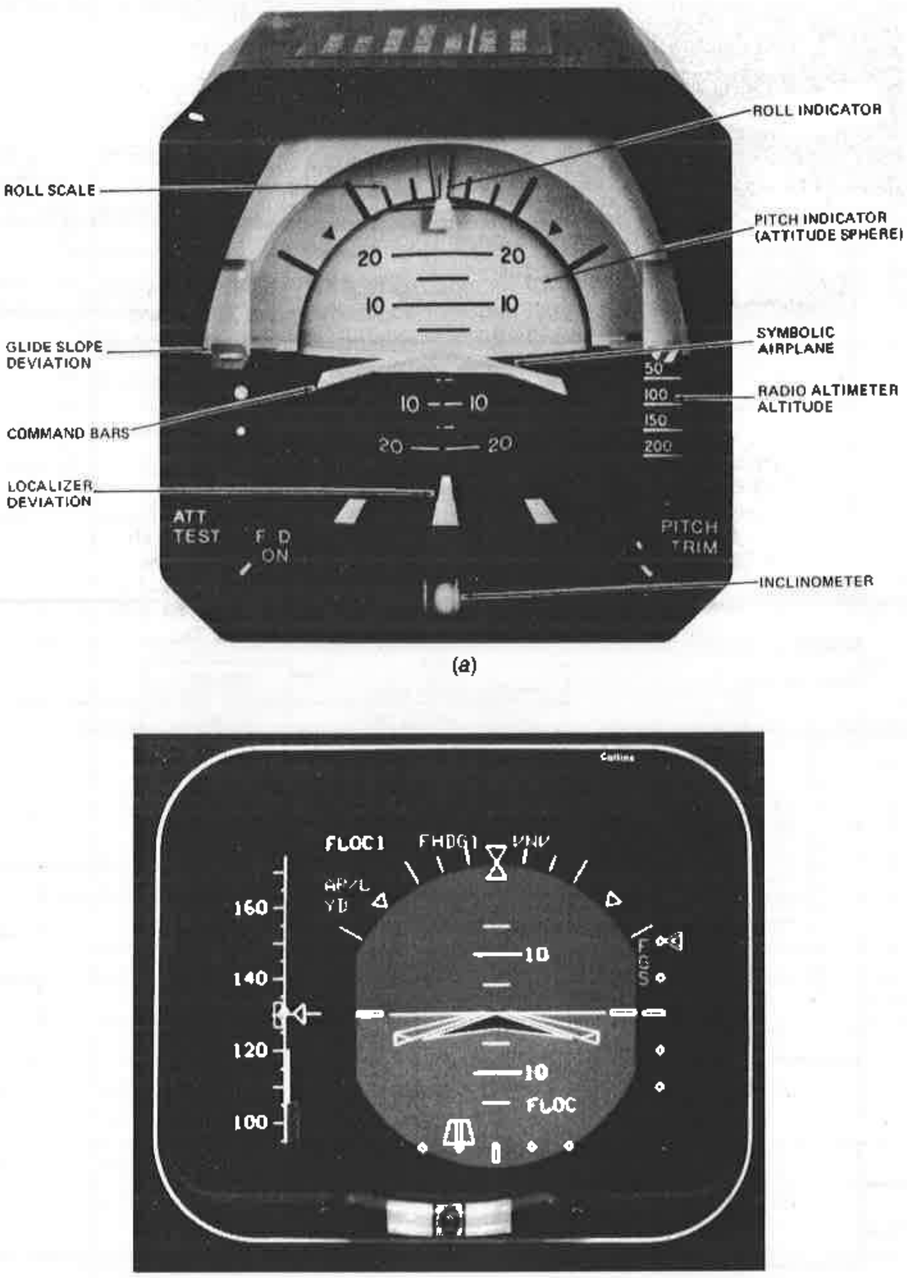


FIGURE 17-13 Two common ADIs: (*a*) an electromechanical ADI (*b*) electronic ADI or EADI.

and pitot static sensors. The flight director computer then processes these inputs and electronically sends the information to the electromechanical ADI and HSI. The autopilot system may also receive information from the flight director computer.

Air-data systems are another type of hybrid electromechanical instrument package. The instruments in these systems display all parameters associated with the aircraft's movement through the air. Newer air-data systems are often used as inputs to the electronic flight instrument systems. The air-data-system computer receives inputs from the various pressure and temperature sensors throughout the aircraft (Fig. 17-14). The air-data computer processes the input data and sends output signals to electromechanical display instruments such as the altimeter, the Mach/airspeed indicator, the vertical-speed indicator, and the temperature indicator. Air-data outputs are also used by various navigational systems.

ELECTRONIC FLIGHT SYSTEMS

In a further attempt to reduce pilot workload and instrument panel clutter, **electronic flight instrument systems (EFISs)** were developed. These systems first appeared as dedicated displays used for flight instruments only. Eventually the display systems become integrated and could be used for indication of a variety of aircraft, engine, weather, flight, and preflight information. Once the display systems became integrated, they were no longer called electronic flight instruments; other terms are used for advanced systems, such as **electronic instrument systems** or **integrated instrument systems**. The first-generation EFIS employ state-of-the-art CRTs to display alphanumeric data and representations of aircraft instruments. Each EFIS display replaces several conventional instruments and caution and warning annunciators.

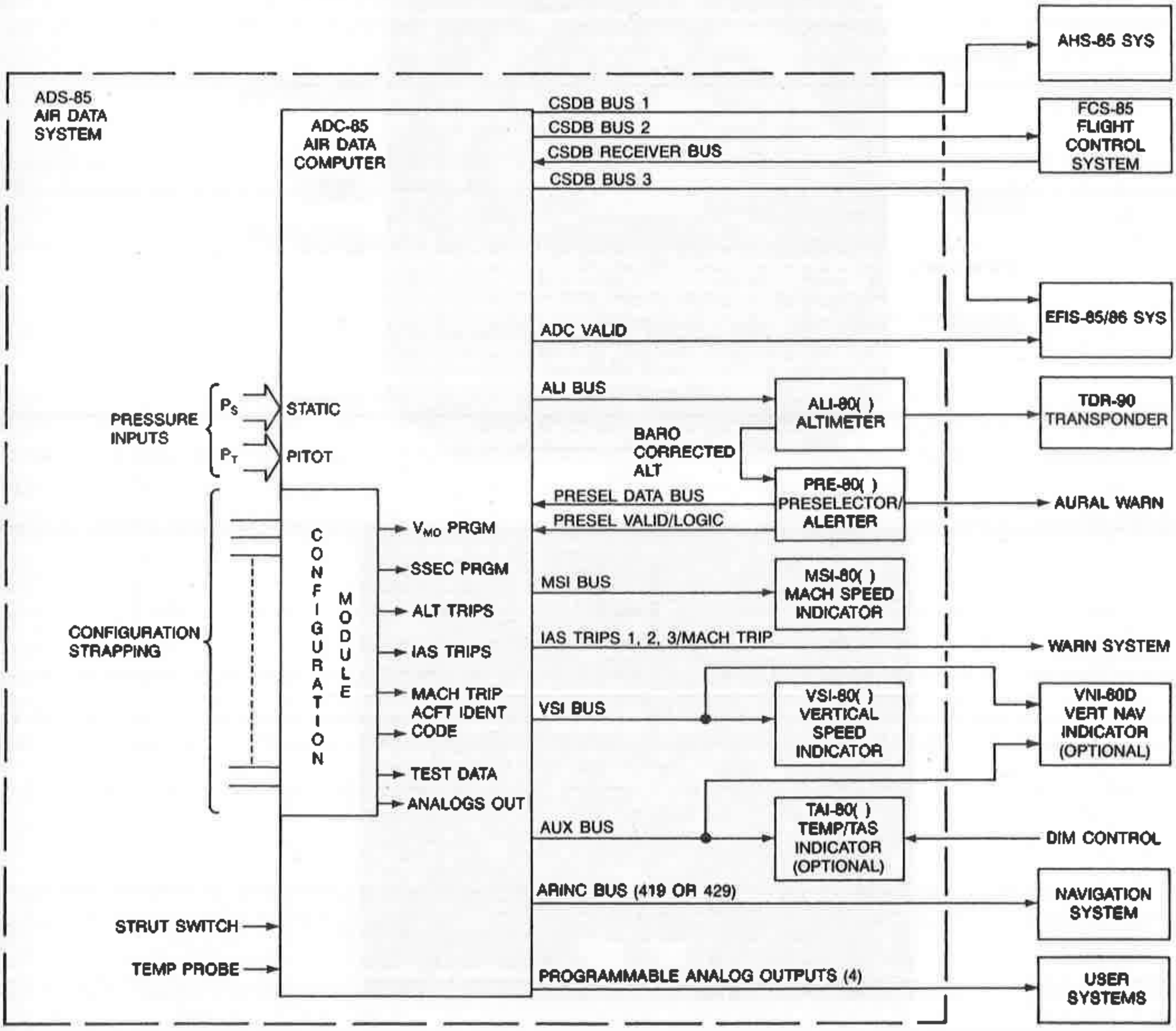


FIGURE 17-14 A typical air-data-system block diagram. (*Collins Divisions, Rockwell International.*)

FIGURE 17-15 The A-320 instrument panel. (*Airbus Industrie.*)

Figure 17-15 shows the instrument panel of an Airbus Industrie A-320. This aircraft employs six CRT displays in order to eliminate most of the separate electromechanical instruments found on traditional aircraft.

Electronic flight instruments became possible with the development of a sunlight-readable CRT display and sophisticated aircraft computer interface systems. A digital data bus system is used to transfer a majority of information between the various components of an EFIS. With large amounts of data to transfer, analog systems would add hundreds of pounds to the aircraft in additional wiring. Several common data bus systems are described in Chap. 7.

Electronic flight instruments used to display horizontal-situation indicators (HSIs) and attitude-director indicators (ADIs) are becoming very popular on all types of high-performance aircraft. An illustration of an **electronic horizontal-situation indicator** (EHSI) is shown in Fig. 17-16*a*, and an **electronic attitude-director indicator** (EADI) is shown in Fig. 17-16*b*.

A common first-generation EFIS is composed of three subsystems, as illustrated in Fig. 17-17: the pilot display system, the copilot display system, and the weather radar system. The weather system provides weather data for either the pilot's or copilot's display system or for both. The pilot's and copilot's display systems are identical, each containing two CRT displays, a symbol generator (sometimes called the processor), a display controller, and a source select panel. In the unlikely event of one system failure, the backup cross-fed circuit allows the operational symbol generator to drive all four electronic displays.

The **symbol generator** (SG) receives input signals from several aircraft and engine sensors, processes this information, and sends it to the appropriate display. Inputs to the symbol generator include data from the various navigation radios, flight control computers, thrust management computers, the inertial reference system, and the weather radar system.

Another version of the EFIS found on many corporate aircraft is shown in Fig. 17-18. This system incorporates two EADIs and two EHSIs, one each for the pilot and copilot. These four tubes are referred to as the **primary displays.** The term *tube* is often used to refer to the *display.* The right-side electronic displays receive data inputs from the right-side **display processor unit** (DPU). The left-side displays receive data from the left DPU. The DPUs receive data inputs directly from the aircraft systems and from the **multifunction processor unit** (MPU). Figure 17-19 shows an operational EADI and EHSI. In the event of one primary display failure, the system can be switched into the **reversionary mode**, which allows one tube to display a compact form of both the ADI and HSI.

The **multifunction display** (MFD), typically located in the center console of the flight deck, is used as the fifth display of the system. An EFIS with an MFD is often referred to as a **5-tube EFIS**. The MFD unit is typically installed in the location reserved for the radar display and is therefore accessible to both members of the flight crew. The MFD is different from the other two displays in that it contains its own power unit, checklist data file, and display controls. During a normal flight, the MFD will display navigation and weather radar information. In the event of a system malfunction, the MFD can be used as a backup for the primary displays. The MFD will also display diagnostic information. The MFD receives its display information from the multifunction processor unit (MPU).

The MPU, typically located in the avionics rack, receives input signals from the various aircraft sensors on both the right and left sides of the aircraft. Weather input data are received from the weather radar r-t unit. As shown in Fig. 17-18, the MPU communicates with both the right and left DPUs as well as the MFD. The MPU can supply input data to the right or left DPU in the event of a sensory data failure to a DPU.

A variety of electronic flight instrument systems are available today, each with its own distinguishing characteristics. A variety of data bus systems are used for information transfer between EFIS components. Before troubleshooting, always become familiar with the particular system on the aircraft. Most EFISs do include some type of built-in test equipment (BITE). Diagnostic data from the BITE are often accessible from one of the electronic displays.

Some of the more common failures that occur in an EFIS are caused by wiring problems. Connector plugs often become loose or corroded and cause an intermittent or constant failure. Before replacing the various line replaceable units (LRUs) in the system, always check the system wiring. The LRUs have an extremely high average time before failure. Therefore, it is unlikely that swapping an LRU will solve the problem. LRUs do fail; but efficient troubleshooting means checking the wiring and system sensors before sending an LRU to the repair shop.

On most EFISs the left and right components are interchangeable. If this is the case on your aircraft, simply remove the suspect LRU, and replace it with the same unit from the other side of the aircraft. **Always be sure the LRUs are compatible before swapping, and always remove power from the system before removing or installing any unit.**

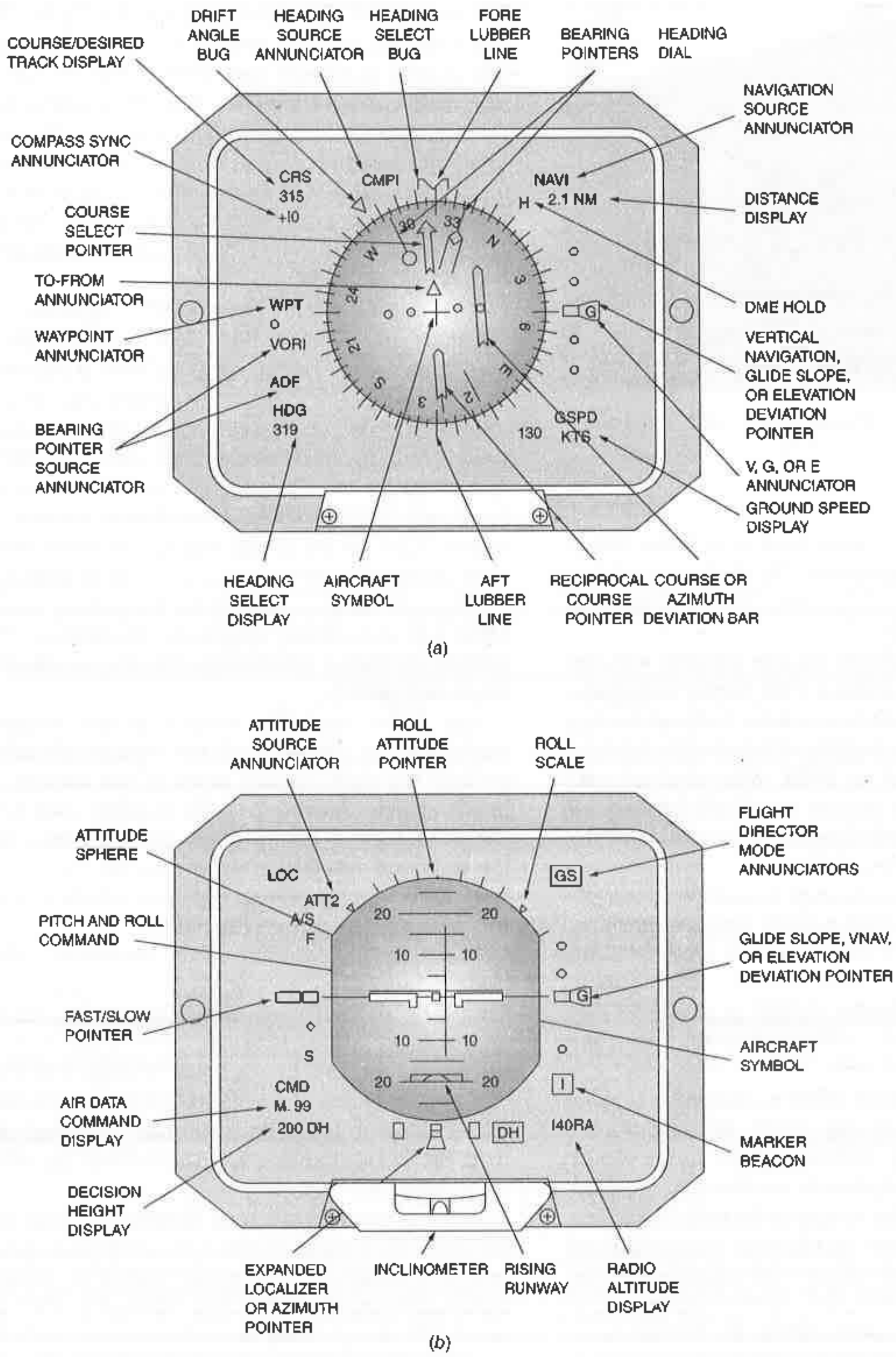


FIGURE 17-16 Electronic flight instruments: (*a*) electronic horizontal-situation indicator (EHSI) and (*b*) electronic attitude-director indicator (EADI).

EICAS and ECAM

The **engine indicating and crew alerting system** (EICAS) and the **electronic centralized aircraft monitoring** (ECAM) system are two variations of the basic electronic flight instrument system. Like the EFIS, the first generation EICAS and the ECAM system employ digitally controlled CRT displays. Newer systems have increased systems integration and use LCDs. The EICAS and the ECAM are used to display various system parameters, such as engine pressure ratio, **rpm**, and exhaust gas temperature. Other parameters, such as hydraulic system pressures and electrical system parameters, can be displayed or, in some cases, removed from the screen at the discretion of the pilot. Another vital function of the EICAS and the ECAM system is to monitor the various aircraft systems and display

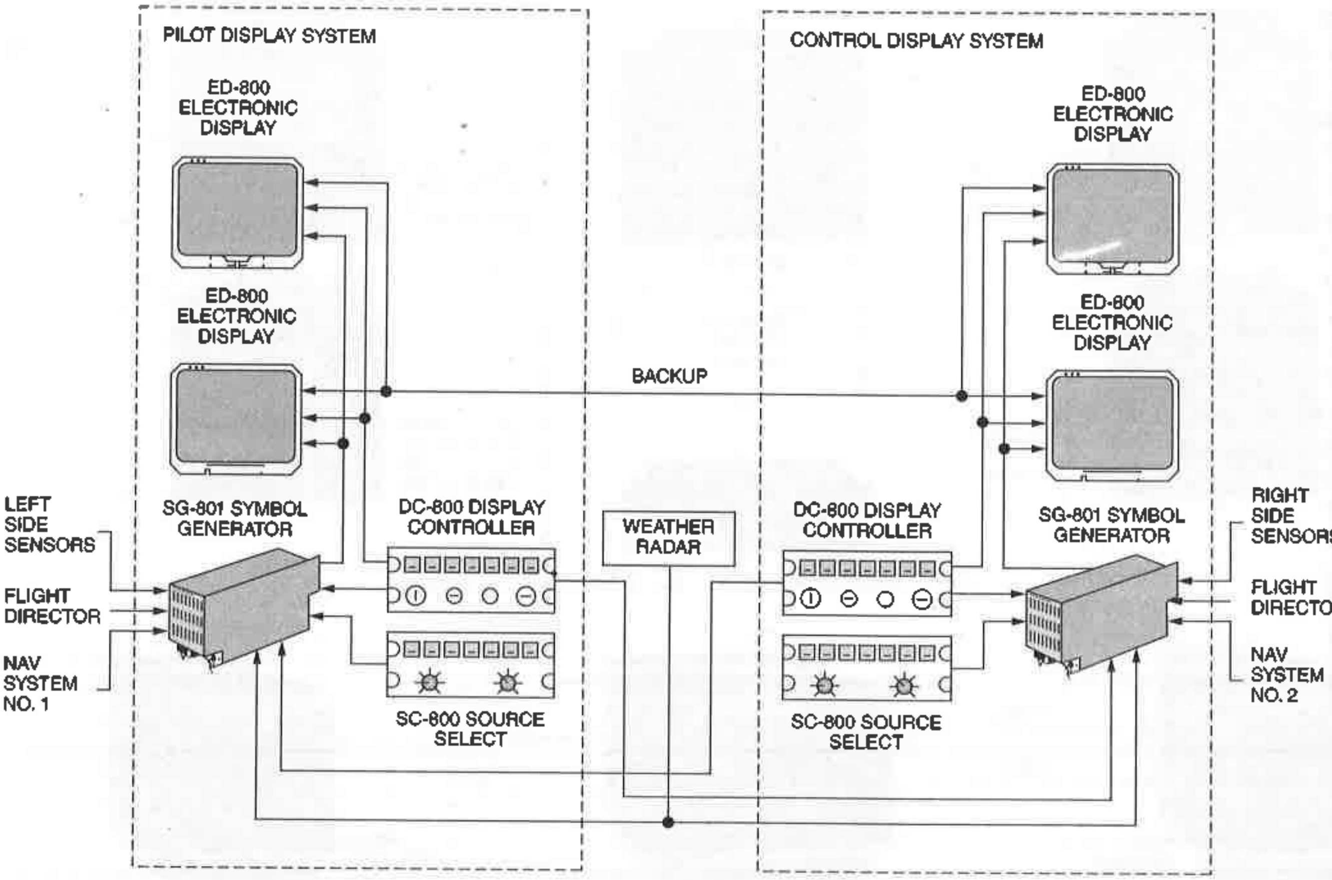


FIGURE 17-17 Block diagram of an electronic flight instrument system.

caution and warning information in the event of a system failure. The EICAS is used on modern Boeing aircraft; the ECAM system is used on modern Airbus aircraft. Many corporate and commuter aircraft also employ digital systems to show engine and airframe data on LCD or CRT displays.

EICAS

The **EICAS** displays certain aircraft system and engine parameters on a need to know basis. That is, not all system data are displayed continuously. In the event of a system malfunction, any vital information automatically appears on the display, and the appropriate caution or warning signals are activated. During normal operation, only a minimum amount of information is displayed; additional system data may be displayed upon activation of the appropriate EICAS control. The Boeing 757 and 767 utilize an EICAS containing two CRT displays as shown in Fig. 17-20. During normal flight configurations, the lower CRT is typically blank. The lower CRT is used to display the status of any malfunctioned system, and it acts as a backup display in the event the top CRT fails. The upper CRT is called the **main EICAS display**, and the lower **CRT** is called the **auxiliary EICAS display**. It should be noted that the latest B-757 and 767 aircraft are now constructed using LCD instruments instead of the CRT units on the earlier aircraft designs. LCDs offer both weight and energy savings when compared to CRT displays; therefore, virtually all new aircraft employ LCD technologies for flight deck instruments.

Several formats are used by the various EICASs. These formats vary with the aircraft model. Some common formats include primary, secondary, and compact modes. The primary format shows on the main display during normal operation. Four different colors are used to display information. A change in color indicates a change in system status. Four alert messages are available in the primary format. **Level A** messages are **warning** messages and are shown in red. These are the most important messages. **Level B** messages are **caution** messages and are displayed in amber. **Level C** messages are **advisories** and are displayed in amber or light blue, depending on the specific EICAS model. **Level D** messages, called memos, are displayed in white.

Warnings, or level A messages, indicate conditions that require immediate attention and immediate action by the flight crew. Level A alerts include cabin depressurization and engine fire. Warnings activate other discrete aural and visual annunciators on the flight deck, such as the fire bell. There are very few possible level A alerts. Level B messages, or cautions, appear in amber just below any level A message. A different discrete sound and annunciator light will be activated for these alerts. Cautions require immediate crew awareness and future crew action. Advisory messages require immediate crew awareness and possible future action. Memos are used for crew reminders. For all levels of alerts, the most recent message appears at the top of its category. Level A messages appear at the top of the display, level B is below level A, level C is next, and level D is shown at the bottom of the list.

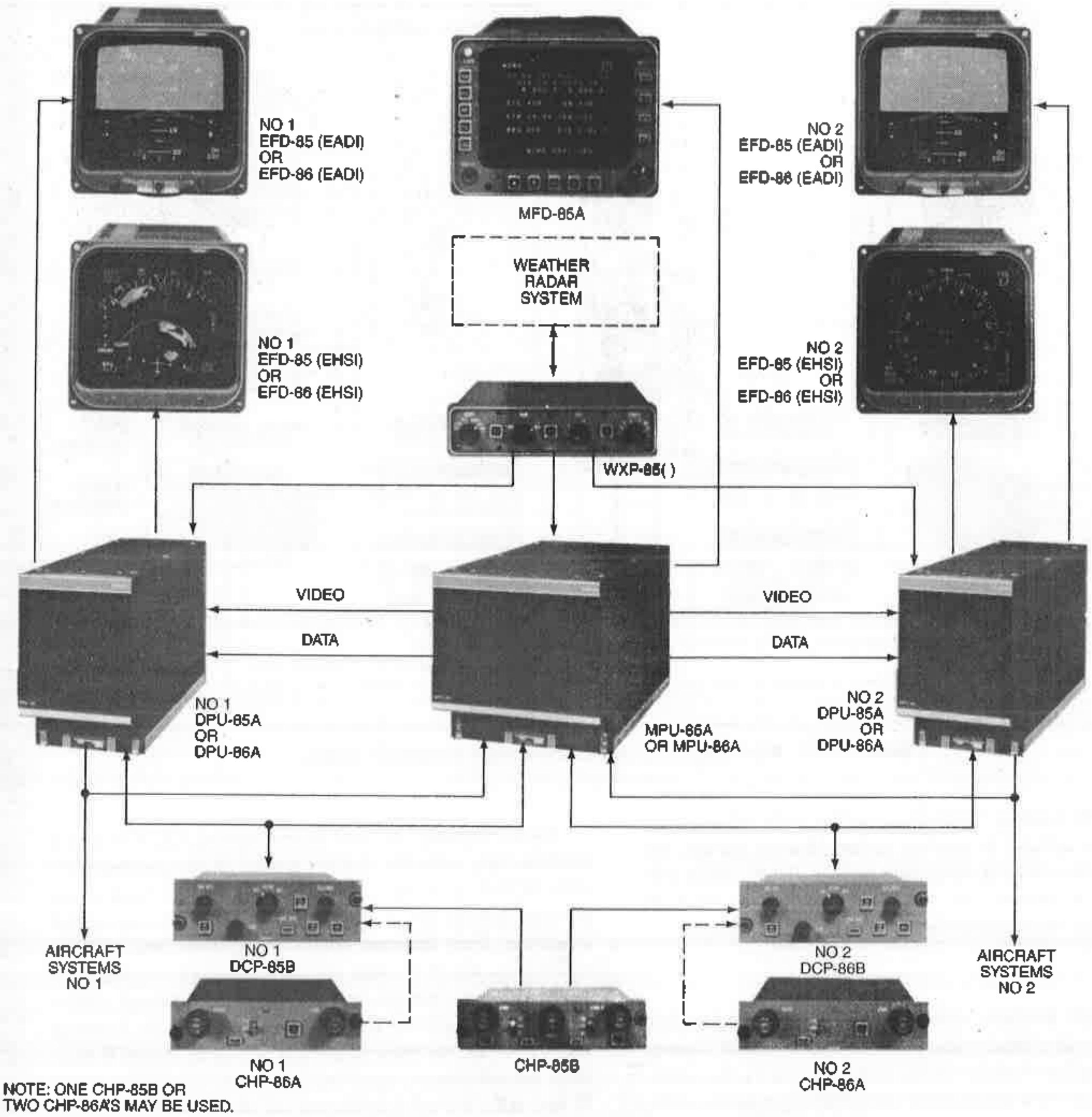


FIGURE 17-18 A typical EFIS system. (*Rockwell Collins.*)

At power-up the secondary format automatically appears on the auxiliary EICAS display. The secondary format shows engine parameters, such as N2 rotor speed, fuel flow, oil pressure, oil temperature, oil quantity, and engine vibration.

The compact mode is used when one display is inactive or being used to show maintenance pages. In the compact mode the data are typically displayed in digital format only. In other words, vertical or round dial instrument representations are eliminated. The compact mode is used during flight if one display becomes inactive. Compact information can be shown on either the main or auxiliary display.

A block diagram of the B-757 EICAS is shown in Fig. 17-21. The two EICAS computers monitor over 400 inputs from engine and airframe systems to alert the crew in the event of a system malfunction. An EICAS computer uses both analog and digital data to communicate with the various components of the system. The ARINC 429 data bus system is used for most EICAS digital data transmission and reception processes. But be aware that other data bus formats may be used on certain systems.

ECAM System

The **ECAM** system is very similar to the EICAS just described. The ECAM system also employs two LCD or CRT displays. On some aircraft, such as the A-310, the displays are mounted side by side. On other aircraft, such as the A-320 and A-340, they are mounted one above the other. The ECAM system incorporates a more graphic representation for many

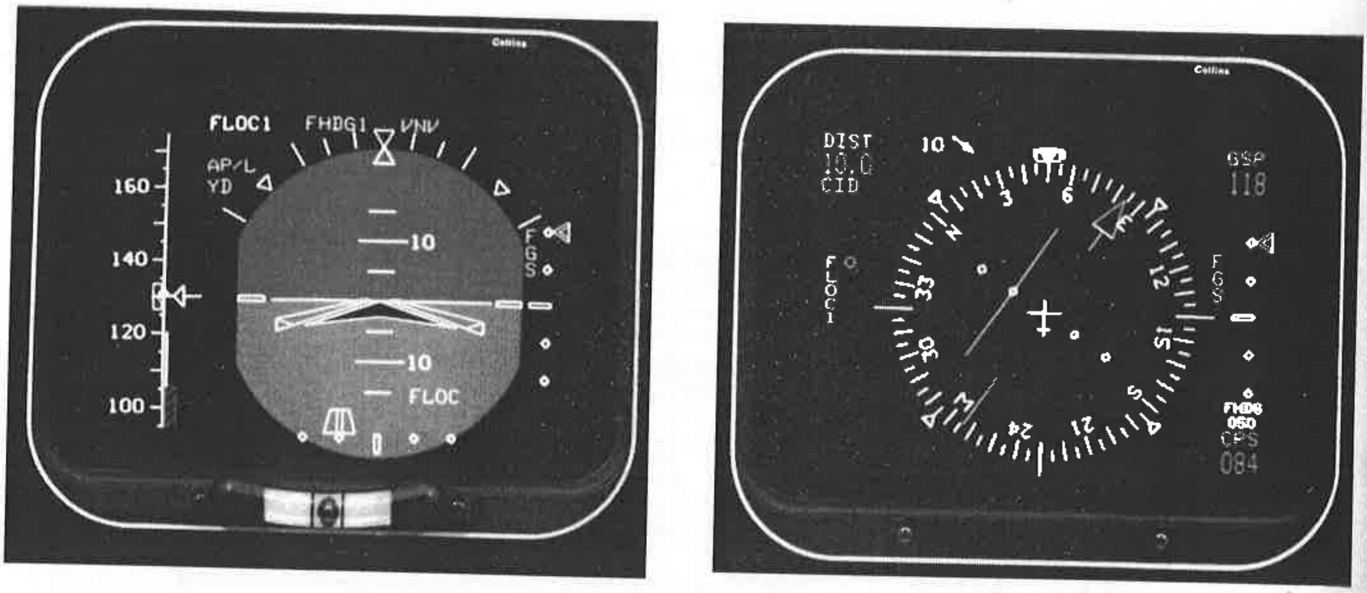


FIGURE 17-19 A typical EADI (*left*) and EHSI (*right*). (*Rockwell Collins*.)

of the aircraft systems, when compared to the Boeing EICAS design.

Four display modes are used by the ECAM system; the **flight phase, advisory, failure-related**, and **manual** modes. The flight phase displays information needed for a particular segment of a flight. The advisory mode displays information about system status that may require crew attention. The failure-related mode takes precedence over the other two automatic modes and displays information on system status that requires immediate crew action. The manual mode is used to select the status of any monitored system.

The ECAM system also has a system test routine. The self-test is performed during each power-up. The test mode can also be activated manually from the maintenance panel.

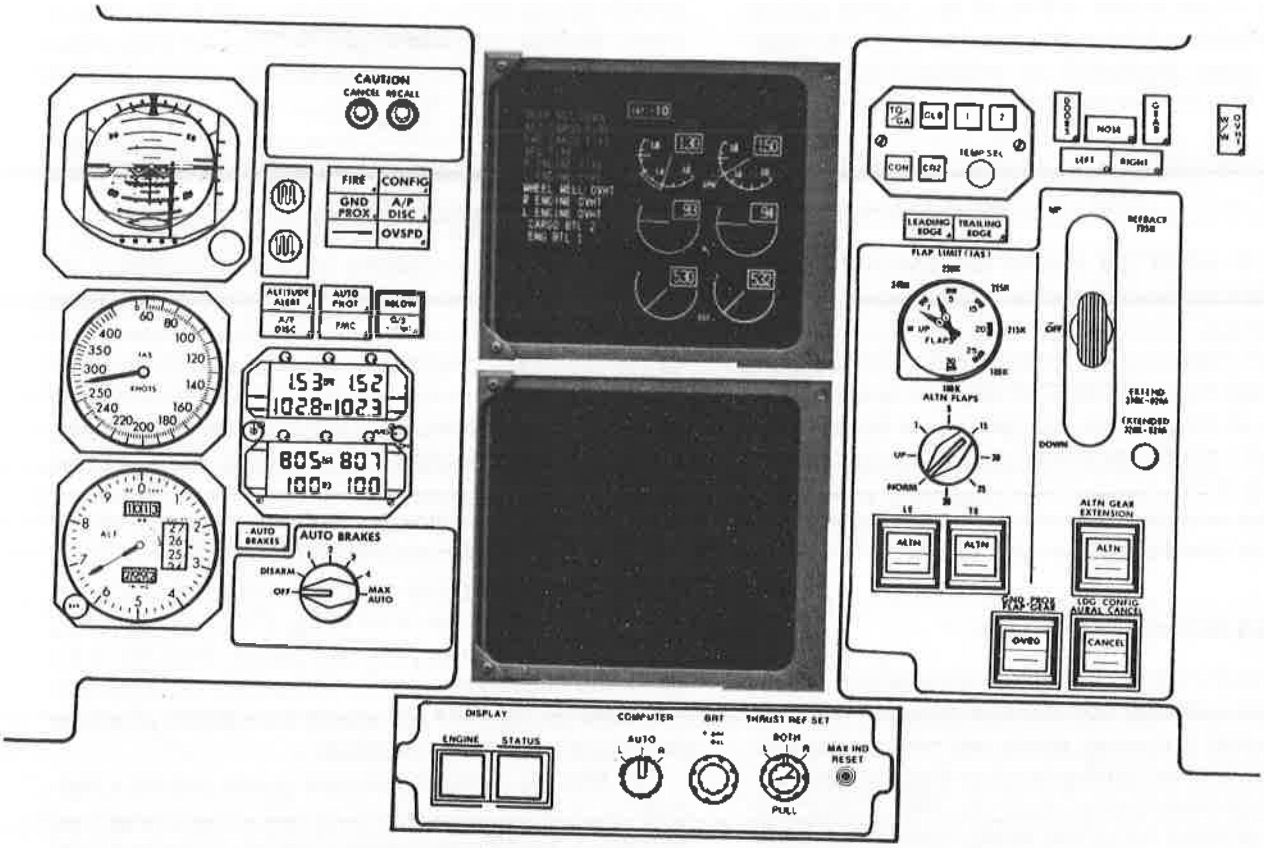


FIGURE 17-20 Two EICAS displays from a Boeing 757. (*Boeing Corporation*.)

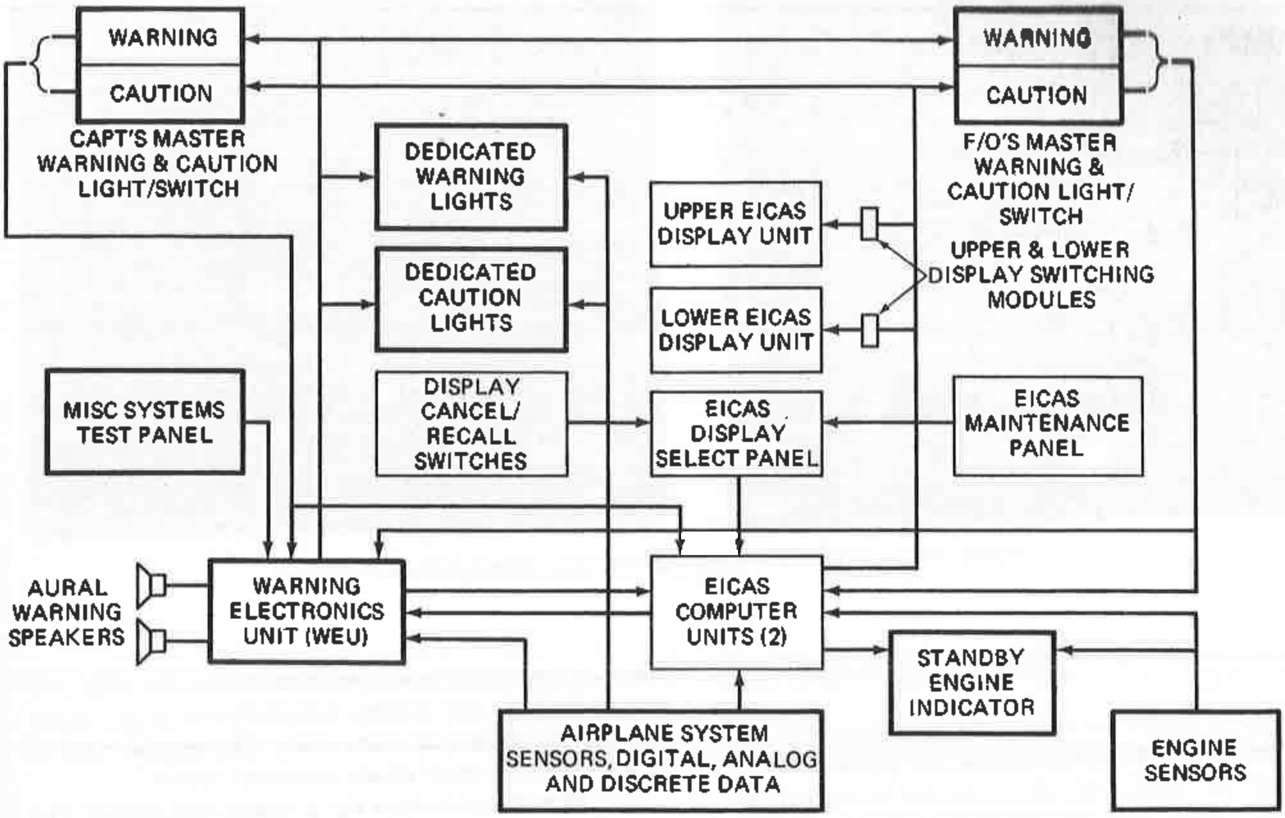


FIGURE 17-21 Block diagram of the B-757 engine indicating and crew alerting systems. (*Boeing Company.*)

This portion of the system will recall any system defects from a nonvolatile memory to aid in system troubleshooting.

Since so many parameters are monitored by both the EICAS and ECAM computers, they are valuable troubleshooting tools for airline technicians. A quick reference of the EICAS or ECAM displays will provide much of the preliminary information needed for troubleshooting defective systems.

The EICAS and ECAM systems just described contain elements which are similar between various aircraft. In general, newer aircraft employ greater integration and use LCDs for flight deck displays; older systems tend to contain more stand-alone processors and use CRT displays. In either case, the concepts of the previous descriptions can be generally applied to many aircraft and should be studied to help gain an understanding of the systems. However, prior to performing any inspection or maintenance on aircraft display systems always become familiar with the exact system.

Integrated Display Systems

As mentioned earlier, flight deck display systems have continued to undergo significant improvements through integration of data collection, processing power, and even the displays themselves. Second- and third-generation display systems are found on aircraft manufactured during the 1990s, 2000s, and beyond. The evolution of aircraft display systems continues to move toward smaller, lighter, and faster processing units as well as larger instrument panel displays which on the latest aircraft replace virtually all traditional mechanical instruments. Modern integrated display systems are often called EFIS, although this is incorrect because the systems do much more than just display flight information. Common names of second- and third-generation systems include: **integrated display system (IDS), electronic instrument system (EIS)**, and **integrated avionics system (IAS)**.

Second-generation display systems are found on a variety of corporate, commuter, and transport-category aircraft. Although systems designed by different manufacturers and found on specific aircraft may be slightly different, all second-generation systems are very similar to the concepts presented here. In general, second-generation systems contain a **primary flight display (PFD)**, a **navigational display (ND)**, and a **multifunction display (MFD)**. These units are arranged on the instrument panel as shown in Fig. 17-22. Here it can be seen that the PFD and ND have replaced the EADI and EHSI found on first-generation systems. The displays are typically larger than earlier systems and many use the newer technology of LCDs. As shown in Fig. 17-22, the flight deck contains two PFDs; one pilot, one copilot. The PFD is the most critical display because it contains basic flight information; therefore, the PFD will always have display priority in the event of a partial system failure.

The NDs on a second-generation system provide a horizontal view of the aircraft's position and certain navigational information. The ND can typically be switched between several formats and allows for overlay of flight plans and weather radar information. The MFD is located on the right side of the panel

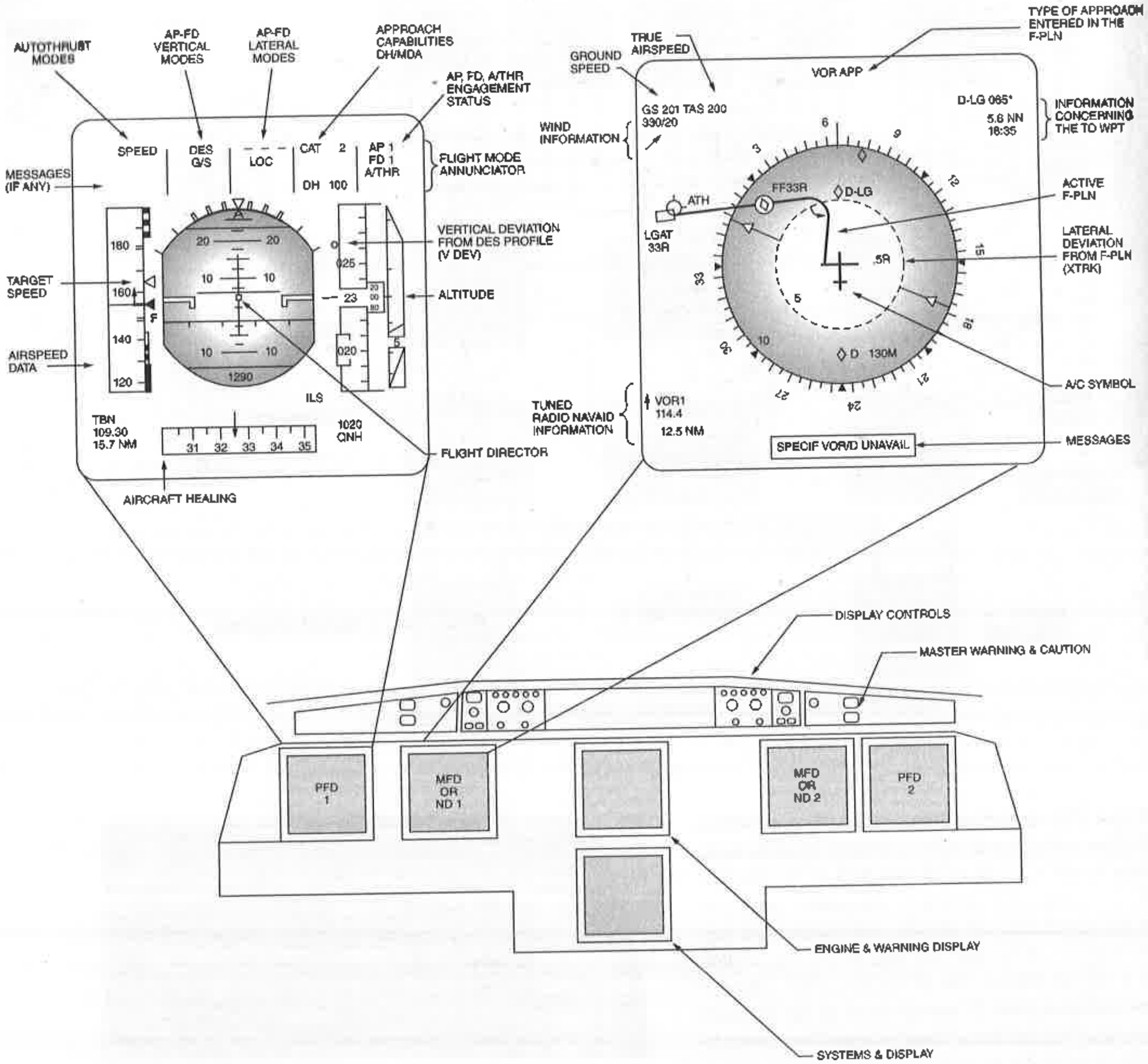


FIGURE 17-22 Second-generation electronic instrument system.

and the first officer uses it to access checklist information and navigational maps. One big advantage of a second-generation system is that all displays are integrated and communicate during operation. If one or more displays or processors fail, the system automatically reconfigures in order to keep critical information available to the pilot. This provides an additional layer of safety compared to first-generation systems and therefore during aircraft certification, the FAA requires fewer of the traditional electromechanical backup instruments. Some systems will contain six displays arranged in a horizontal format; two PFDs, two NDs, and two EICAS displays located in the center of the instrument panel as shown in Fig. 17-23. The exact arrangement and type of displays will likely be different between various aircraft manufacturers.

Second-generation systems typically combine processing circuitry in order to improve redundancy and save weight

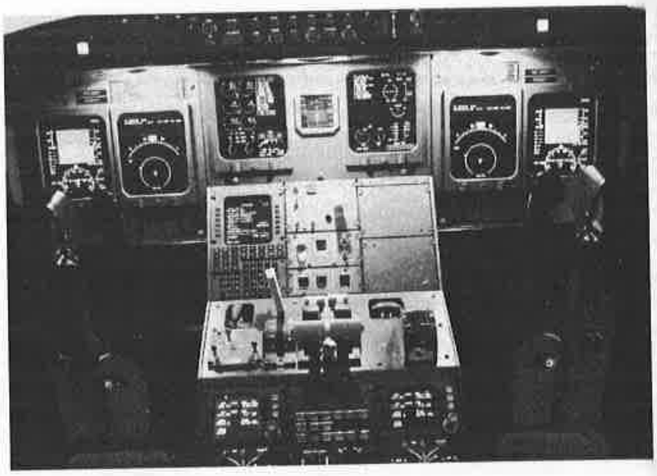


FIGURE 17-23 Instrument panel of a Canadair CRJ.

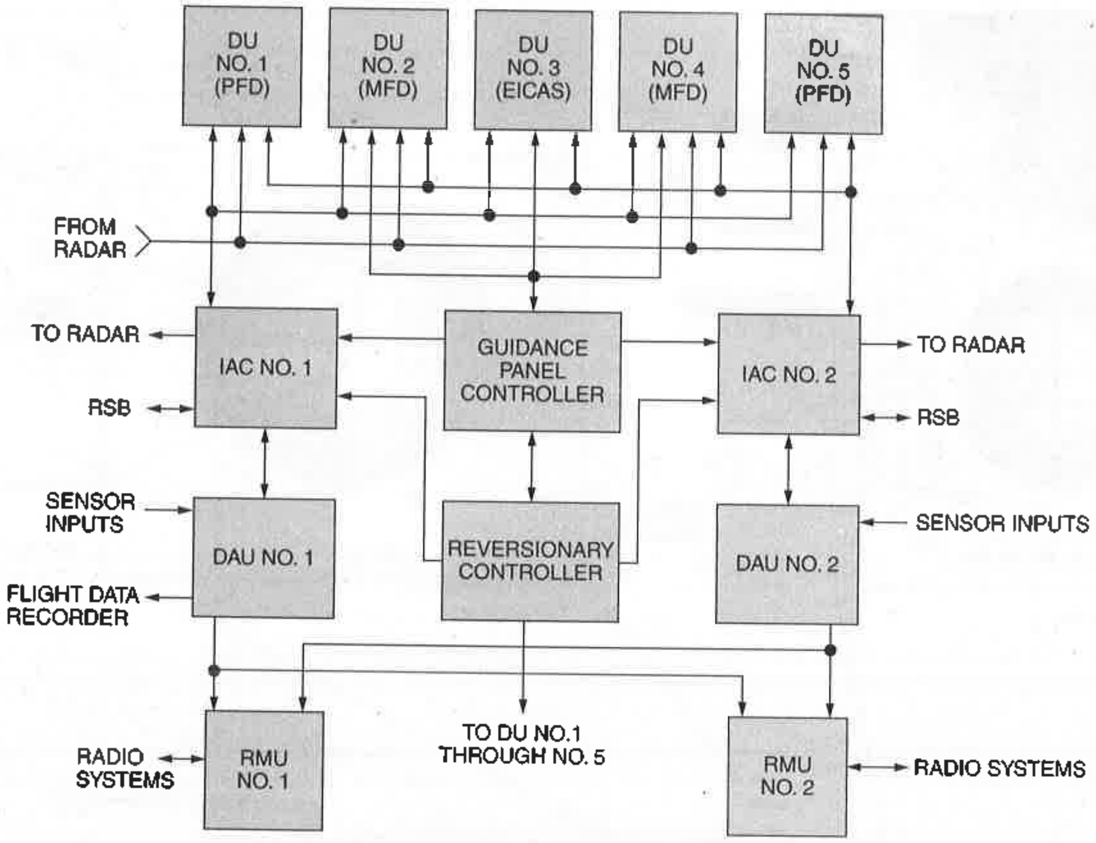


FIGURE 17-24 Second-generation integrated display system.

(see Fig. 17-24). This aircraft contains two **data acquisition units (DAUs)** for collection and processing of systems data; the DAU then sends a string of digital data to the display processor. The **integrated avionics computer (IAC)** is responsible for processing all display information on this system. The outputs of the IAC are sent to the flight deck displays in a digital format for all LCDs; CRT displays may receive analog signals. If one or more of the displays or processor units fail, the reversionary controller is used to automatically or manually reconfigure the system for proper operation. This aircraft also contains a radio management unit (RMU) shown at the bottom of the diagram. The RTU is used to set all navigation and communication radio frequencies and functions as discussed in Chap. 15.

Third-generation electronic instrument systems found on the latest aircraft, have increased integration, larger displays, weigh less, and require less power than earlier systems. The design and construction of these advanced display systems has allowed engineers to install modern electronic displays even on light single-engine aircraft. Many modern personal aircraft such as the Cirrus SR20 contain an integrated system designed by Garmin International; this system uses two 12 in. by 12 in. LCD flat panel displays, see Fig. 17-25. On larger aircraft such as the B-787 and A-380, the integrated display system has created a flight deck completely void of electromechanical instruments; they have all been replaced by LCD units. Aircraft with third-generation electronic flight decks are truly computerized, so much so that the latest transport-category aircraft contain more than a dozen LCD displays, computer-type keyboards, and cursor control devices similar to a touch pad or trackball.

FIGURE 17-25 Light aircraft electronic display systems (the Cirrus SR20).

The integrated display system found on the Cirrus SR20 employ two **integrated avionics units (IAUs)** as the main processor units; the IAUs feed data to the two large LCD flat panel displays. The IAU receives inputs from various airframe and engine sensors, and a multitude of flight information as well as signals from various control panels. The IAUs are designed to process the data and sends output signals to the video display units as well as other systems, such as the autopilot. Figure 17-26 shows the data bus connections between the IAU and the two display units. The number 1 and 2 IAUs receive data from four additional processors, all of which are located behind the two flat panel

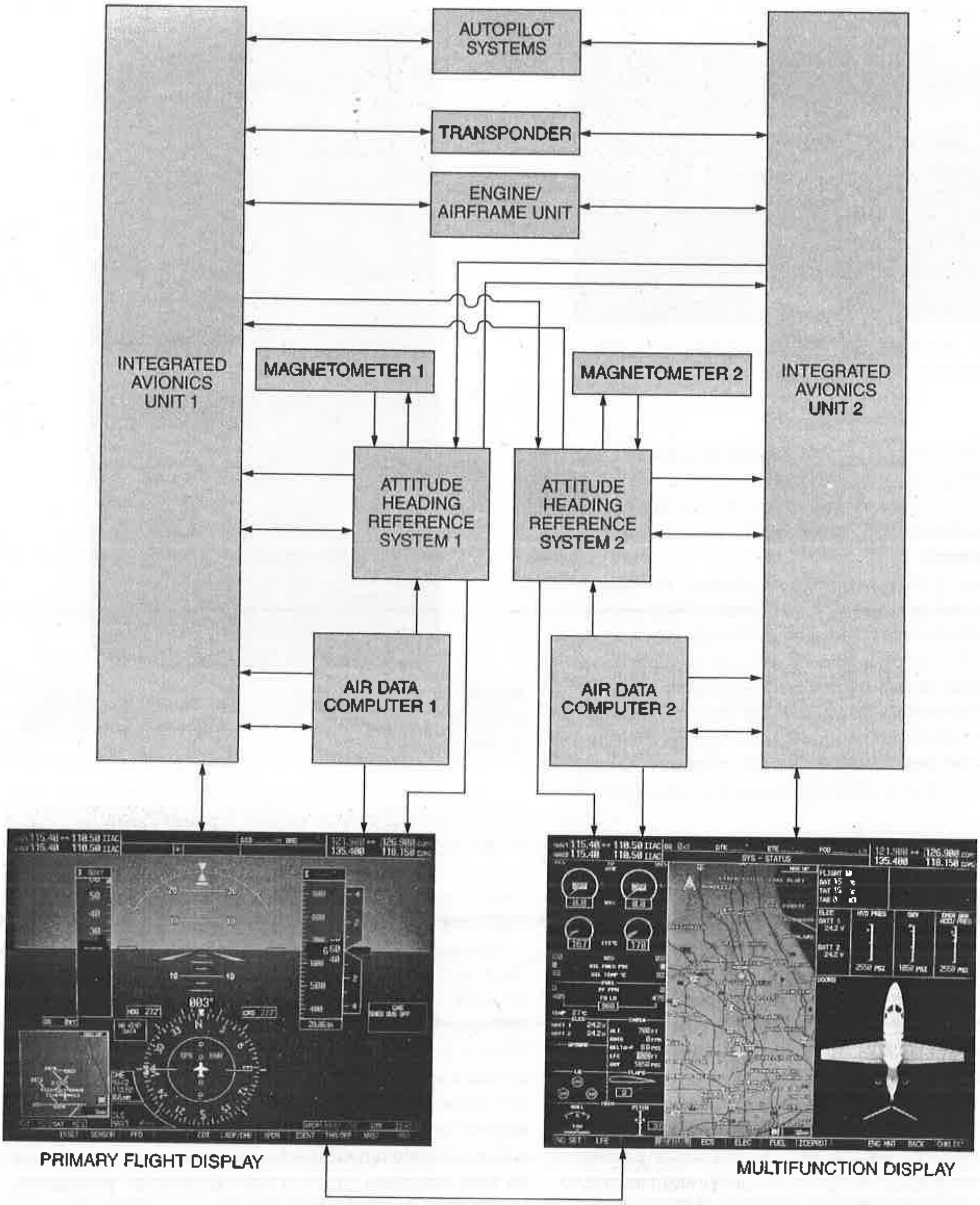


FIGURE 17-26 Simplified Garmin electronic instrument system found on modern light aircraft.

displays as seen in Fig. 17-27. These processors send a variety of aircraft system data and engine information to the IAUs using four different data bus formats: (1) a high-speed Ethernet, (2) an RS-232, (3) an RS-485, or (4) an ARINC 429. There are hundreds of sensors located throughout the aircraft which report to the various processors; these processors send information to the IAUs which eventually feed the PFD and ND. During normal operation, IAU #1 feeds the PFD and IAU #2 feeds the MFD. The two displays then share data through the Ethernet cross-talk data bus connection; hence providing true redundancy.

This system employs two 12-in. LCD displays with the PFD located on the left and an MFD installed on the right side of the panel. Both units contain a series of controls located around the perimeter of the displays; this area of the display is known as the **bezel** (see Fig. 17-25). Some of the

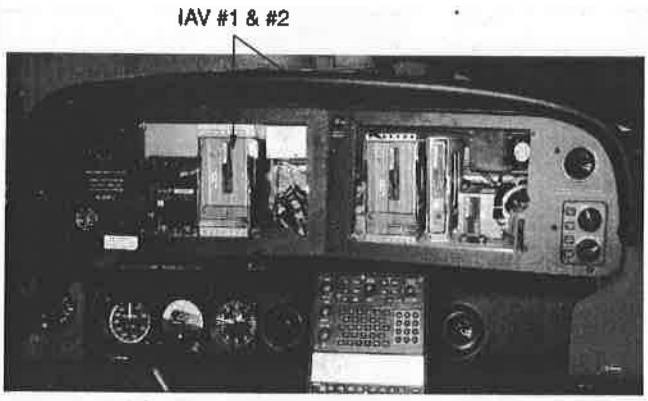


FIGURE 17-27 The processor units located behind the LCD instrument units on a Cirrus SR20 aircraft.

controls are dedicated to a specific function, such as radio frequency tuning; some controls can be changed according to the items listed on the display. If one display should fail, the flight information has priority and the IAU will process the data accordingly.

As with most modern computerized systems, the Garmin flight displays and processors are extremely reliant on software for troubleshooting, operational updates, and system configuration. If a system requires a software update because of system changes or improvements by Garmin, the software update would most likely be downloaded from the manufactures' website and loaded into the aircraft system. The software updates are then installed into the processor circuits through a secure digital (SD) card located on the bezel of the PFD.

Other light aircraft systems have also become popular due to the use of GPS and the increased capabilities of microprocessor circuits. Many navigational aids are even designed to be portable table-style computers; there are even aviation apps available for various tablet computers. Of course, carry-on table-type displays do not communicate with aircraft systems and therefore have limited capabilities; however, they can provide excellent flight planning and aid with navigation using GPS. Many of these units are called **electronic flight bags (EFBs)** because they contain charts and approach plates which pilots would traditionally carry in their "flight bag." The Bendix/King division of Honeywell Corporation produces the portable multifunction display with a variety of features (Fig. 17-28). This unit provides operations for preflight planning, real-time GPS positioning during flight, as well as synthesized terrain maps to aid navigation.

Electronic Flight Bags

As previously mentioned, the **EFB** is a new electronics component designed to help the pilot perform preflight and/or flight management tasks. The earliest EFBs were simply laptop computers which contained software designated for specific aircraft applications. Today, EFBs can be completely portable hand-held devices (see Fig. 17-28) or they can be permanently installed in and interactive with aircraft systems.

FIGURE 17-28 The AV8OR portable multifunction display designed for light aircraft. See also color insert. (*Bendix King, by Honeywell.*)

EFBs have become very popular because they reduce paper on the flight deck, document revisions are made electronically and often through a wireless connection. EFBs can even improve safety and decision making through better display of flight data and even weather information.

According to the FAA advisory circular AC 120-76A, there are three classes of EFB hardware: Class I, Class II, and Class III. Class I EFBs are portable electronic devices (PEDs) and must be stowed during takeoff and landing operations. Class II EFBs are portable devices that are designed to be mounted in the aircraft and used during flight. Keep in mind, any permanently installed items, such as an external GPS antenna or electrical power connections for a Class II EFB will most likely require FAA approval such as a supplemental type certificate (STC). Class III units are permanently installed on the flight deck and often contain touch screen capabilities, a keyboard, and/or trackball device for pilot inputs. There is an extensive FAA certification process for the installation of Class III EFBs; therefore, these units are part of an integrated instrument system found only on the latest aircraft. Figure 17-29 shows the EFB found on the flight deck of the Airbus A-380.

Synthetic Vision

Many of the most modern flight displays receive a computer-generated image of terrain outside the aircraft as it would appear in daylight conditions with good visibility; this concept

FIGURE 17-29 A-380 Class III electronic flight bag (first officer's station).

is called **synthetic vision.** The display provides "real-looking" visual information no matter what the weather or daylight conditions. In many ways the imagery presented on a synthetic vision display is very similar to a modern computer, or video game. The purpose of synthetic vision is to improve flight safety by providing the pilot a better visual reference to local terrain. Most synthetic vision information is displayed on either the PFDs or NDs.

Synthetic vision systems are an integral part of many modern flight display systems. Through the use of GPS to determine aircraft position, the processor can reproduce an artificial image of the ground surface below and in front of the aircraft. This requires an extensive database with a 3-D "map" of the entire region the aircraft would normally fly. The database contains all the necessary terrain data, such as ground levels and contours, roads, bridges, lakes, and even large buildings. The system may also contain airspace information and airport data such as runway lengths, headings, and taxiway information. The system can also be designed to monitor current air traffic using TCAS (traffic collision avoidance system).

Heads-Up Displays

Some modern corporate and transport-category aircraft now employ a system which allows pilots to view critical flight instruments while at the same time keeping their "head up" in order to view the area outside the airplane windshield; this system is called a **heads-up display (HUD).** The purpose of HUD is to eliminate the transition time required for the pilot to change from a view outside to inside the aircraft. Tests have shown that HUD significantly increases safety, especially during landing and takeoff. Common applications of HUD employ a transparent display (known as the combiner) mounted in the vision path between the pilot and the aircraft windshield; some military pilots use a helmet-mounted HUD. Currently HUD systems are commonly found on the Gulfstream G-V, the Airbus A-380, and the Boeing B-777; HUD systems for both the captain and first officer are standard equipment on all B-787 aircraft.

As shown in Fig. 17-30, there are four basic elements to a common HUD system;

1. The combiner assembly contains a transparent screen mounted between the pilot and the aircraft windshield. The combiner can typically be folded upward for storage when not in use. The image is projected onto the combiner from a projector unit typically mounted overhead just behind the pilot.

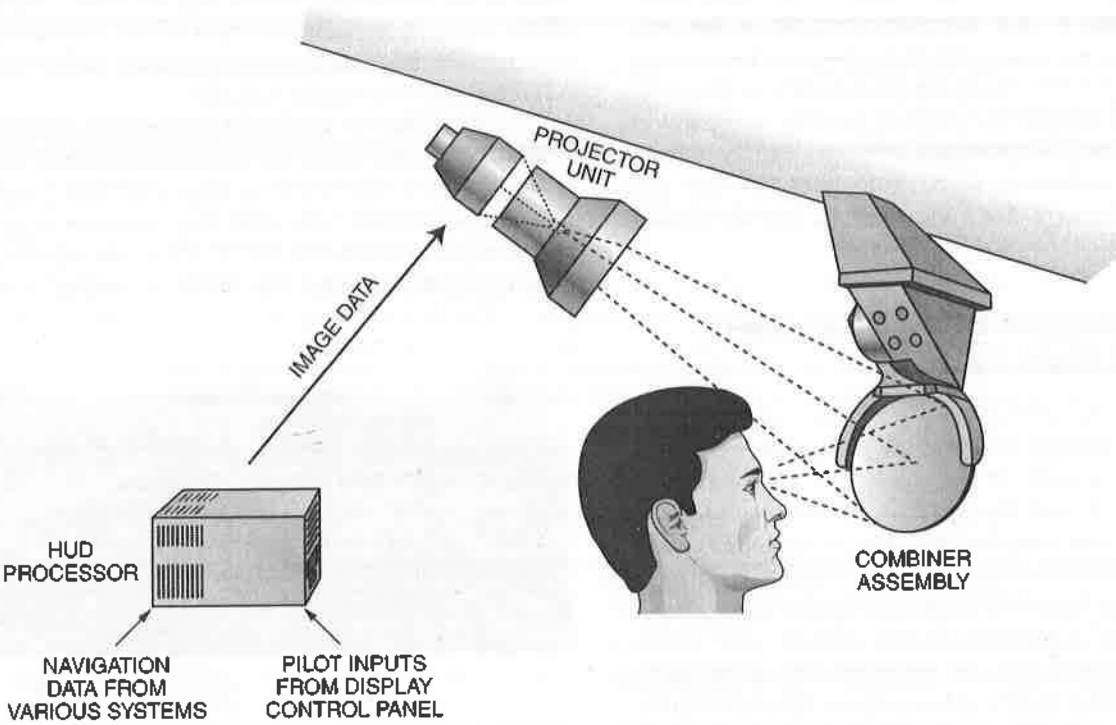


FIGURE 17-30 Functional diagram of a common heads-up display.

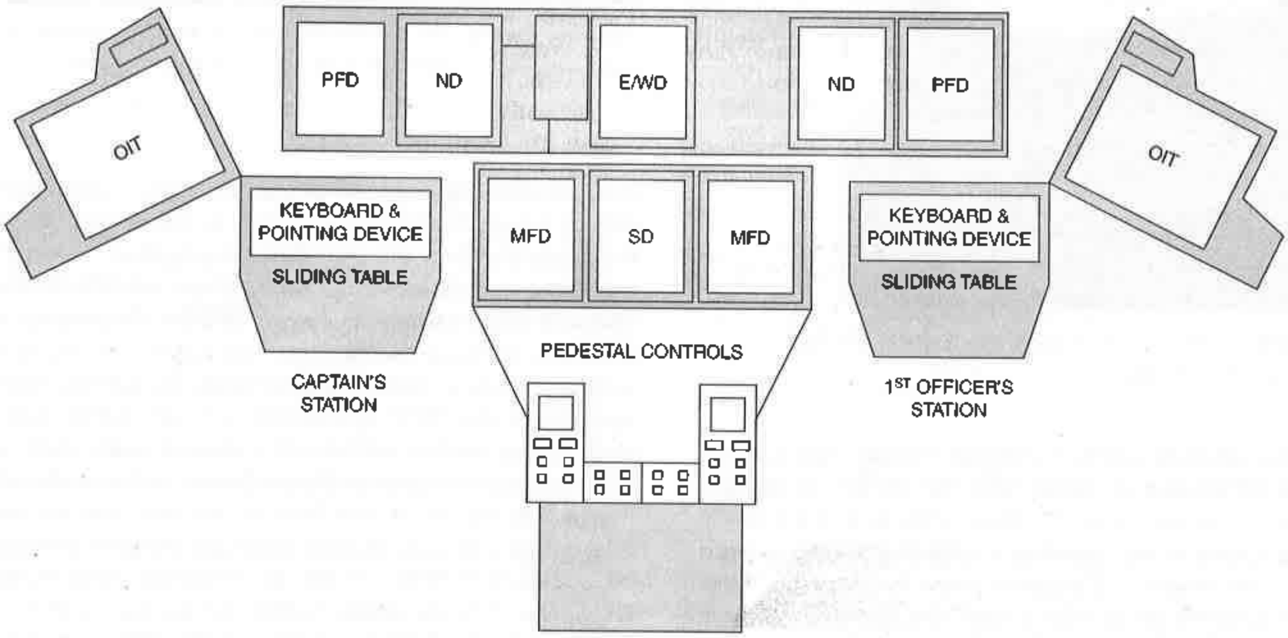


FIGURE 17-31 Airbus A-380 instrument panel.

2. The overhead unit will contain an LCD or CRT projector system which receives the image data from the HUD processor.
3. The processor assembly is typically located in the equipment bay or integrated with other display processing units.
4. The HUD controls can be located on a designated unit or integrated into the display system controls.

The HUD projector unit must include a complex series of lenses in order to focus the image correctly on the combiner. The pilot must have the HUD image in focus at the same time the horizon outside the windshield is in focus; the pilot must look through the combiner in order to see a clear HUD image. The HUD processor receives a variety of input data regarding navigation, aircraft attitude, and altitude; this data is typically received in a digital format from the display processing unit.

Modern Transport-Category Aircraft Integrated Flight Deck

Today aircraft engineers have gone well beyond the simple integration of display systems; integration now includes virtually every system on the flight deck. Planes such as the Boeing B-787 and the Airbus A-380 are more reliant on electronics than any previous aircraft. Aircraft maintenance is simplified through use of an extensive onboard analysis system which receives information from almost every electrical component on the aircraft. Any maintenance information can be automatically downloaded through a wireless Wi-Fi connection or the information can be accessed through various maintenance terminals located throughout the aircraft. The B-787 and A-380 even incorporate a secure wireless connection dedicated to maintenance which allows technicians access to system data anywhere on, or near, the aircraft using a portable computer.

The main instrument panel of the Airbus A-380 includes eight identical LCDs as part of the integrated system called the **control and display system (CDS)**. As seen in Fig. 17-31, the top row of displays contains the PFDs, two NDs, and in the center, the engine/warning display (E/WD). The center console includes three displays; two used as MFDs and one system display (SD). Located at a slight angle on the outboard ends of the instrument panel are two Onboard Information Terminals (OITs); this unit is an elaborate version of an EFB.

The A-380 has two **keyboard and cursor control devices (KCCDs)** located on the center console between the pilots (see Fig. 17-32). The KCCD employs a QWERTY alphabetic key pad, a trackball with palm rest, validation keys, and a wheel control device. The KCCD allows the pilot/copilot to directly interact with the ND, MFD, or sections of the SD.

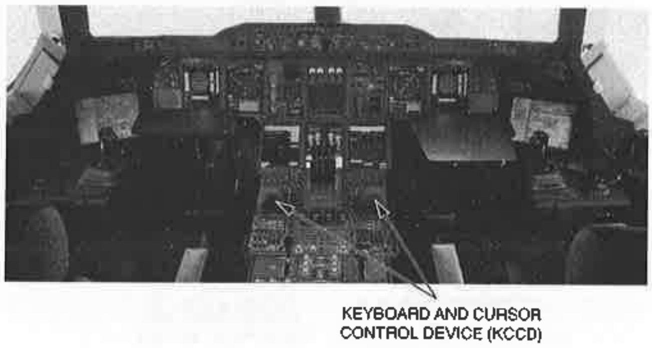


FIGURE 17-32 Airbus A-380 flight deck. See also color insert. (*Airbus S.A.S.*)

This type of control device has become common on the newest commercial aircraft; although they will differ slightly, each unit will contain some type of handrest in order to allow for steady entry of data.

An enormous amount of data must be collected and processed to create all the needed video information for each A-380 display; this requires a highly efficient data bus system. The KCCD transfers data using an Ethernet-type data bus system known as ADFX; this bus was described in Chap. 7. The A-380 CCD system employs the design concepts of **integrated modular avionics (IMA)** to reduce the number of LRUs needed to processing display data. In general, these design concepts employ extreme integration of modular systems to reduce aircraft weight and improve system performance, reliability, and maintainability.

AUTOMATIC FLIGHT CONTROL SYSTEMS

Systems designed to assist the pilot during normal flight operations have been used on aircraft for decades. These systems, commonly referred to as an **autopilot**, can be found on light as well as heavy transport-category aircraft. Initially an autopilot system was relatively simple and designed to hold a given altitude, heading, and/or airspeed. Today complex aircraft employ **autoflight** systems which perform virtually every facet of flight. These systems can tune radios, fly holding patterns, and even perform autoland functions; of course, the correct ground-based navigational aids must also be available. For the most part, the terms **autopilot** and **autoflight** generically describe an automated system used to assist the pilot fly the aircraft; this text will use both terms during the following discussions.

Basic Autopilot Theory

In order to understand the functional theory of a modern autoflight system, it is important to know the basic operations of the various system components. On a modern aircraft, most of the autoflight subsystems and operational components are controlled electronically; and in many cases the control circuits operate using digital signals. ARINC 429 is the digital data bus standard most commonly found on many systems; however, Ethernet-type bus systems are gaining popularity and are used for information transfer on many modern autoflight systems. Digital systems are discussed in Chap. 7. Since modern systems operate using digital technologies, these will be the focus of the following autopilot discussions. Analog signals may still be used on modern systems for certain input or output signals; however, the main processors and controls each employ digital circuits.

Every autoflight system is basically designed to perform pilot duties automatically. Although the complexity of different systems will vary between aircraft, all autopilots will contain the functional elements shown in Fig. 17-33. The system must contain one or more processor units, often

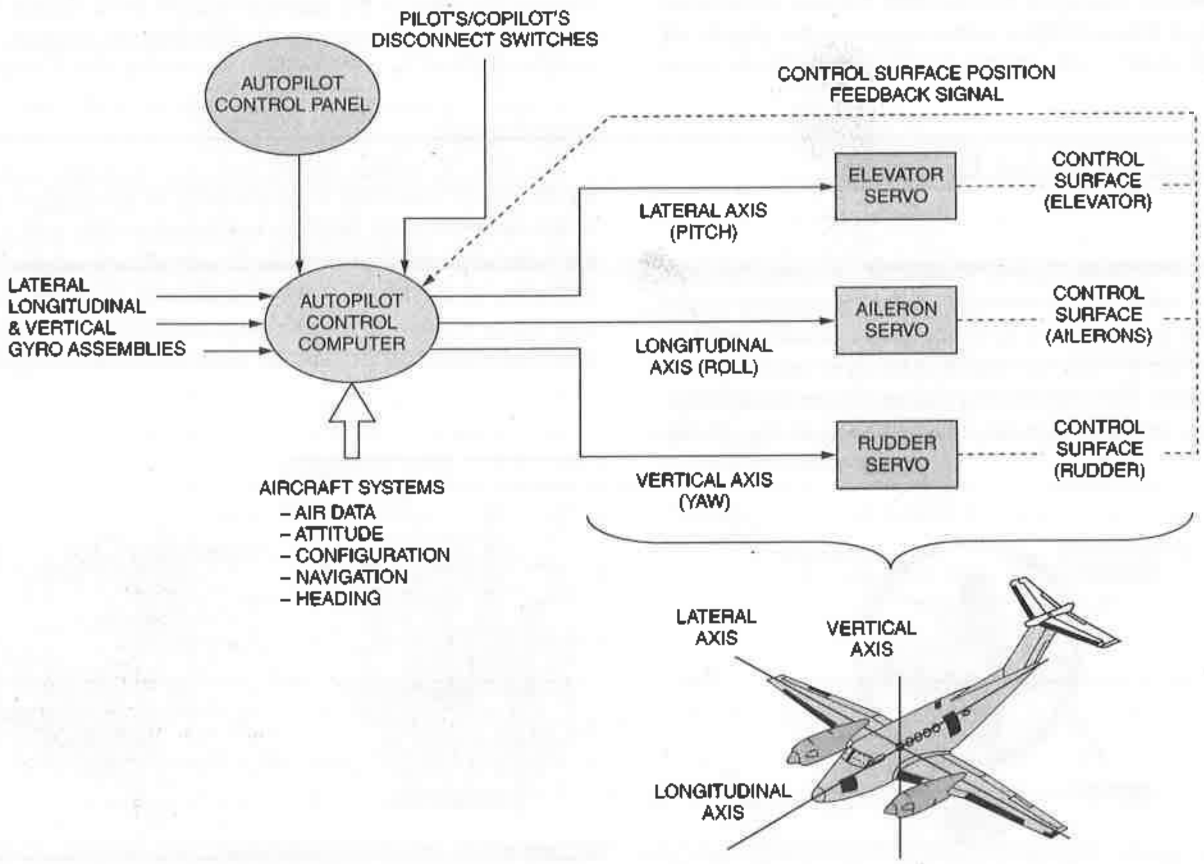


FIGURE 17-33 Electromagnetic signal-generating device for a gyro sensing unit.

referred to as the **autopilot computer**, this unit is typically an LRU located in the electrical equipment bay. The computer receives inputs from the main autopilot control panel through a digital data bus; discrete inputs are also sent from the pilot's and copilot's autopilot disconnect switch. Data from various aircraft systems must be sent to the computer in order for the autoflight system to "know" important flight parameters such as airspeed and altitude. The processor unit then follows a computer software program to determine any change needed to the aircraft control surfaces. The autopilot control computer will send output signals to the servos in order to control the aircraft. A feedback signal must be returned to the computer to verify control surface position.

In short, a complex autoflight system must perform all the duties a human pilot would conduct. Those include the following: (1) Become familiar with all navigational routes and radio systems. This is done through the preflight programming of the autoflight computer. (2) Continually monitor aircraft position, altitude, configuration, and other parameters; accomplished through the use of sensors and digital data sent to the autoflight processor circuits. (3) Analyze the current situation and perform decisions about any needed corrections. This is done by the system software. (4) Anticipate any upcoming changes to aircraft configuration to establish the correct flight path. Once again software performs these functions. (5) Reposition control surfaces, throttles, and radio frequencies as needed. The autoflight computer sends control signals to the positioning servos for this purpose. (6) A human pilot can see and feel the aircraft change position when a control surface is moved; the autopilot system requires an electrical feedback signal for this purpose. And again the computer software will analyze the feedback data to confirm correct control of the aircraft. Of course, this process will repeat and continue through the entire flight.

Individual Autopilot Elements

Gyros

In order to determine the aircraft attitude, an autopilot must rely on the stability of gyroscopic sensors. Commonly called a **gyro**, the purpose of a gyroscope is to remain stable in space regardless of any movement of the gyro mounting support, or frame. The traditional gyroscope generates stability through the use of a spinning mass as seen in Fig. 17-34. These are called **rotating mass gyros**. This is the same concept that allows a bicycle rider to stay upright on two wheels; the spinning mass of the bike wheels creates stability through gyroscopic action. Aircraft gyros are mounted on a gimbal platform which contains some form of rate sensor which can detect aircraft motion. The combination of a spinning gyroscope and a gimbal platform allows the assembly to remain parallel to the earth's surface regardless of the aircraft's attitude. A simple autopilot may only contain one gyro/rate sensor assembly; complex systems contain at least three. In order to measure movement around the longitudinal, lateral, or vertical axis, a minimum of three gyro/sensor assemblies are needed (see Fig. 17-33).

The rate sensor used to create an electrical signal during aircraft movement must be extremely sensitive so as not to affect the stability of the gyro. A common means to achieve this uses a transformer-like device which requires no physical connection between moving parts.

In this way no friction is developed, and very little mechanical force is evident to restrict the movement of the gyro. One type of signal-generating device is called an **EI pickoff** and is diagrammed in Fig. 17-35. The pickoff consists of three coils mounted on an E-shape piece of laminated steel. The coils wound on the outer legs of the E are connected together in such a phase relationship that the voltages induced from the center coil cancel. A movable steel armature, called the I member, provides a low-reluctance path for the magnetic field. When this armature is moved relative to the E section, it changes the ratio of coupling between the secondary windings and the primary, and this changes the value of the induced voltages in the outside legs so that they are no longer equal. The result is a voltage that is either in phase or out of phase with the excitation voltage. Note that the excitation voltage is applied to the center leg of the E section.

The electric voltage output from the secondary coils of the EI pickoff assembly is proportional to the displacement of the elements away from the null position. The null is the mechanical position that results in zero electric output; it is indicative of the fact that the aircraft is in its proper flight position in relation to the reference established by the gyro unit. Movement of the aircraft away from the established

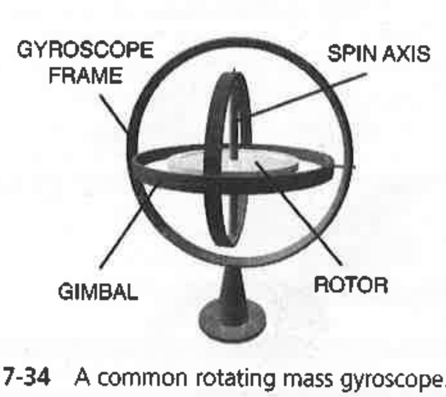


FIGURE 17-34 A common rotating mass gyroscope.

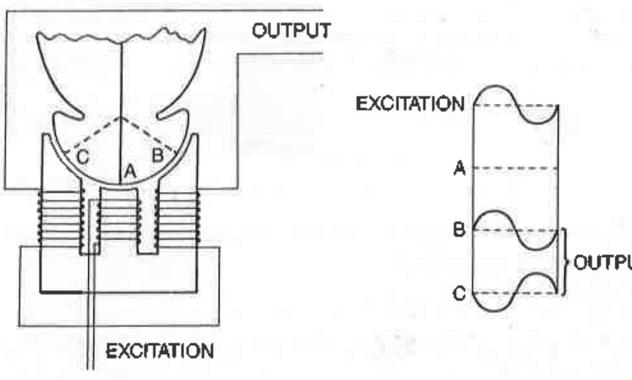


FIGURE 17-35 Electromagnetic signal-generating device for a gyro sensing unit.

flight reference causes relative mechanical displacement of the pickoff elements away from the electrical null, thus producing an electric output voltage that is the signal to the system calling for a corrective action.

Another option to the rotating mass gyro employs no moving parts and therefore creates a much more accurate and reliable system. The ring laser gyro (RLG) does not rely on the gyroscopic force produced by a spinning mass; instead, the RLG detects aircraft motion through the use of accurate rate sensors which measure changes in light frequency. This system requires a high voltage of approximately 3.5 KV to power two helium-neon lasers and produces a digital output that can be used by modern autoflight systems.

The term *laser* stands for "light amplification by stimulated emission of radiation." The RLG system utilizes a helium-neon laser; that is, the laser's light beam is produced through the ionization of a helium-neon gas combination. A typical RLG is shown in Fig. 17-36. This system produces two laser beams and circulates them in a contrarotating triangular path. As shown in Fig. 17-37, the high-voltage potential between the anodes and cathode produces two light beams traveling in opposite directions. Mirrors are used to reflect each beam around an enclosed triangular area. The resonant frequency of a contained laser is a function of its optical path length. When the RLG is at rest, the two beams have equal travel distances and identical frequencies. When the RLG is subjected to an angular displacement around an axis perpendicular to the plane of the two beams, one beam has a greater and the other a shorter optical path. Therefore, the two resonant frequencies of the individual laser beams change. This change in frequency is measured by photosensors and converted into a digital signal. Since the frequency change is proportional to the angular displacement of the unit, the system's digital output signal is a direct function of the angular rate of rotation of the RLG.

The RLG system is typically coupled to a complete navigation system. The digital signals from the RLG can be used to control autoflight functions. An inertial sensor assembly containing the triangular lasers is shown in Fig. 17-38. Strapdown technology makes possible a new era of aircraft safety. The elimination of moving parts greatly improves this system's reliability.

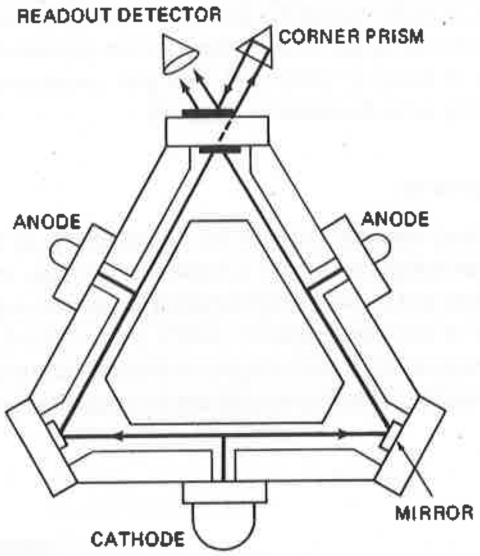


FIGURE 17-37 A pictoral diagram of a ring laser gyro. (*Honeywell.*)

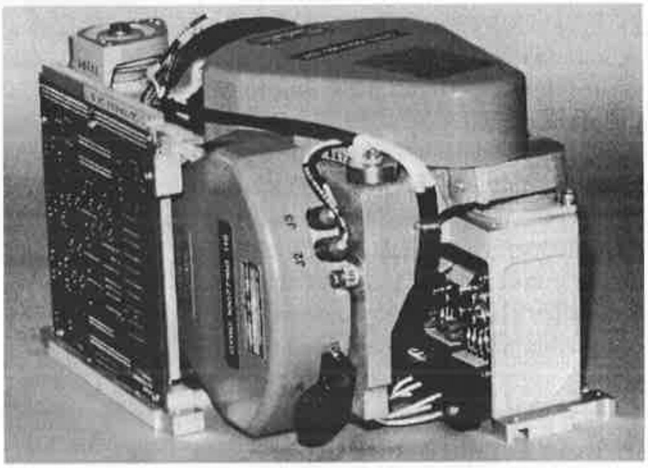


FIGURE 17-38 An inertial sensor assembly containing three ring laser gyros. (*Honeywell.*)

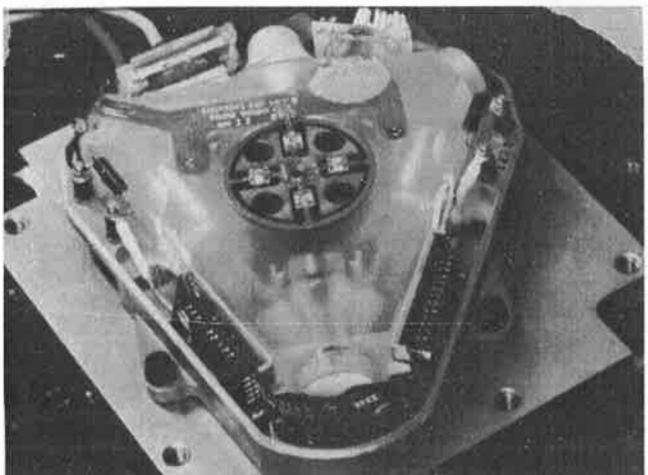


FIGURE 17-36 A ring laser gyro. (*Honeywell.*)

During installation or inspection of any gyro system, it is important that the assembly be aligned correctly with the aircraft axis; this can be performed through accurate measurements or through electronic alignment. Traditional rotating mass gyros are relatively high-maintenance systems due to their high-speed rotation and delicate nature. Laser gyros, on the other hand, are more reliable and less prone to failures. In the event of an autopilot system malfunction, the electrical output signals from a gyro rate sensor can easily be tested according to the aircraft service manual.

Accelerometers

As the name implies, an **accelerometer** is a device that senses acceleration; and because this is a vector force, both magnitude and direction must be measured. Since the aircraft can move in three dimensions a minimum of three accelerometers are needed; one to measure pitch, roll, and yaw movements. Accelerometers were discussed in Chap. 15.

Air Data Systems

The information obtained through the measurement of the air mass surrounding the aircraft is known as air data; systems that collect and record this information are known as **air data systems** or **air data computer (ADC)** systems. Air data must be collected to determine airspeed, altitude, and vertical speed of the aircraft. This is accomplished by measuring both static and pitot pressure, as well as the static and true air temperatures. **Pitot pressure** is a measure of the air pressure as it is pressed into the front of a moving aircraft; **static pressure** is the absolute pressure of the undisturbed air that surrounds the aircraft. **Static air temperature (SAT)** is the temperature of the undisturbed air surrounding the aircraft and **true air temperature (TAT)** is the temperature of the air as it is compressed by the moving aircraft.

There are basically two types of air data systems; pneumatic and electropneumatic. Earlier air data systems relied solely on pneumatic pressures to drive pressure-sensitive instruments as shown in Fig. 17-39*a*. If a pneumatic system was connected to an early autopilot, the static and pitot tubing,

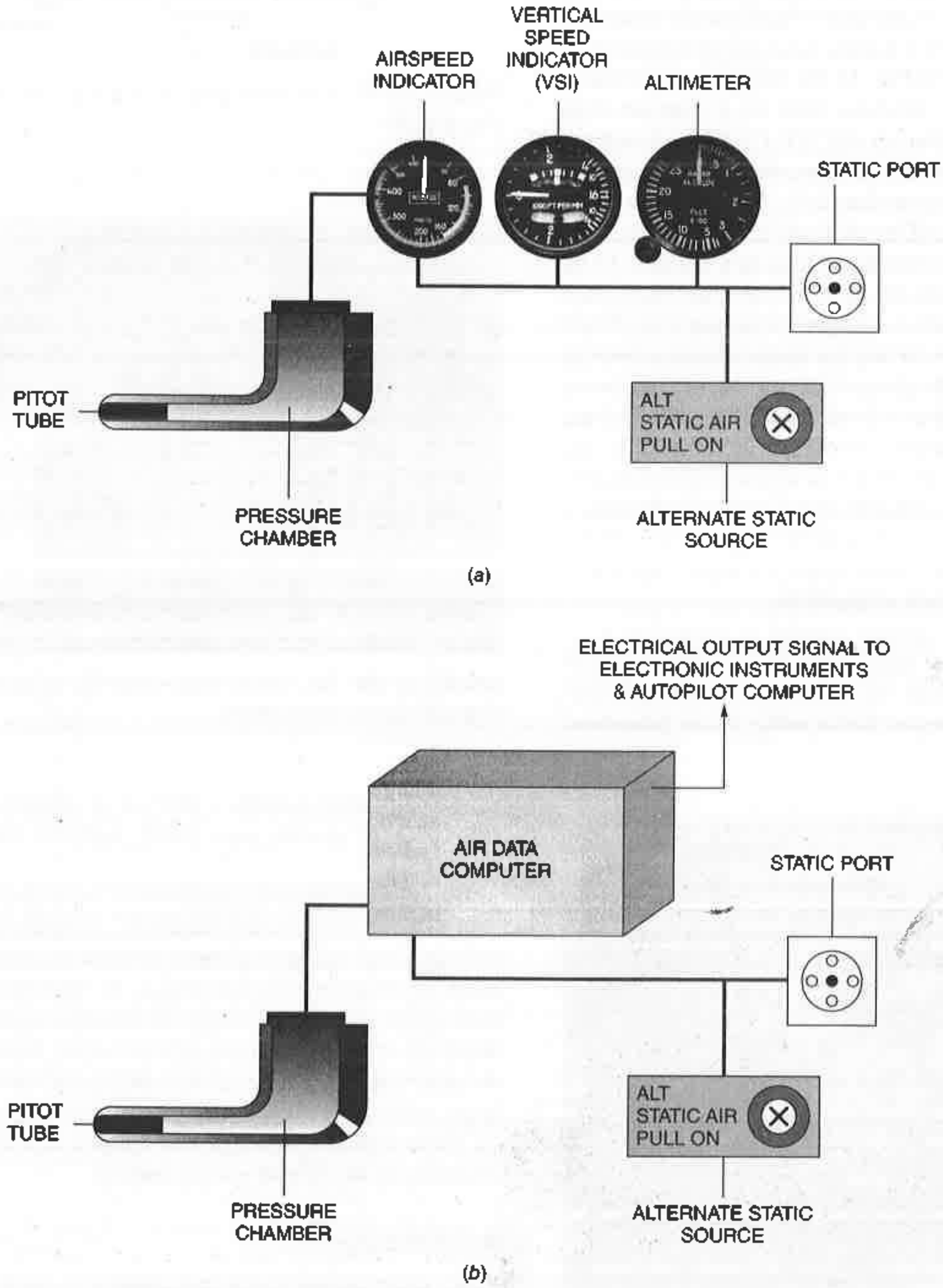


FIGURE 17-39 Air data systems: (*a*) pneumatic and (*b*) electropneumatic.

or "plumbing," was connected to the autopilot system as well as the instruments. The electropneumatic system uses an ADC to monitor pitot pressure, static pressure, and air temperature and determine various parameters such as airspeed, altitude, and vertical speed. The ADC then outputs either an analog or digital signal which is sent to the autoflight computer and the electrically operated instruments. All modern aircraft use an ADC system; however, some still maintain pneumatic systems for backup instruments.

Compass Systems

Since the magnetic compass is inherently unstable and lacks accuracy, a modern electronic compass system has become necessary for autoflight navigation functions. The electronic compass, often called a remote compass or slaved compass system, contains an electronic unit that measures the earth's magnetic flux. Another term used to identify this system is **magnetometer**. The remote sensor unit is called the flux detector or flux valve and produces an electric signal relative to the magnetic heading of the aircraft. A typical flux detector requires an input of 115 V ac, or 28 V ac at 400 Hz; the output voltage/phase is a function of the alignment of the detector with the earth's magnetic field. The flux detector shown in Fig. 17-40 is mounted inside the wing structure of a composite airplane.

Since the flux detector must accurately measure the earth's magnetic field, it is an extremely sensitive unit and care must be taken to ensure proper installation. The unit is typically installed near the aircraft wingtips to prevent interference from any electrical system that might create magnetic fields. The flux detector must also be carefully aligned with aircraft and tested for accuracy after installation.

Inertial Reference Systems

A combination of laser gyros and accelerometers are used to measure angular rates and accelerations in a system known as the **inertial reference system (IRS)**. The theory of operation is that if the IRS can accurately measure any change in position, it can also determine the aircraft's location, direction of travel, and other navigational data. The IRS uses an elaborate computerized processor known as the inertial reference unit (IRU) which contains three laser gyros and three accelerometers. There is typically a minimum of two IRUs on each aircraft in order to provide the redundancy required for safe flight. The newest IRSs are often called micro-IRS units because they have been reduced in size and weight through the use of modern technology.

IRSs are a relatively expensive system and commonly used only on corporate and transport-category aircraft which fly intercontinental routes. The output data from an IRS is a primary input for modern autoflight systems. In order to calculate aircraft position, the aircraft's initial latitude and longitude must be programmed into the system. Since the IRS is always found on modern computerized aircraft, any fault isolation or system tests would be conducted using the aircraft's centralized maintenance computer system.

FIGURE 17-40 A typical flux detector for an electronic compass system.

Servos

A device used to automatically move the aircraft's control surface or engine throttles in response to an autopilot command is known as a **servo**. There are three common types of servos; pneumatic, electric, and hydraulic; although some aircraft contain a hybrid system combining both electrical and hydraulic components. Pneumatic servos are vacuum-actuated units used on simple autopilots for light aircraft. These units have limited range of travel and provide a relatively weak actuating force; therefore, these systems are not used on modern aircraft.

Electric servos employ a simple electric motor and clutch assembly to connect autopilot commands to the aircraft flight controls. As seen in Fig. 17-41, an electric motor drives a clutch and capstan drive assembly; the capstan connects to a small ($\frac{1}{8}$ in.) control cable called the bridal cable. The bridal cable is used to move a mechanical bellcrank assembly which in turn moves the control surface through a larger ($\frac{1}{4}$ in.) control cable. This figure should be used as an electric servo installation example; the exact arrangement and control cable size will vary between aircraft.

Due to their simplicity and reliability, electric servos are very common on many types of aircraft. In all installations a clutch mechanism must be installed for manual override by the pilot in the event of a system failure. This is typically a simple friction-type clutch designed so the pilot can manually override a failed servo. An electric clutch will also be installed on all servos of this type; this clutch is used for autopilot disconnect by command of the pilot or the autoflight computer.

Large aircraft require a powerful autoflight system which uses electrical signals to activate the hydraulic servo. Most transport-category aircraft contain a central hydraulic system to move flight controls such as rudders, flaps, and ailerons. The servos use a solenoid-activated valve to regulate hydraulic fluid and change control surface movement. The autopilot computer sends an electrical signal to the solenoid, which in turn controls

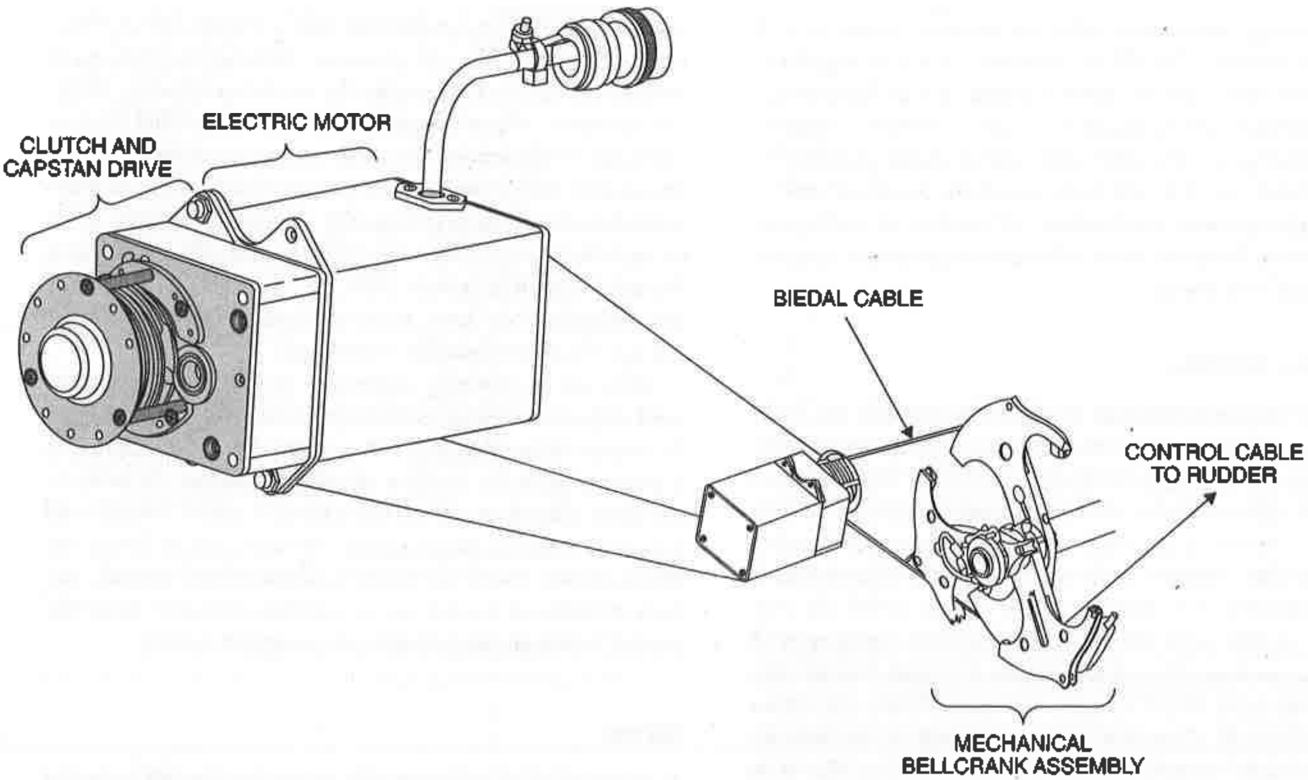


FIGURE 17-41 Electric servo for rudder control.

the flow of hydraulic fluid, which in turn moves the appropriate control surface.

The Boeing B-787 and Airbus A-380 are the first commercial aircraft to incorporate electrohydraulic servos. These systems use large electric motors to power dedicated hydraulic pumps that control one or more flight controls. The B-787 is currently the only civilian aircraft that employs electrohydraulic actuators as the primary means to position certain control surfaces.

Servo Feedback Systems

To inform the autopilot computer that the servo has successfully moved a control surface, a feedback signal is required. An electrical signal that is directly proportional to the movement of the servo, the actuator or the control surface is called a **feedback signal.** There are two common types of feedback systems; **ac synchro** and **differential transducer**. Any type of servo can employ an ac synchro feedback system. Simply put the ac synchro is a variable transformer device that monitors angular displacement as described earlier in this chapter (see Fig. 17-7). **Differential transducers** are also used to create an autopilot feedback signal. The two common types are the **linear voltage differential transducer** (LVDT) and the **rotary voltage differential transducer** (RVDT). These systems were discussed earlier in this chapter (see Fig. 17-10). When troubleshooting feedback systems consider that the electrical coils of the transformer are very reliable; therefore, both the ac synchro and differential transducers seldom fail. However, mechanical components such as pivot bearings can become worn causing inaccurate readings. Also any mechanical linkage connecting the sensors to the control surface can become worn or bind; the mechanical systems might also require adjustment periodically to maintain accuracy of the feedback loop.

Yaw Damper

Although the **yaw damper (YD)** is a system, not a component it will be presented here because it is a vital element of many autoflight systems. The wing design on modern high-speed aircraft causes a stability problem known as dutch roll, a slow oscillation of the aircraft about its vertical axis. This constant oscillation causes passengers to become uncomfortable and even sick. The pilot can correct for dutch roll by manually adjusting the rudder; however, this requires constant attention and becomes tiresome and distracts the pilot from more important duties.

Modern autopilots typically incorporate a system designed to control the rudder and eliminate dutch roll; this system is called the *yaw damper*. On most aircraft, the yaw damper can operate independent of the autopilot; however, the system shares many of the same controls, sensors, and other components.

TYPICAL AUTOMATIC PILOT AND FLIGHT CONTROL SYSTEM

Automatic pilots are manufactured in many configurations by a number of companies. Some systems are comparatively simple, while others become complex, especially when integrated with navigation systems. As explained previously, all systems utilize gyros to sense aircraft attitude and provide signals for correction. More advanced systems, commonly found on modern aircraft, receive signals for gyros as well as numerous other systems. This allows for an autoflight system capable of virtually all phases of flight from takeoff to landing. This section of the text will present several common autopilot/autoflight systems.

The first system presented is found on older piston-engine aircraft, such as a Piper Twin Comanche or Cessna 310. These systems employed analog technologies, and on many aircraft they have been replaced by lighter and more reliable digital autopilots.

This system includes not only the basic elements of autopilot operation but also components that give it all the capabilities of an automatic flight control system. A number of systems by other manufacturers utilize similar principles and perform the same functions.

The system described here can be programmed to fly a predetermined course (either NAV or RNAV), maintain a selected altitude, capture a VOR radial or ILS beam from any angle, make back-course approaches, and perform other functions. The system also includes automatic pitch trim, pitch synchronization, pitch integration, and altitude control. The computer portion of the system can also be used to display computed command data on a director-horizon indicator (flight director) and give directional data on a horizontal-situation indicator. Thus the aircraft is provided with a fully integrated flight control system.

System Components

The arrangement of the principal components of an analog automatic pilot and flight control system is shown in Fig. 17-42. The basic autopilot is composed of the controller, gyros, servos, and the section of the computer-amplifier that accepts signals from the gyros and converts them into flight commands for the servos. The autopilot controller, or control panel, is used as the interface between the pilot and the automated system. Typically, a variety of operating functions can be selected and any preflight programming can be done using this panel. A thorough description of an autoflight control panel will be presented during review of an upcoming system.

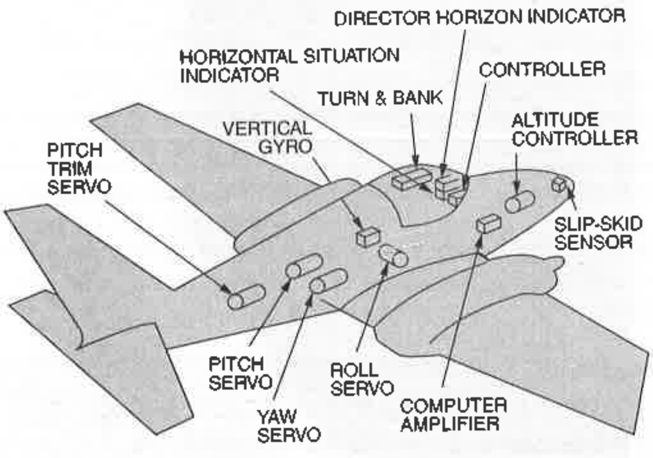


FIGURE 17-42 Arrangement of the components of an automatic pilot and flight control system. *(Bendix King by Honeywell.)*

FIGURE 17-43 Horizontal situation indicator (HIS).

The **horizontal situation indicator (HSI)** is a panel-mounted instrument that combines heading information (compass data) and NDs (VOR and ILS/glide slope). By combining instruments, the HSI reduces pilot workload and improves safety. The HSI receives navigational data from the autopilot computer for display of aircraft heading and any course deviation. A typical HSI is shown in Fig. 17-43.

The **director-horizon indicator** is another multifunction panel-mounted instrument found on many aircraft; other common names for this unit are **flight director (FD)** and **attitude director indicator (ADI)**.

This instrument, shown in Fig. 17-44, serves several functions. It is an attitude indicator and an attitude sensor. That is, it senses attitude and develops electric signals that are sent to the computer-amplifier. These signals are amplified and sent to the primary servos commanding control-surface movement for control of pitch and roll. At the same time, the instrument is indicating the degree of pitch and roll for the information of the pilot.

The vertical gyro in the instrument can be driven either by a vacuum system or electrically, depending on the particular instrument selected for the system. Since the gyro remains vertical with respect to the surface of the earth, the pitch and roll movements of the airplane cause relative movements between the gyro and the instrument case, thus producing signals for the autopilot and indications on the instrument.

Servos. Three primary servos control pitch, yaw, and roll by moving the elevators, rudder, and ailerons in response to commands from the autopilot. These servos

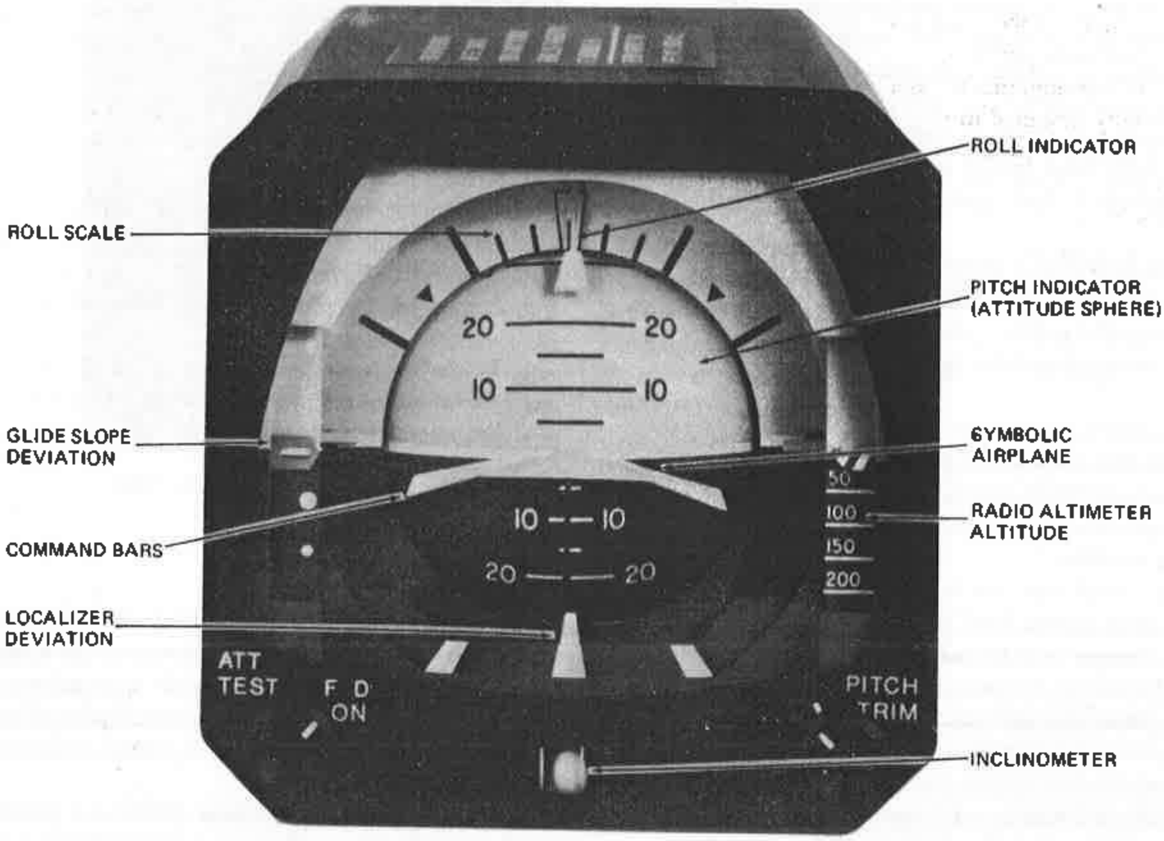


FIGURE 17-44 Atitude director indicator (ADI).

are small electric motors that drive capstans through magnetic clutches.

The **trim servo** is used to activate an elevator trim tab control to relieve long-term aerodynamic loading and generally assist in smoother operation of the elevator surface without requiring large amounts of power from the primary servo. Its operation is either automatic, using the composite pitch error signal from the computer-amplifier, or both automatic and manual if an optional manual electric trim adapter is utilized.

The location and installation procedures for all the servos depend on the type of aircraft in which they are being installed. Detailed instructions concerning cable tensions, clutch settings, and other pertinent data are included in the installation kit for the particular aircraft involved.

Computer-Amplifier. Figure 17-45 shows the computer-amplifier for the Bendix M-4D automatic flight control system. The computer-amplifier is the heart and brain of the system. It consists of plug-in modules, one of which is peculiar to a particular aircraft-type installation and another of which relates to a specific type of flight director installation. The modules can be removed and replaced easily in case of malfunction.

The computer-amplifier combines inputs from the gyro sensors, control panel, and heading and radio sources (NAV and RNAV) to compute appropriate electrical commands

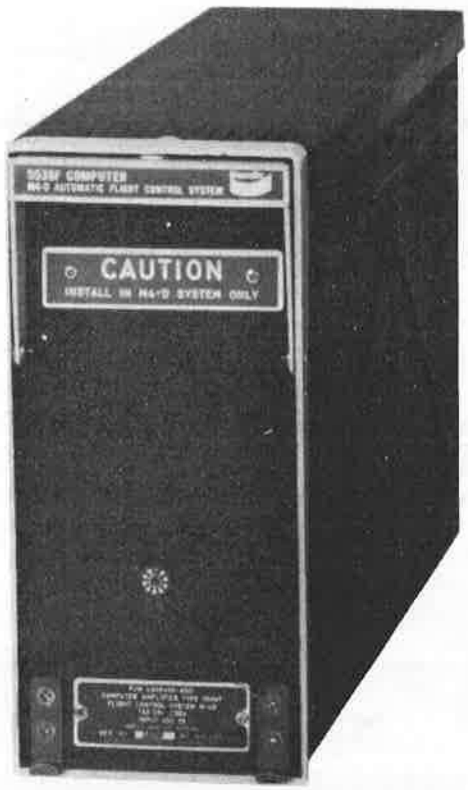


FIGURE 17-45 Autopilot computer. (*Bendix King by Honeywell.*)

and deliver them to the control-surface servos and to the flight-director instrumentation.

The computer-amplifier is mounted on a shock-absorbing rack especially designed to receive the LRU. The location of the installation depends on the type of aircraft in which the equipment is being installed. The installation kit for the particular aircraft gives detailed instructions.

Many corporate and commuter type aircraft are equipped with an integrated digital system known as **Primus**, produced by Honeywell. The integration combines the autoflight systems, all electronic displays, as well as engine indicating and warning systems. The Primus systems were produced in a variety of configurations designed for a particular turbine-powered or turboprop aircraft. The following discussions will focus on a generic Primus system, always consult current approved data for specifics about any given aircraft. The major system elements of the IAS include the following systems; the electronic display, attitude and heading reference, air data, automatic flight control, weather radar, integrated radio, and flight management. There are also several optional systems such as inertial reference and traffic alert and collision avoidance (TCAS); although most aircraft employ these systems. The high level of integration allows the integrated avionics computer (IAC) to perform the functions previously completed using several LRUs. The IAC uses very large-scale integrated circuits which are surface-mounted to multiple circuit cards within the LRU. The IAC replaces several conventional LRUs, such as the flight warning, the flight management, and the display management computers. This level of integration improves system reliability, improves overall safety, and reduces aircraft weight. Figure 17-46 shows a simplified diagram of the Honeywell integrated avionics system (IAS); please refer to this diagram during the following discussion.

The IAS is designed for data transfer in a digital format; there are several formats used on this system including ARINC 429 and ASCB. Data bus systems are discussed in Chap. 7. Some electrical signals are analog or discrete; such as autopilot disconnect, or servo control signals. On the top of the diagram, there are five electronic display units. The outermost displays are the captain's and first officer's PFDs, moving inboard, the next two displays are MFDs, and the center display is the EICAS use to display engine and airframe systems data. This system employs line select keys at the bottom of the bezel on the MFDs and the EICAS display. The IACs are used to input data to all displays.

The software for the flight management and autoflight systems is contained in the two IACs. Several "subsystems" send digital data to the IACs as needed for aircraft control; these subsystems include the air data computer, the attitude heading reference unit (AHRU), and the data acquisition unit. After receiving data from the various aircraft systems, the IAC transmits the necessary control signals to the flight control servos located at the bottom of the diagram. This system uses electric servo motors connected to a capstan drive through the clutch assembly.

The air data computer system monitors pitot and static pressure to create a digital signal for the IAC. The AHRU monitors magnetic heading through the flux valve and measures accelerations using microsensors. The AHRU transmits all necessary attitude and heading information to the IAC through a digital data bus.

The flight management system (FMS) software within the IAC is responsible for control of all lateral and vertical navigation guidance. To provide high-accuracy long-range navigation, the FMS circuitry connects to the IRS, GPS, and/or VOR/DME as needed. With links to the onboard navigation sensors, the computer develops an FMS position. The fundamental purpose of the FMS is to provide navigational information to the IAC and autoflight system. The software data loader (center of the diagram) is used for system software updates. Updates to navigational charts must be performed on a regular basis, updates to IAC system software can also be installed using the data loader. Specific FMS flight information is entered by the pilot using the control display unit (CDU) (see the left side of Fig. 17-46). The CDU is located on the center pedestal between the two pilot seats. The CDU is the main input device for a variety of navigational information, such as destination airports, flight routes, and waypoints. This type of data entry unit is now found on most aircraft with a complex autoflight and flight management system. A typical CDU is shown in Fig. 17-47.

The autoflight system receives inputs from the various aircraft and navigational systems through the IAC as just described. The IAC performs all necessary autoflight calculations in accordance with the guidance panel controller. The controller is located in the center of Fig. 17-46; and a detail of the panel can be seen in Fig. 17-48. The controller is divided into three sections; the two outer elements control the five electronic display units, the center section is used for autoflight controls. The A/P push-button is used to engage the autopilot and yaw damper system. The Y/D push-button will turn on/off the yaw damper function of the autopilot. The CPL push-button is used to choose which PFD, captain's or first officer's, will provide navigational information to the autoflight system.

The guidance control panel includes a pitch wheel that is used by the pilots to "manually" trim the aircraft (pitch up or down). The 10 push buttons on the left side of the control panel are used to set autoflight functions. The pilot can choose various modes of operation as needed for a given flight condition. These include the following: (1) Heading mode—the system will fly the aircraft on a set heading, (2) NAV mode—the aircraft will follow the selected navigational route, (3) APP—is the mode used for a runway approach to land, (4) BC—used to fly a back-course instrument landing, (5) Bank—changes the angle of bank during autopilot turns, (6) STBY—standby mode, (7) FLCH—flight level change, (8) VS—the system will hold a selected vertical speed or rate of climb/descend, (9) ALT—the autopilot will hold a given altitude, and (10) VNAV—the system will follow a vertical navigation profile.

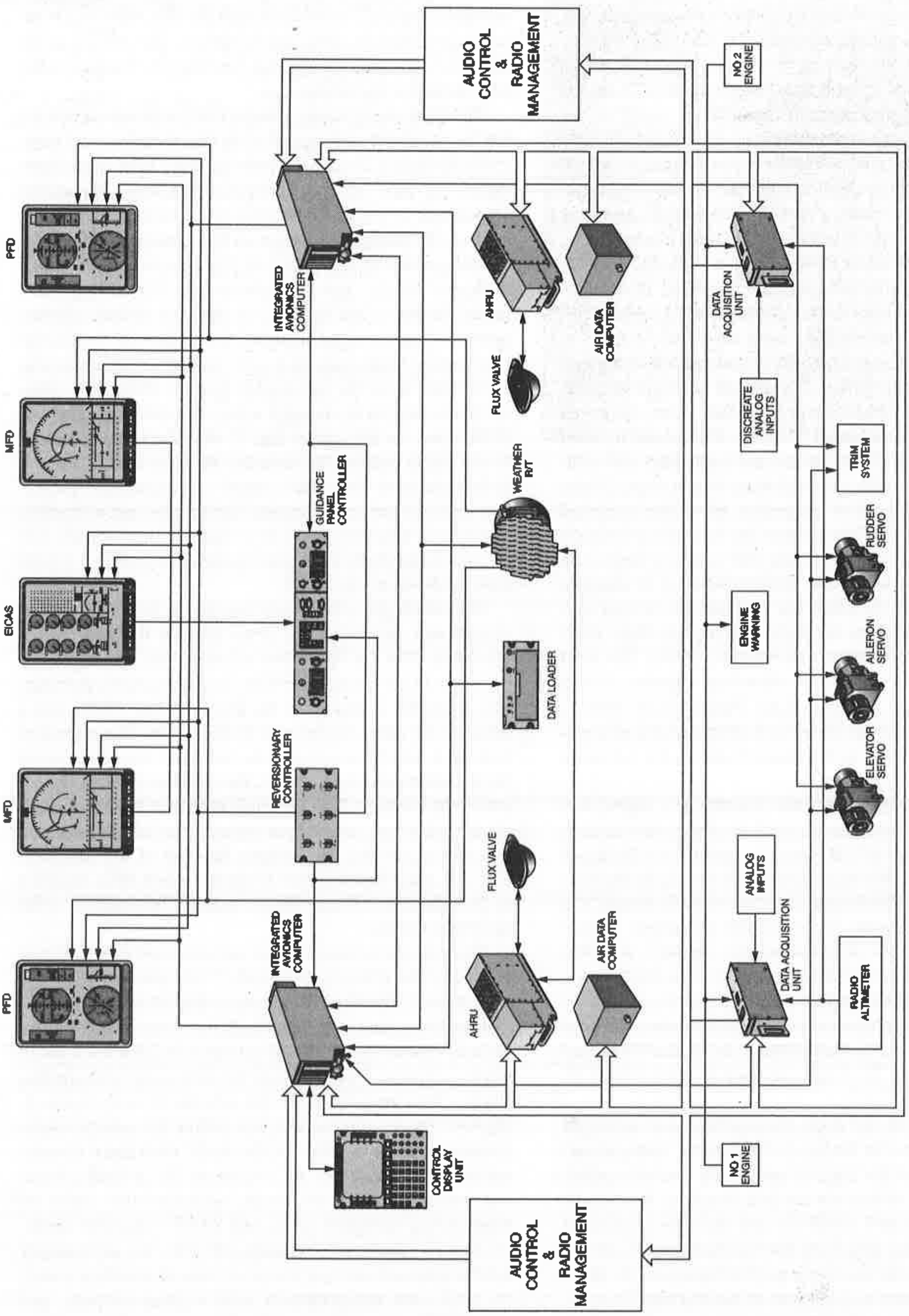


FIGURE 17-46 Primus integrated avionics system.

FIGURE 17-47 Control display unit (CDU). See also color insert.

THE BOEING B-757 FLIGHT MANAGEMENT SYSTEM

Many modern autopilot systems have become integrated with other systems and perform a variety of functions; these are often called **flight management systems (FMSs).** In general, some version of FMS is used on all transport-category aircraft; although on some planes, a different term may be used to describe the system or the FMS may be contained within the software of other processor units.

A typical FMS is capable of four functions; automatic flight control, performance management, navigation and guidance, and operation of status and warning displays. Simply stated, an FMS is a complex digital, autopilot/flight director system that is capable of flight control and thrust management to a least-cost or least-time configuration.

Figure 17-49 illustrates the components of the FMS on a Boeing 757. This system utilizes two **flight management computers** (FMCs) for redundancy purposes. During

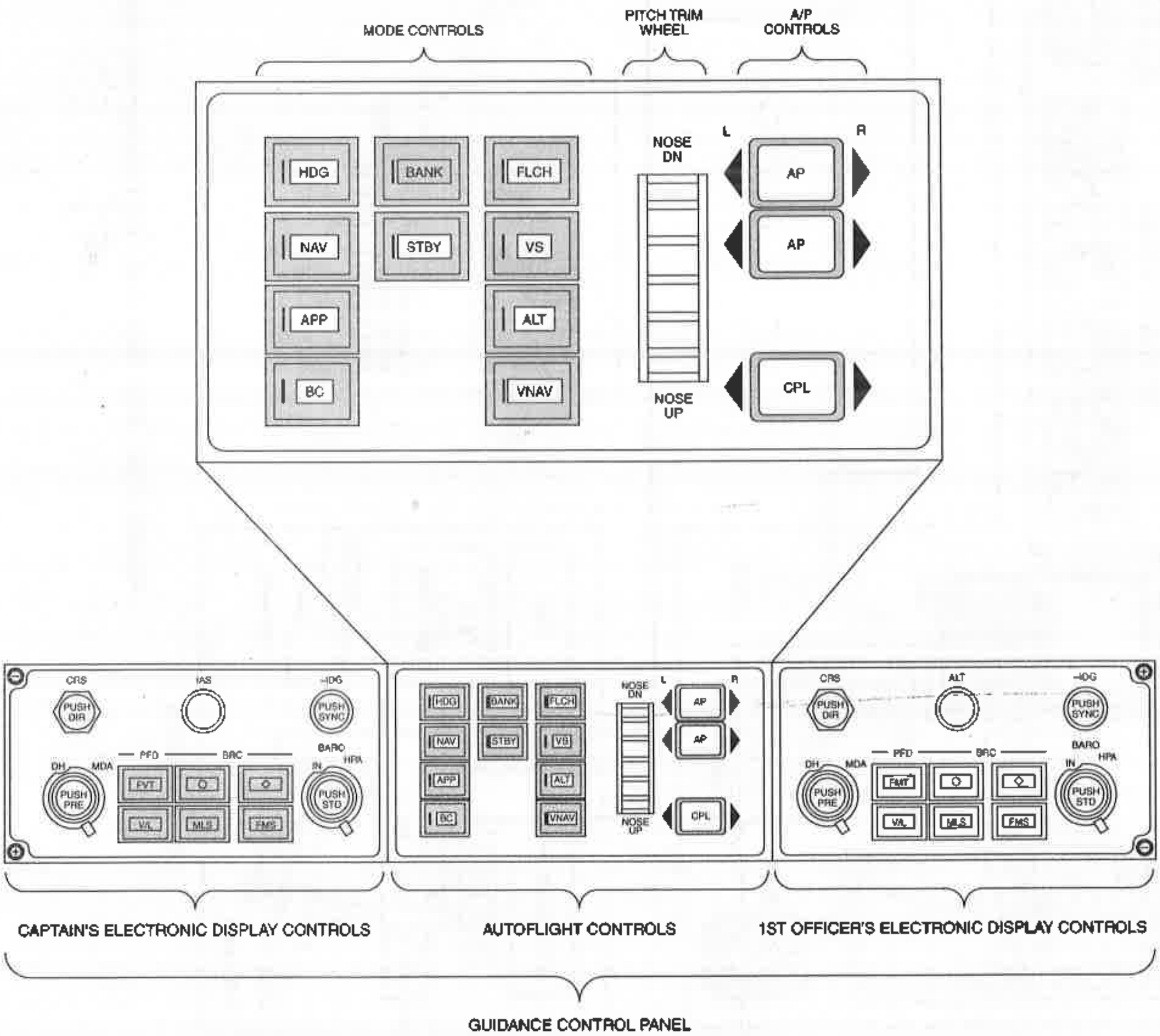


FIGURE 17-48 Autoflight controls.

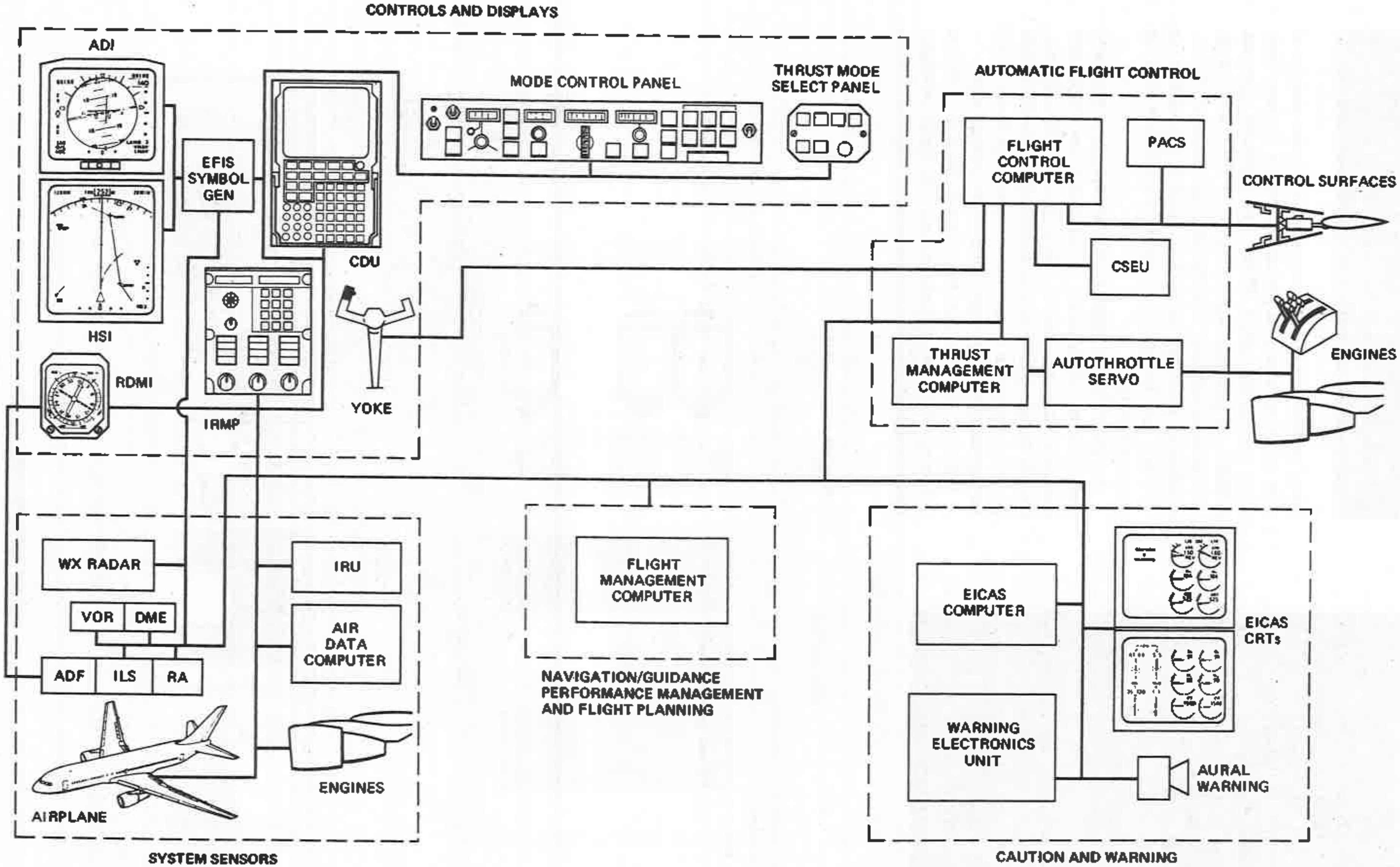


FIGURE 17-49 Block diagram of a flight management system. (*Boeing Company.*)

normal operation both computers **cross-talk**; that is, they share and compare information through the data bus. Each computer is also capable of operating completely independently in the event of one failed unit. An FMC receives input data from four subsystem computers: the **flight control computer** (FCC), the **thrust management computer** (TMC), the **air-data computer** (ADC), and the **engine indicating and crew alerting system** (EICAS) computer. The communications between these computers are typically in an ARINC 429 data format. Other parallel and serial data inputs are received from flight deck controls, navigation radios, and various airframe and engine sensors. Each vital component of the FMS is duplicated to ensure system reliability.

A flight management computer and control display unit are shown in Fig. 17-50. The FMC contains a 4-million-bit nonvolatile memory, which stores the performance and navigation data along with the necessary operating programs. Portions of the nonvolatile memory are used to store information concerning airports, standard flight routes, and various navigational aids. Since this information changes from time to time, the FMS incorporates a **data loader**. The data loader is a tape or disk drive that can be plugged into the FMS. Any data updates are entered periodically through the data loader.

The variable flight parameters for a specific flight are entered into the FMS by means of the alphanumeric keyboard of the **control display unit** (CDU) (Fig. 17-50). During preflight the flight crew first enters all flight plan information. Data such as initial latitude and longitude of the aircraft, navigational waypoints, destination, alternates, and flight altitudes are all entered into a temporary legend. The flight plan is then generated and displayed by the FMS. If the crew agrees with this flight plan configuration, the temporary information is transferred to active status. The performance data are selected in a similar manner. Performance data include takeoff, climb, cruise, and descent parameters. Performance can be set at a least-cost or least-time en route configuration.

During a normal flight, the FMS sends navigational data to the electronic flight instrument system. The EFIS then displays a route map on the EHSI. If the flight plan is altered by the crew, the EHSI map will change automatically. Since there are two CDUs in an FMS, during flight one unit is commonly used to display performance data, and the other is used to display navigational information. Both CDUs are located in the center console, between the pilot and copilot stations.

Fly-by-Wire

Many modern transport-category aircraft now employ **fly-by-wire (FBW)** design concepts. This design uses electrical wiring, circuits, and controls to replace cables and hydraulic systems found on traditional aircraft. Fly-by-wire is currently found on only the newest large aircraft, such as the A-380 and B-787, as well as some military aircraft; however, for years many aircraft have used electrical signals to move control surfaces. For example, the Cessna 310 uses an electric motor and simple controls for flap operation. In effect, this system

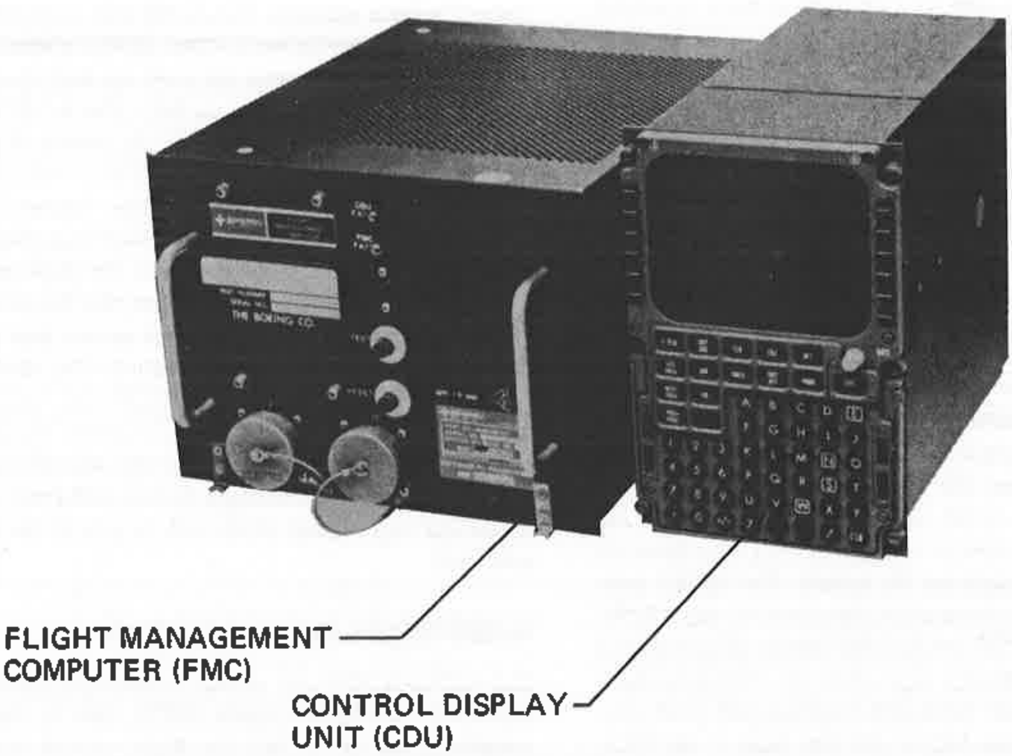


FIGURE 17-50 Flight management computer and control display unit.

operates the flaps "by wire." Modern FBW aircraft all contain multiple computer and redundant data systems in order to provide the safety needed for flight. These aircraft must also contain an elaborate electrical system that will provide the needed power for FBW controls in the event of multiple system failures.

Today's aircraft use electrical signals to move primary flight controls, such as elevators, rudders, and ailerons. Primary flight controls require constant repositioning by the pilot and therefore require a complex computerized system with multiple inputs from various sensors. A modern FBW design permits a more efficient aircraft which flies faster and saves fuel. This portion of the text will examine the basic design concepts of a fly-by-wire flight control system. It should be noted that although FBW systems are produced by different manufacturers and for different aircraft, they all contain many similarities. One of the most obvious similarities of all FBW aircraft is the level of integration between all instrumentation and control systems; this is made possible through the use of high-speed computer processors and large capacity digital memory.

The Boeing B-777 aircraft became the first commercial aircraft to be completely FBW. The system used on this aircraft is called the **autopilot flight director system (AFDS)** and operates using the ARINC 629 data bus standard for much of the system communications. The AFDS has two main purposes; to automatically control the airplanes attitude to meet navigational requirements set by the flight plan and to supply indications so the flight crew can manually control the aircraft. The system is capable of all facets of flight, from takeoff through cruise to autoland. The flight director function, previously discussed in this chapter, provides a visual reference to the pilot through the command bars on the PFDs. The crew uses the flight director command bars as a guide to control the aircraft.

The AFDS subsystems include: (1) AIMS—airplane information management system, (2) ADIRU—air data inertial reference unit, (3) SAARU—secondary attitude air data reference unit, (4) PFC—primary flight computer, (5) ACE—actuator control electronics unit, and (6) PCU—power control unit. The AIMS employs several line replaceable modules (LRMs) to integrate various systems by sharing common functions and components. AIMS integrates data collection, computing functions, power supplies, and output functions for several subsystems. A multitude of aircraft systems communicate with AIMS including the electronic instrument system; therefore, all flight director data is sent through the AIMS modules.

Figure 17-51 shows the basic components and related interconnects of the AFDS. Here it can be seen there are three autopilot flight director computers (AFDCs); these are the main processing units for the system. The AFDCs each receive redundant data from other processors via the ARINC 629 data bus. The AFDS monitors the various pilot activated inputs using three autopilot flight director computers. Each computer calculates the necessary response and sends output signals through three ARINC 629 data buses to the PFCs. The PFCs then send digital command signals back to the ACEs. The ACEs convert the information into analog signals for command of the power control units (PCUs). The PCUs each contain an electrically operated servo valve which controls hydraulic actuators that move the control surface. It is important to note that the actual force used for control surface movement is provided by the aircraft's central hydraulic system, the PCUs simply provide control of the hydraulics. Each control surface will be connected to one, two, or three PCUs depending on load demands.

As a control surface is moved, the PFC software calculates the backdrive commands which are sent to the AFDCs. The AFDCs then send the backdrive signals to the appropriate backdrive actuators which reposition the rudder pedals and/or control the wheel/yoke as needed (see Fig. 17-51). The backdrive actuators are needed to provide a "realistic" feel to the flight controls; for example, as the pilot moves the control wheel, the backdrive actuator applies a backpressure on the wheel. The actuator assembly contains an electric servo motor similar to those discussed earlier in this chapter. All fly-by-wire aircraft must incorporate a similar backdrive system.

The control panel for the AFDS is located within the glare shield just above the center electronic displays. As shown in Fig. 17-52, the AFDS mode control panel allows pilots to select a variety of autoflight and functions. This type of autoflight control panel is found on many transport-category aircraft.

The Airbus A-380 and the Boeing B-787 are also fly-by-wire aircraft and have added one more level of electrical sophistication to the flight control system; both aircraft employ electrohydraulic control surface actuators. Electrohydraulic actuators use powerful electric motors to drive dedicated hydraulic pumps designed to power a specific control surface actuator. The A-380 still employs a central hydraulic system similar to other Airbus planes; however, electrohydraulic actuators are used for backup systems in the event that the main system fails. The B-787 uses electrohydraulic actuators as the primary source of power for control surface movement.

Another design concept that has emerged with the development of the integration and large computer capacity of a fly-by-wire aircraft is known as **envelope protection**. Envelope protection is used to ensure that the aircraft never exceeds the operational limits and enters into an unsafe configuration, such as a stall condition. The autoflight system uses system software to calculate the "envelope" for safe flight. For example, if the pilot moves the flight deck controls in such a manner to take the aircraft outside this safety envelope, the autoflight system will ignore the command and only change pitch, roll, or yaw to the maximum safe limit.

A-380 Flight Control System

The Airbus A-380 uses an advanced flight control system called the **autoflight system (AFS)**. Due to the size and complexity of the A-380, the flight control system contains near 50 separate control surfaces, each monitored and

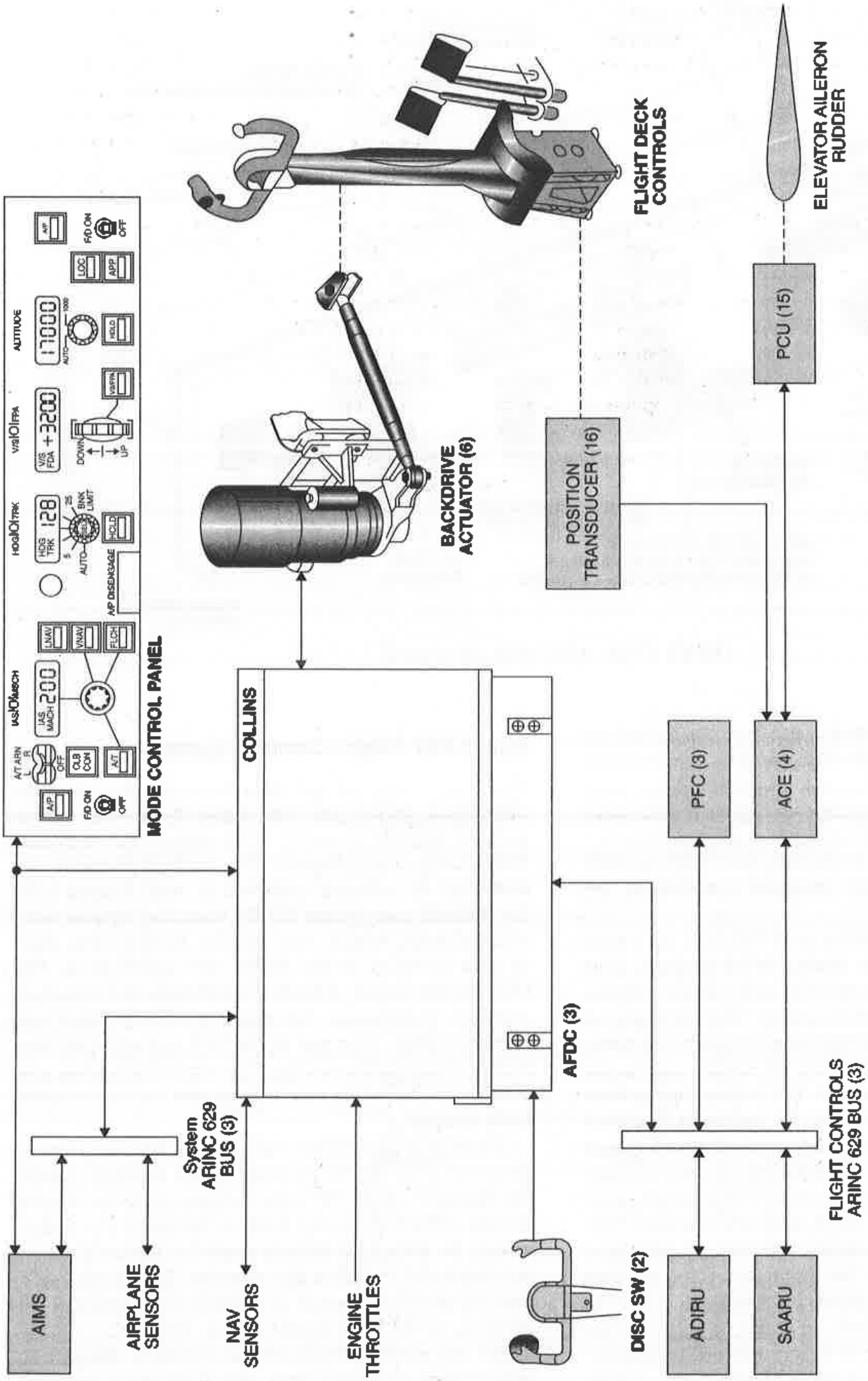


FIGURE 17-51 B-777 autopilot flight director system (FFDS).

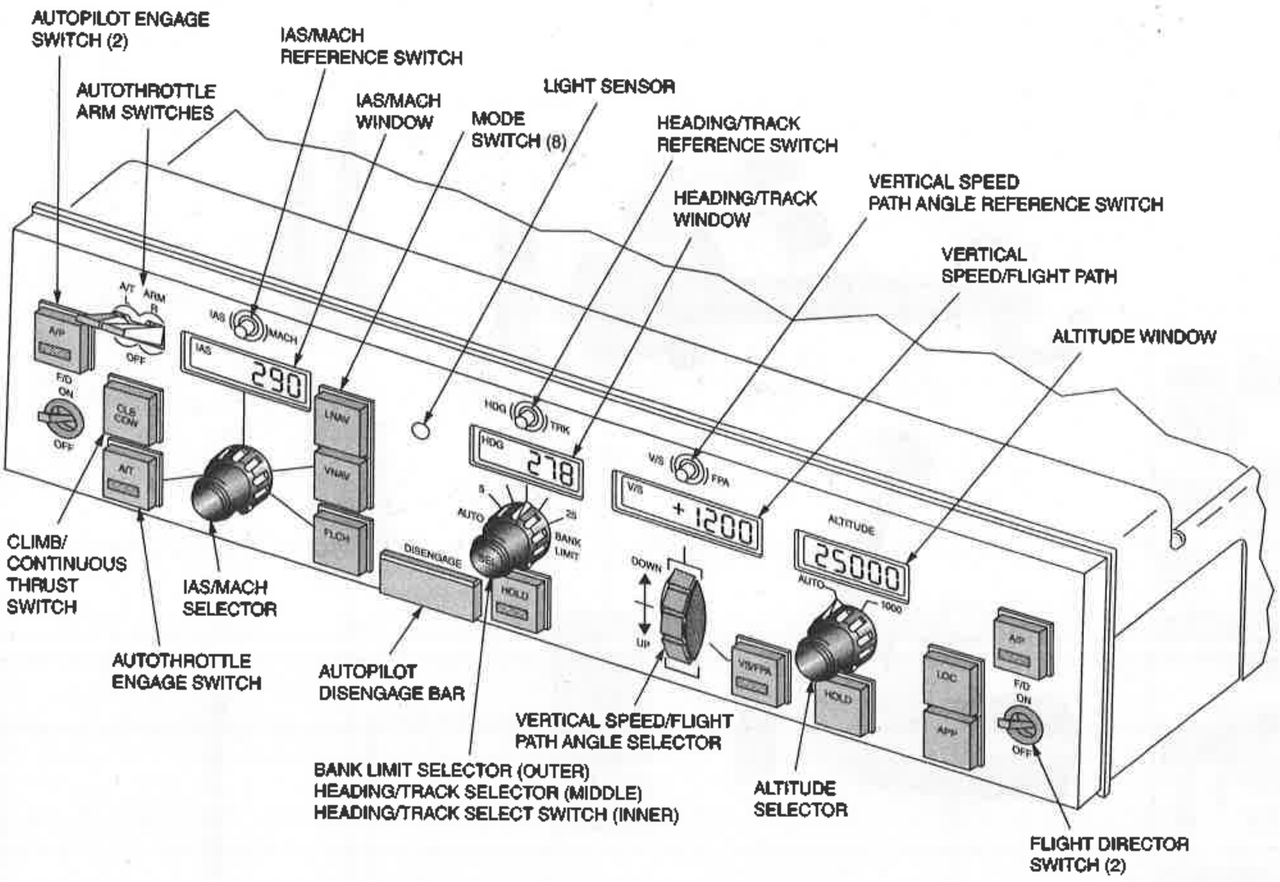


FIGURE 17-52 AFDS mode control panel.

activated by the AFS. The flight controls are divided into two categories, the primary flight controls and the slats and flaps. The primary flight control system uses three primary computers and three secondary computers to provide redundancy as shown in Fig. 17-53. The system also employs three secondary computers (SECs). Each computer, PRIM and SEC, can perform two functions; command computations and command executions.

If a malfunction is detected in A-380 AFS, all control functions will be passed to another PRIM computer. If all PRIMs experience a failure, each SEC will perform computation and execution functions as needed. When operating on secondary systems, only the flight control system will downgrade and the autotrim function is no longer available and all envelope protections are lost. The A-380 employs three different types of servo actuators for movement of control surfaces. Each servo is electrically controlled from one or more of the AFS computers. The three types of servo actuators are (1) conventional hydraulic actuators, (2) electrohydrostatic actuators, and (3) electrical backup hydraulic actuators. Conventional servos employ hydraulic actuators, operated from a central hydraulic system. The electrohydrostatic actuators are hydraulic units which contain their own electric motor and self-contained hydraulic system. Electrical backup hydraulic actuators use a combination of the conventional and electrohydrostatic actuators; these can operate in either mode and are used in the event of multiple system failures.

The B-787 Flight Control System

The B-787 is by far the most electronically controlled commercial aircraft yet. The digital fly-by-wire system uses an integrated processor which replaces the traditional flight management computer. The autoflight functions are controlled by software contained in what Boeing calls the common core system (CCS). Both fiber optical cable and traditional copper wire provide Ethernet-type digital data according to the ARINC 664 specification. The CCS increases data collection capabilities and improves autoflight performance; this allows for better control and improved safety. Also part of the CCS software functions include electronic sequencing of the retractable landing-gear system, the control-by-wire braking function, and electric brake actuators.

The most unique feature of the B-787 autoflight system is the use of 270 V dc electric motor–driven hydraulic pumps. The engineers of the 787 have designed dedicated electric systems with specific control functions that power four electric motors; the motors are directly coupled to hydraulic pumps installed to the control surface actuators. This design eliminates the need for long runs of hydraulic lines and increases efficiency of the flight control system. Due to their critical nature, the autoflight/flight control system is designed to receive electrical power from several power-conditioning modules.

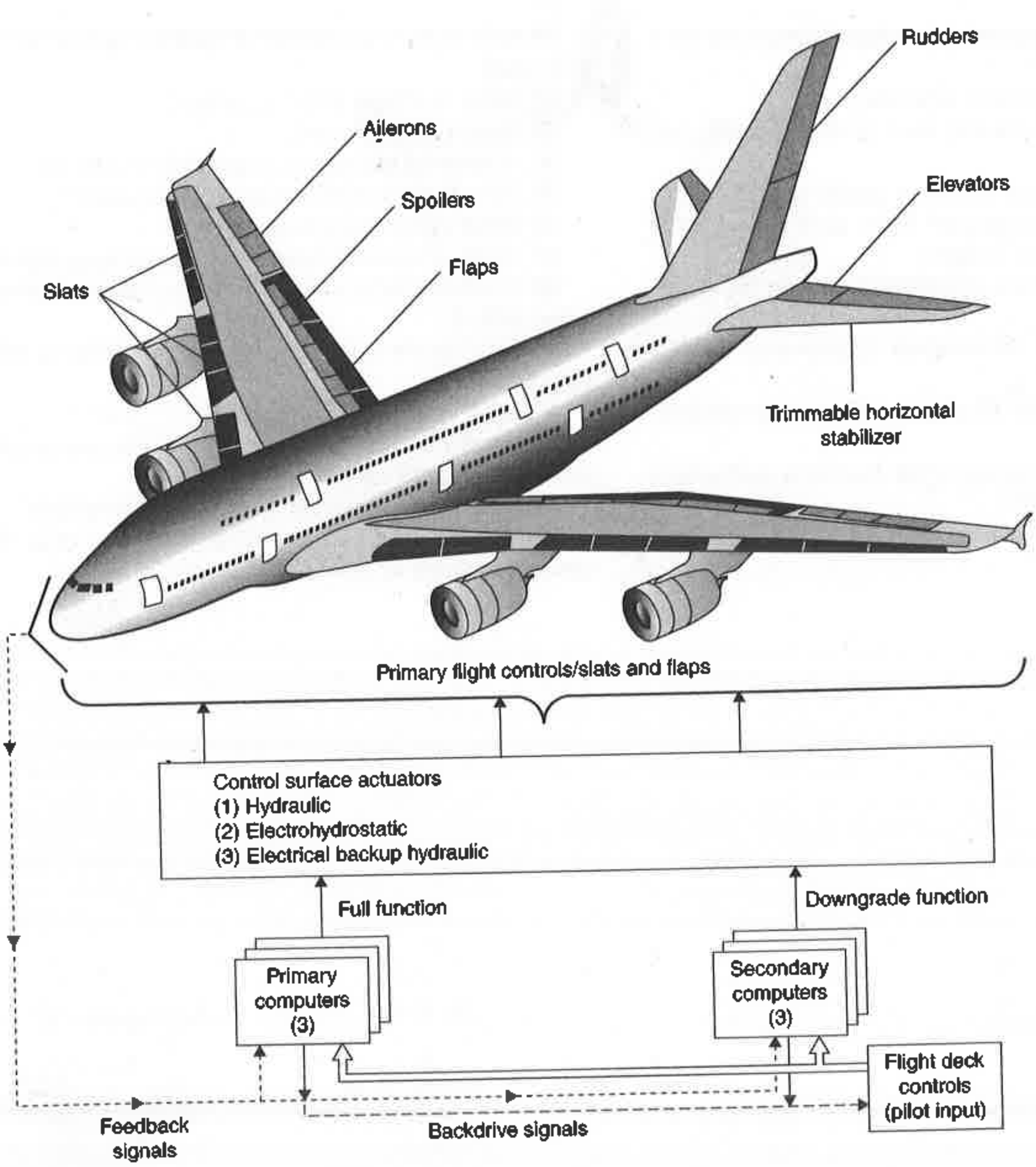


FIGURE 17-53 A-380 autoflight system.

REVIEW QUESTIONS

1. List some of the parameters that are indicated by electric instruments in aircraft.
2. What are some advantages of electric or electronic instruments compared to mechanical instruments?
3. Why is a tachometer important in the operation of an aircraft engine?
4. Explain why an electric tachometer is more suitable than a mechanically driven tachometer in large aircraft.
5. Explain the basic operating principles of an electric-operated tachometer.
6. Describe the operation of a thermocouple temperature indicator.
7. Explain the important factors in the installation of a thermocouple system.
8. What is an LVDT and how does it function?
9. What is a synchro system?
10. Describe the operation of a common synchro system.
11. Describe the operation of a float-type electric fuel-quantity indicator.
12. Explain the operation of a capacitor-type fuel-quantity indicator.
13. Why does the capacitance of the fuel-level sensor change as fuel level changes?
14. Describe a typical electronic flight instrument.
15. Describe the changes that have occurred between early and modern electronic instruments.
16. Explain how a flat panel display is used in a modern instrument system.
17. What is the function of the processor unit in an electronic instrument system?
18. What is meant by a 5-tube EFIS?
19. Explain what is meant by the term *integrated display system*.
20. What type of information is displayed on a PDF?

21. Describe a typical integrated display system for light aircraft.

22. What is an electronic flight bag?

23. What is meant by the term *synthetic vision*; and how is it used?

24. Describe a typical heads-up display system.

25. Describe the integrated flight deck found on a Boeing B-787 or Airbus A-380.

26. What are the basic differences between the EICAS and ECAM systems?

27. What type of information is displayed by the EICAS?

28. How does the EICAS display information concerning a failed system?

29. What are the fundamental functions performed by an autopilot system?

30. What is the difference between an autopilot and autoflight system?

31. Why is there a need for a feedback system for an autopilot?

32. What is a flight director system?

33. Describe a *servo* unit.

34. What is the purpose of a slip clutch on a servo?

35. What is the function of an air data system?

36. What are accelerometers?

37. What are common types of servos used by autopilots?

38. Describe the function of the yaw stability augmentation system.

39. Describe the basic concept of the strapdown technology theory.

40. What is a strapdown gyro?

41. What is the main advantage of the laser gyro as compared to a conventional gyro?

42. Describe the principle of a fly-by-wire system.

43. What is envelope protection and how does this concept improve air safety?

Appendix

USEFUL EQUATIONS

Ohm's law

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

where I = current (intensity of current flow)
E = voltage (emf)
R = resistance

Resistances in series

$$R_t = R_1 + R_2 + R_3 \cdots$$

Resistances in parallel

$$R_t = \frac{1}{1/R_1 + 1/R_2 + 1/R_3} \cdots$$

or

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \cdots$$

Two resistances in parallel

$$R_t = \frac{R_1 \times R_2}{R_1 + R_2}$$

Capacitances in series

$$C_t = \frac{1}{1/C_1 + 1/C_2 + 1/C_3 \cdots}$$

or

$$\frac{1}{C_t} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \cdots$$

Capacitances in parallel

$$C_t = C_1 + C_2 + C_3 \cdots$$

Inductances in series, no magnetic coupling

$$L_t = L_1 + L_2 + L_3 \cdots$$

Inductances in parallel, no coupling

$$\frac{1}{L_t} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} \cdots$$

Electric power in a dc circuit

$$P = EI \quad \text{or} \quad P = I^2R \quad \text{or} \quad P = \frac{E^2}{R}$$

where P = power, W
1 hp = 550 ft · lb/s = 746 W
1 J = 1 W/s

Frequency and wavelength

$$f = \frac{300000000}{\lambda}$$

$$\lambda = \frac{300000000}{f}$$

where f = frequency, Hz
λ = wavelength, m

Capacitive reactance

$$X_c = \frac{1}{2\pi fC}$$

where X_c = reactance, Ω
f = frequency, Hz
C = capacitance, F

Inductive reactance

$$X_L = 2\pi f L$$

where X_L = inductive reactance, Ω
f = frequency, Hz
L = inductance, H

Resonant frequency

$$f = \frac{1}{2\pi\sqrt{LC}} \quad \text{or} \quad f = \frac{0.159155}{\sqrt{LC}}$$

Impedance: series circuit

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

where Z = impedance, Ω
X_L = inductive reactance, Ω
X_C = capacitive reactance, Ω
R = resistance, Ω

Impedance: parallel circuit

$$\frac{1}{Z} = \sqrt{(I/R)^2 + (1/X_L - 1/X_C)^2}$$

or

$$Y = \sqrt{G^2 + (B_L - B_C)^2}$$

and

$$Z = \frac{1}{Y}$$

where Z = impedance, Ω
X_L = inductive reactance, Ω
X_C = capacitive reactance, Ω
R = resistance, Ω
$Y = 1/Z$
$G = 1/R$
$B_L = 1/X_L$
$B_C = 1/X_C$

Impedance: parallel (tank) circuit

$$Z_{par} = \frac{L}{RC}$$

Copper Wire
Single Strand, American Wire Gauge

Gage	Diameter, mils	Cross section, cir mils	Resistance, Ω/1000 ft (25°C)	Weight, lb/1000 ft
0000	460.0	211 600.0	0.0500	641.0
000	410.0	167 800.0	0.0630	508.0
00	365.0	133 100.0	0.0795	403.0
0	325.0	105 500.0	0.1000	319.0
1	289.3	83 690.0	0.126	253.0
2	258.0	66 370.0	0.159	201.0
3	229.0	52 640.0	0.201	159.0
4	204.0	41 740.0	0.253	126.0
5	182.0	33 100.0	0.319	100.0
6	162.0	26 250.0	0.403	79.5
7	144.3	20 820.0	0.508	63.0
8	128.5	16 510.0	0.641	50.0
9	114.4	13 090.0	0.808	39.6
10	102.0	10 380.0	1.02	31.4
11	91.0	8234.0	1.28	24.9
12	81.0	6530.0	1.62	19.8
13	72.0	5178.0	2.04	15.7
14	64.1	4107.0	2.58	12.4
15	57.1	3257.0	3.25	9.9
16	50.8	2583.0	4.09	7.8
17	45.3	2048.0	5.16	6.2
18	40.3	1624.0	6.51	4.9
19	35.9	1288.0	8.21	3.9
20	32.0	1022.0	10.4	3.09
21	28.5	810.0	13.1	2.45
22	25.3	642.4	16.5	1.95
23	22.6	509.0	20.8	1.54
24	20.1	404.0	26.2	1.22
25	17.9	320.0	26.2	0.97
26	15.9	254.0	41.6	0.769
27	14.2	202.0	52.5	0.610
28	12.6	160.0	66.2	0.484
29	11.3	127.0	83.4	0.384
30	10.0	100.5	105.2	0.304
31	8.93	79.70	132.7	0.241
32	7.95	63.21	167.3	0.191
33	7.08	50.13	211.0	0.152
34	6.31	39.75	266.0	0.120
35	5.62	31.52	335.5	0.095
36	5.00	25.00	423.0	0.0757
37	4.45	19.83	533.4	0.0600
38	3.96	15.72	672.6	0.0476
39	3.53	12.47	848.1	0.0377
40	3.14	9.98	070.0	0.0299

Electric power in an ac circuit

$$U = E \times I$$

where U = apparent power, VA
E = voltage, V
I = current, A

$$P = I \times R$$

where P = true power, W
I = current, A
R = resistance, Ω

Greek Alphabet

Name	Capital	Lowercase	Use in Electronics
Alpha	Α	α	Angles, area, coefficients
Beta	Β	β	Angles, flux density, coefficients
Gamma	Γ	γ	Conductivity
Delta	Δ	δ	Variation, density
Epsilon	Ε	ε	
Zeta	Ζ	ζ	Impedance, coefficients, coordinates
Eta	Η	η	Hysteresis coefficient, efficiency
Theta	Θ	θ	Temperature, phase angle
Iota	Ι	ι	Current
Kappa	Κ	κ	Dielectric constant
Lambda	Λ	λ	Wavelength
Mu	Μ	μ	Micro, amplification factor, permeability
Nu	Ν	ν	Reluctivity
Xi	Ξ	ξ	
Omicron	Ο	ο	
Pi	Π	π	Ratio of circumference to diameter (3.1416)
Rho	Ρ	ρ	Resistivity, density
Sigma	Σ	σ	Sign of summation
Tau	Τ	τ	Time constant, time phase displacement
Upsilon	Υ	υ	
Phi	Φ	ϕ	Magnetic flux, angles
Chi	Χ	χ	
Psi	Ψ	ψ	Dielectric flux, phase difference
Omega	Ω	ω	Capital, ohms; lowercase, angular velocity

ELECTRICAL AND ELECTRONIC SYMBOLS

The symbols shown here are those that are likely to be encountered by the aviation maintenance technician. Only the primary symbols are provided in this section. For the addtional symbols representing variations of the primary symbols, the technician should consult the document "Graphic Symbols for Electrical and Electronics Diagrams" published by the Institute of Electrical and Electronic Engineers (IEEE), IEEE Std 315.

Qualifying Symbols

Qualifying symbols are applied to standard symbols to provide an indication of the special characteristics of the symbols as they are employed in specific circuits.

Adjustability or Variability

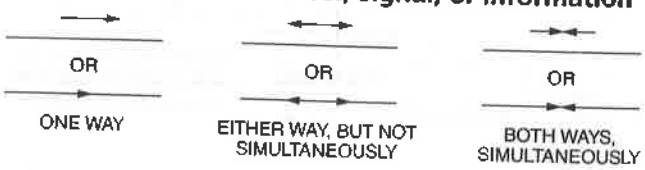
Radiation Indicators

Type of radiation		
	Alpha particle α	Neutron η
	Beta particle β	Pion π
	Gamma ray γ	K-meson κ
	Deutron δ	Muon μ
	Proton ρ	X-ray χ

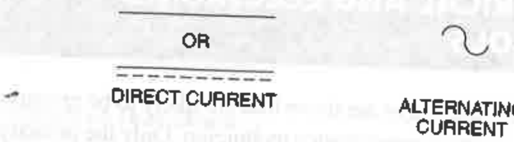
Physical-State Recognition Symbols

Test-Point Recognition Symbol

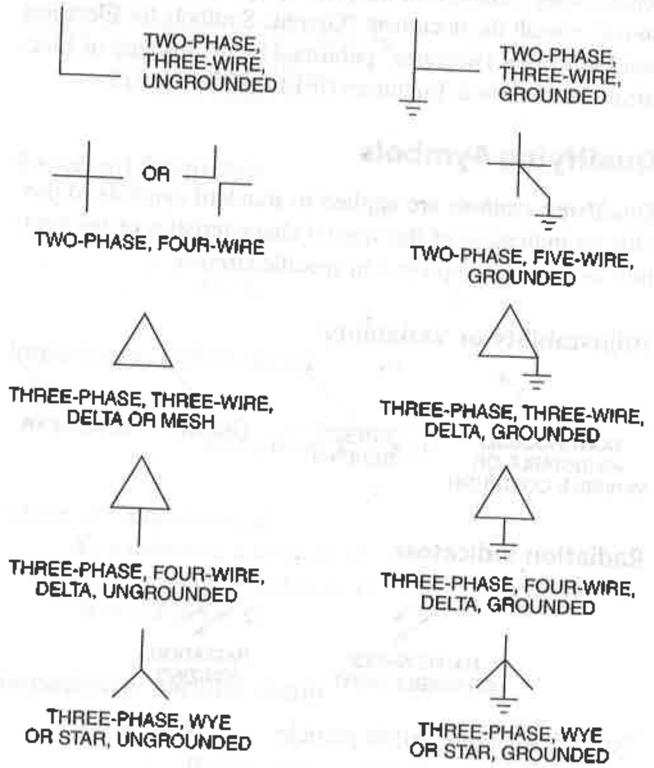
Direction of Flow of Power, Signal, or Information



Kind of Current (General)

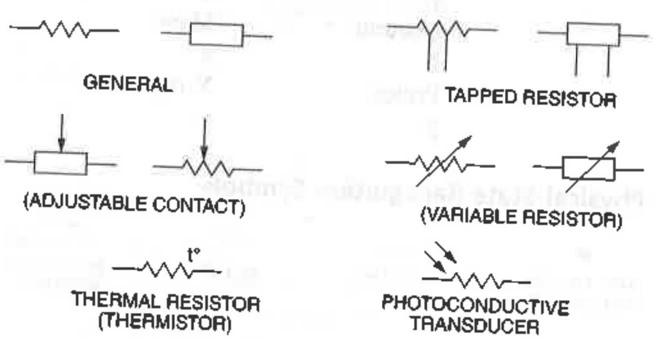


Connection Symbols

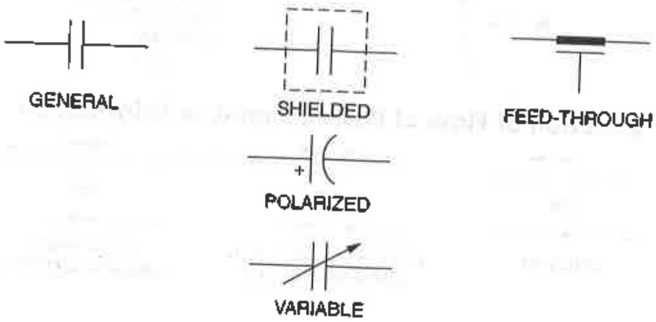


Fundamental Items

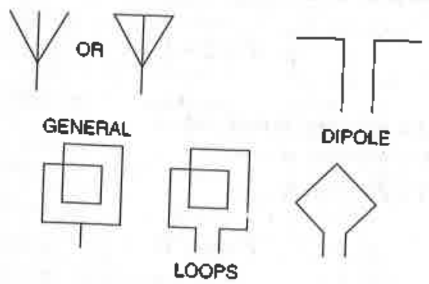
Resistor



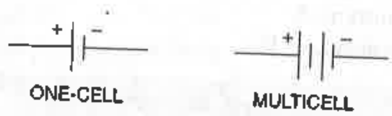
Capacitor



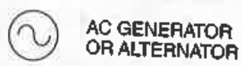
Antenna



Battery



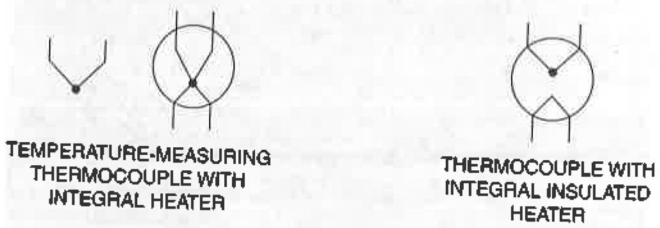
Alternating-Current Source



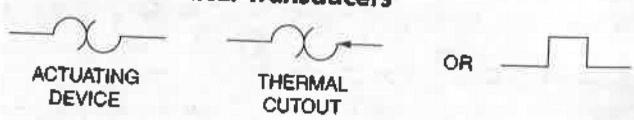
Permanent Magnet

Crystal Unit

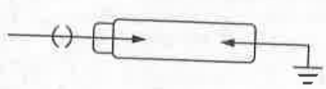
Thermocouples



Thermomechanical Transducers

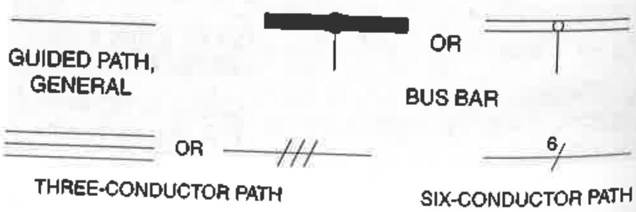


Ignitor Plug

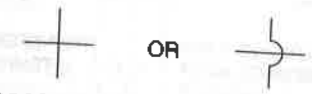


Transmission Path

Conductor, Cable, Wiring

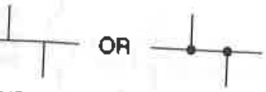


Conductor, Cable, Wiring (con't)

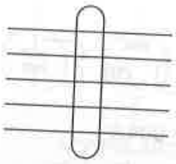


CROSSING NOT CONNECTED

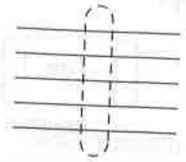
JUNCTION



CONDUCTORS CONNECTED



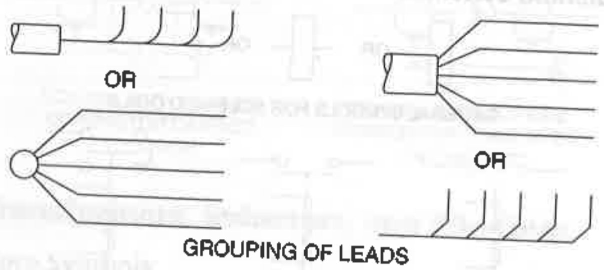
FIVE-CONDUCTOR CABLE



SHIELDED FIVE-CONDUCTOR CABLE

SHIELDED TWO-CONDUCTOR CABLE WITH SHIELD GROUNDED

COAXIAL



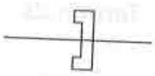
GROUPING OF LEADS

CHASSIS OR FRAME CONNECTION

Waveguides

CIRCULAR

RECTANGULAR

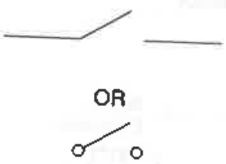


RIDGED

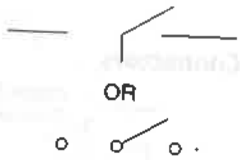
Contacts, Switches, Contactors, and Relays

Switching Function

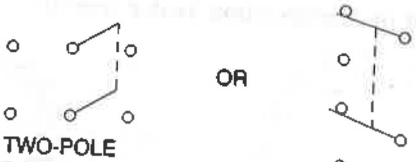
Switch



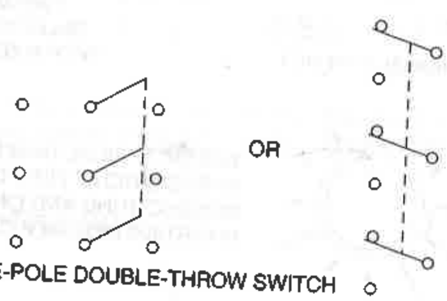
SINGLE-THROW GENERAL



DOUBLE-THROW GENERAL

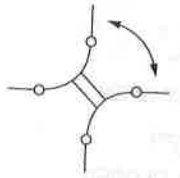


TWO-POLE DOUBLE-THROW SWITCH

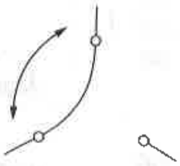


THREE-POLE DOUBLE-THROW SWITCH

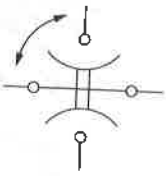
Multiway Transfer Switch



TWO-POSITION SWITCH (90° STEP)

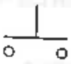


THREE-POSITION SWITCH (120° STEP)

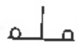


FOUR-POSITION SWITCH (45° STEP)

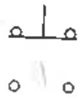
Push Button



CIRCUIT CLOSING NORMALLY OPEN (NO)

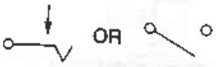


CIRCUIT OPENING NORMALLY CLOSED (NC)

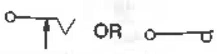


TWO-CIRCUIT

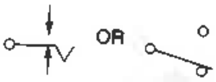
Locking Switch



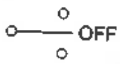
CIRCUIT CLOSING (NO)



CIRCUIT OPENING (NC)



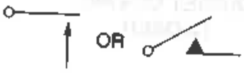
TRANSFER SWITCH, TWO-POSITION



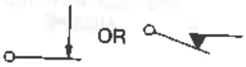
TRANSFER, THREE-POSITION

MAKE-BEFORE-BREAK

Nonlocking Switch, Momentary or Spring Return

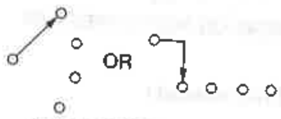


NORMALLY OPEN (NO)

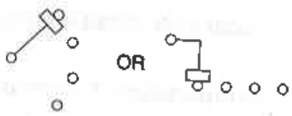


NORMALLY CLOSED (NC)

Selector or Multiposition Switch

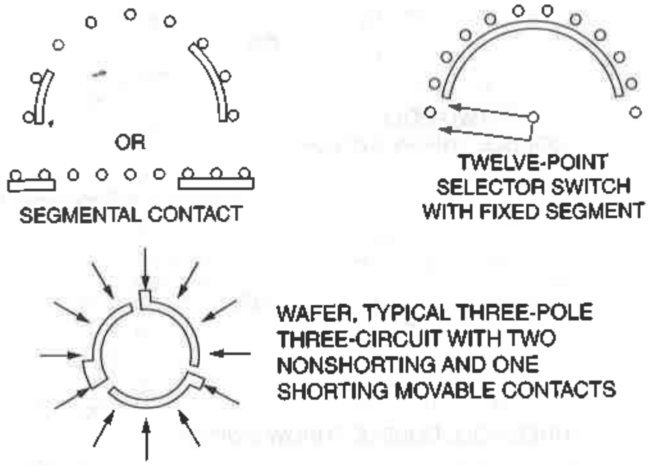


BREAK-BEFORE-MAKE, NONSHORTING DURING CONTACT TRANSFER

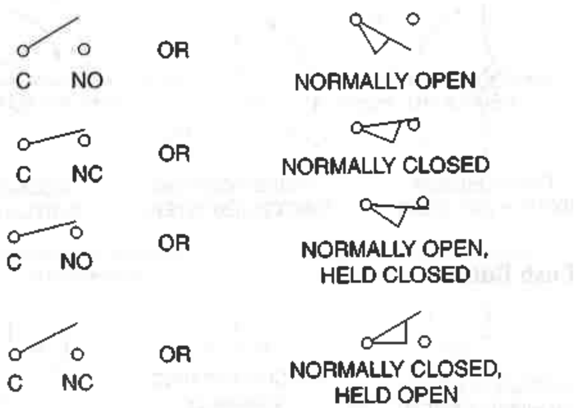


MAKE-BEFORE-BREAK, SHORTING (BRIDGING) DURING CONTACT TRANSFER

Selector or Multiposition Switch (con't)

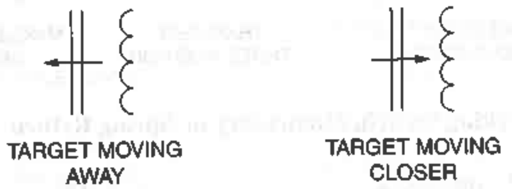


Limit Switch



Liquid-Level-Actuated Switch

Proximity Sensor

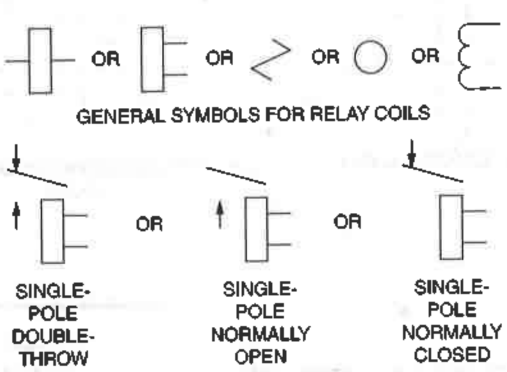


Pressure or Vacuum-Actuated Switch

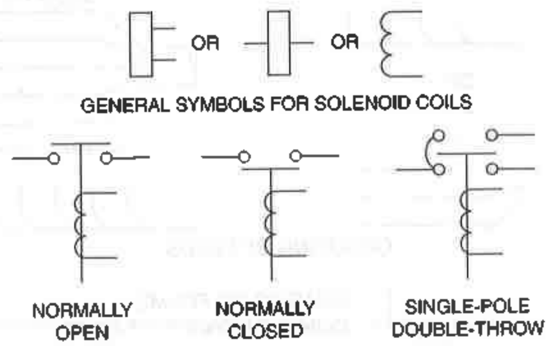
Temperature-Actuated Switch (Thermostat)

Flasher

Relays

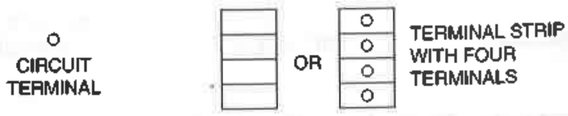


Solenoid Switches



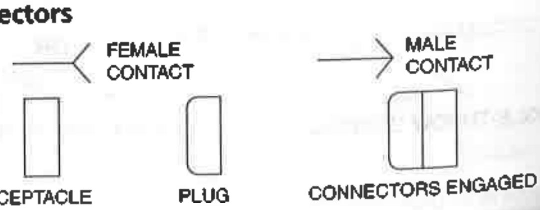
Terminals and Connectors

Terminals

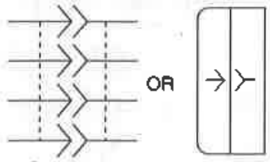


Cable Termination

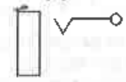
Connectors



(Types of contacts in connectors are indicated as male or female.)



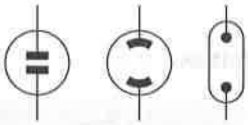
MALE PLUG, FEMALE RECEPTACLE, ENGAGED



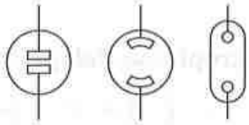
TWO-CONDUCTOR JACK

TWO-CONDUCTOR PLUG

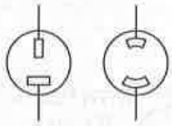
Power Supply Connectors



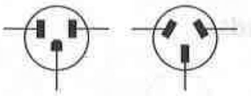
NONPOLARIZED MALE CONNECTOR



NONPOLARIZED FEMALE CONNECTOR

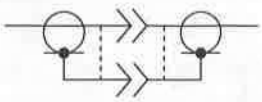


POLARIZED FEMALE CONNECTOR

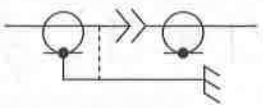


POLARIZED THREE-CONDUCTOR CONNECTOR, MALE

Coaxial Connector



COAXIAL WITH OUTSIDE CONDUCTOR CARRIED THROUGH



COAXIAL WITH OUTSIDE CONDUCTOR TERMINATED ON CHASSIS

Transformers, Inductors, and Windings

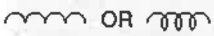
Core Symbols

No symbol is used for an air core.

MAGNETIC CORE OF INDUCTOR OR TRANSFORMER

CORE OF MAGNET

Inductor

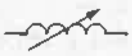


GENERAL SYMBOLS

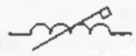
MAGNETIC CORE INDUCTOR

TAPPED INDUCTOR

ADJUSTABLE INDUCTOR

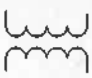


CONTINUOUSLY ADJUSTABLE



COIL-OPERATED INDICATOR

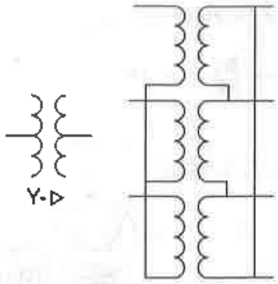
Transformer



GENERAL WINDING SYMBOLS

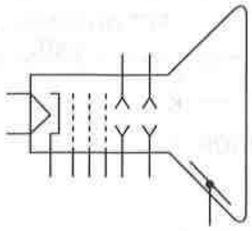
IF IT IS DESIRED TO DISTINGUISH A MAGNETIC-CORE TRANSFORMER

SHIELDED TRANSFORMER WITH MAGNETIC CORE



THREE-PHASE BANK OF ONE-PHASE, TWO-WINDING TRANSFORMERS WITH WYE-DELTA CONNECTIONS

Cathode-Ray Tube



CRT WITH ELECTRIC FIELD DEFLECTION

Semiconductor Devices

Transistors and Diodes

Two-Terminal Devices

ANODE  CATHODE

DIODE RECTIFIER

PHOTOSENSITIVE DIODE

PHOTOEMISSIVE (LIGHT-EMITTING) DIODE (LED)

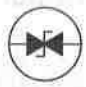
 *nPN*

 *pNP*

BIDIRECTIONAL PHOTODIODE

(ZENER)

STYLE 1 

 STYLE 2

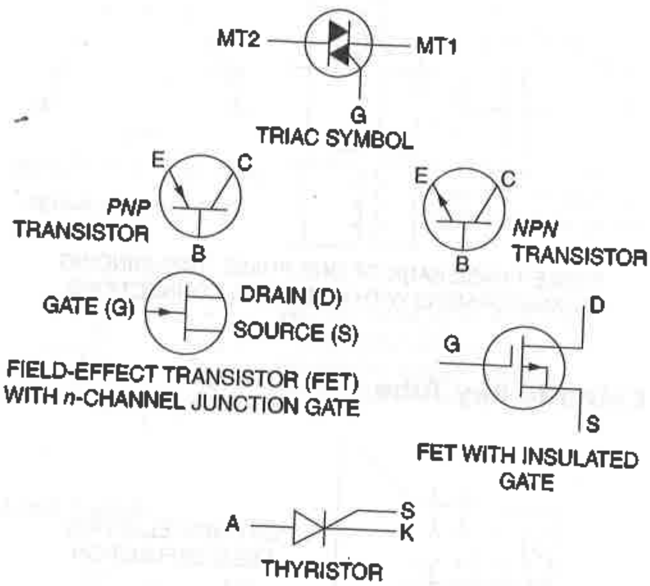
BIDIRECTIONAL DIODE

Anode 2

Diac 

Anode 1

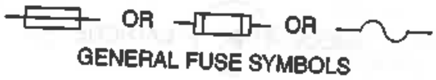
Three-or-More-Terminal Devices



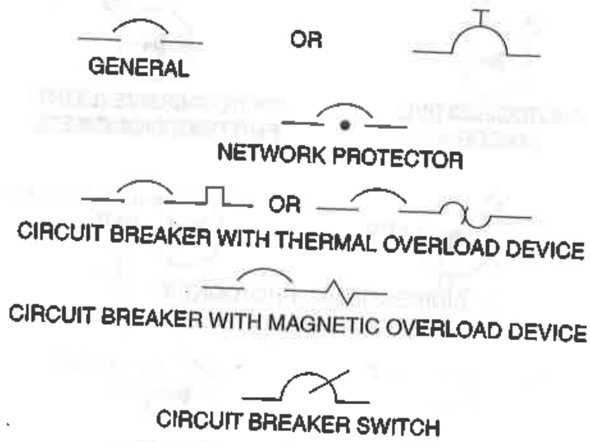
Circuit Protectors

Current Limiter

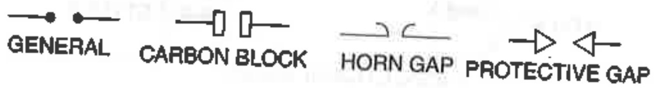
Fuses



Circuit Breaker

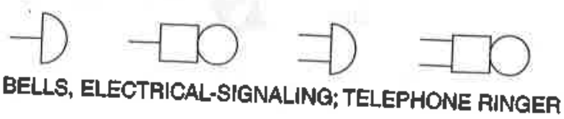


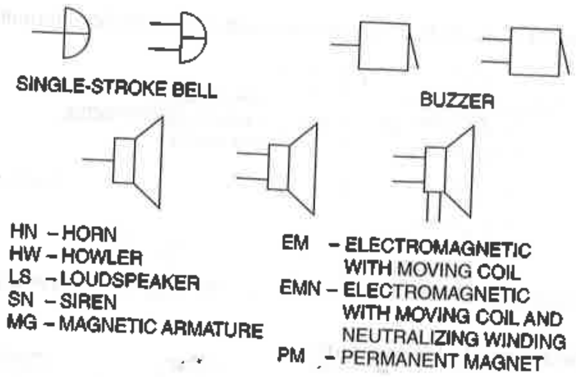
Lightning Arrestor



Acoustic Devices

Audible Signaling Device

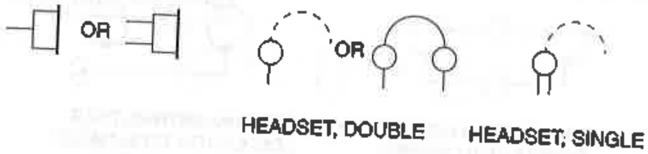




Microphone, Telephone Transmitter

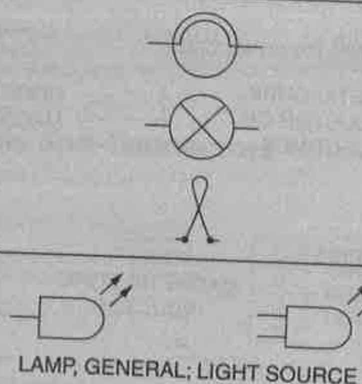
Handset

Telephone Receiver



Lamps and Visual-Signaling Devices

Lamp

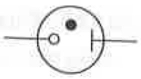


A	AMBER	P	PURPLE
		R	RED
B	BLUE	W	WHITE
C	CLEAR	Y	YELLOW
G	GREEN	IR	INFRARED
O	ORANGE	NA	SODIUM VAPOR
ARC	ARC		
EL	ELECTROLUMINES-CENT	NE	NEON
		UV	ULTRAVIOLET
FL	FLUORESCENT		

HG	MERCURY VAPOR	XE	XENON
		LED	LIGHT-EMITTING DIODE
IN	INCANDESCENT		
OP	OPALESCENT		

Fluorescent Lamps

GLOW LAMP, AC TYPE



GLOW LAMP, DC TYPE

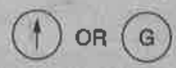
COMMUNICATION-SWITCHBOARD LAMP

Readout Devices

Meter Instrument

GENERAL

A	Ammeter
AH	Ampere-hour meter
C	Coulombmeter
CMA	Contact-making (or breaking) ammeter
CMC	Contact-making (or breaking) clock
CMV	Contact-making (or breaking) voltmeter
CRO	Cathode-ray oscilloscope
dB	dB (decibel) meter
dBM	dBM (decibels referred to 1 mW) meter
DM	Demand meter
DTR	Demand-totalizing relay
F	Frequency meter
GD	Ground detector
I	Indicating meter
INT	Integrating meter
uA or UA	Microammeter
MA	Milliammeter
NM	Noise meter
OHM	Ohmmeter
OP	Oil pressure
OSCG	Oscillograph, string
PF	Power-factor meter
PH	Phase meter
PI	Position indicator
RD	Recording demand meter
REC	Recording
RF	Reactive-factor meter
S	Synchroscope
T°	Temperature meter
THC	Thermal convertor
TLM	Telemeter
TT	Total-time meter Elapsed-time meter
V	Voltmeter
VA	Volt-ammeter
VAR	Varmeter
VARH	Varhour meter
VI	Volume indicator Audio-level meter
VU	Standard volume indicator Audio-level meter
W	Wattmeter
WH	Watthour meter

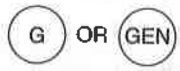


GALVANOMETER

Rotating Machinery

Rotating Machine

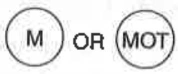
BASIC



GENERATOR, GENERAL

GENERATOR, DC

GENERATOR, AC



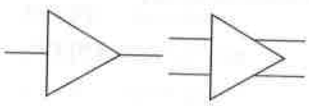
MOTOR, GENERAL

MOTOR, DC

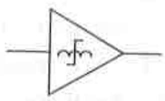
MOTOR, AC

Symbols Used in Logic Circuits and Diagrams

Amplifiers

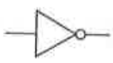


GENERAL SYMBOLS

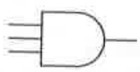


MAGNETIC AMPLIFIER

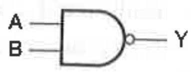
Logic Gates



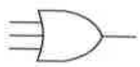
INVERTOR OR NOT GATE



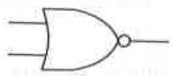
AND GATE WITH THREE INPUTS



NAND (NOT AND) GATE

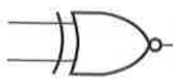


OR GATE



NOR (NOT OR) GAT

EXCLUSIVE OR GATE



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USEFUL ACRONYMS AND ABBREVIATIONS

429 ARINC 429 data bus standard
629 ARINC 629 data bus standard
664 ARINC 664 data bus standard
ac Alternating current
ACARS ARINC Communication Addressing and Reporting System
ACU Alternator control unit
A/D Analog/digital; analog-to-digital
A/D CONV Analog-to-digital converter
ADC Airdata computer
ADF Automatic direction finder
ADI Attitude director indicator
AFC Automatic frequency control
AFCS Automatic flight control system
AFDS Autopilot flight detector system
AFDX Avionics full-duplex switched Ethernet
AGM Absorbed glass mat (a type of battery)
AIMS Airplane information management system
AIRCOM Air/ground communications
A/L Autoland
AM Amplitude modulation
AMP Amperes
AMP or **AMPL** Amplifier
ANT Antenna
AP Autopilot
APB Auxiliary power breaker
APCU Auxiliary power control unit
APU Auxiliary power unit
ARINC Aeronautical Radio Incorporated
ASCB Avionics standard communication bus
ATC Air traffic control
ATCT ATC transponder
AUX Auxiliary
AVC Automatic volume control
BAT or **BATT** Battery
BCD Binary-coded decimal
BIT Binary digit; built-in test
BITE Built-in test equipment
BNR Binary numerical reference; binary
BP Band-pass
BPCU Bus power control unit
BT Bus tie
BTB Bus tie breaker
BUS Electrical bus; 429 digital data bus
CAWS Central aural warning system; caution and warning system
CB, C/B Circuit breaker
CDI Course deviation indication
CDU Central display unit
CDUS Control and display unit system
CFDIU Centralized fault display interface unit
CFDS Centralized fault display unit system
CG Center of gravity
CH or **CHAN** Channel
CHGR Charger
CKT Circuit
CLK Clock
CLR Clear
CMCS Central maintenance computer system
CMPTR Computer
COAX Coaxial
COP Copper
CP Control panel
CPU Central processing unit
CRT Cathode-ray tube; circuit
CSDB Commercial standard digital bus
CT Current transformer
CTN Caution
CU Control unit; copper
CVR Cockpit voice recorder
CW Continuous wave
D/A Digital-to-analog
DAC Digital-to-analog converter
DADC Digital air-data computer
DAU Data acquisition unit
dc Direct current
DCDR Decoder
DDB Digital data bus
DEMOD Demodulator
DEMUX Demultiplexer
DFDR Digital flight data recorder
DG Directional gyro
DGTL Digital
DH Decision height
DISC Disconnect
DMC Display management computer
DME Distance-measuring equipment
DMM Digital multimeter
DU Display unit
DWN Down
EADI Electronic attitude-director indicator
EAROM Electrically alterable read-only memory
ECAM Electronic centralized aircraft monitoring
EDSP EICAS display select panel
E/E or **E & E** Electrical/electronic
EEC Electronic engine control
EFB Electronic flight bag

EFI Electronic flight instrument
EFIS Electronic flight instrument system
EFISCP EFIS control panel
EFISCU EFIS comparator unit
EFISG EFIS symbol generator
EFISRLS EFIS remote light sensor
EGPWS Enhanced ground proximity warning system
EHSI Electronic horizontal-situation indicator
EHSV Electrohydraulic servo value
EICAS Engine indicating and crew alerting system
EIS Electronic instrument system
ELCU Electrical load control unit
ELEC Electric; electronic
ELECT Electrical
ELMS Electronic load management system
EMER GEN Emergency generator
EMI Electromagnetic interference
EP External power
EP AVAIL External power available
EPC External power contractor
EPCS Electronic power control switch
EPGDS Electrical power generation and distribution system
EPROM Erasable programmable read-only memory
EXCTR Exciter
EXT PWR External power
FBW Fly-by-wire
FD Flight director
FDR Flight data recorder
FM Frequency modulation
FMC Flight management computer
FMCS Flight management computer system
FM/CW Frequency modulation continuous wave
FMS Flight management system
FREQ Frequency
FSEU Flap/slat electronic unit
FW or FWD Forward
GAL or GALY Galley
GCB Generator circuit breaker
GCR Generator control relay; generator circuit relay
GCR AUX Generator control relay auxiliary contact
GCU Generator control unit
GEN Generator
GLR Galley load relay
GMT Greenwich mean time
GND Ground
GND PWR Ground power
GND SVCE Ground service
GPCU Ground power control unit
GPS Global positioning system
GPU Ground power unit
GPW Ground proximity warning
GPWS Ground proximity warning system
GRD Ground
G/S Glide slope
GSR Ground service relay
GSSR Ground service select relay
GSTR Ground service transfer relay
GWPC Ground proximity warning cmputer
HEX Hexadecimal
HF (hf) High frequency (3 to 30 MHz)
HID High-intensity discharge
HIRF High-intensity radiated field
HI Z High impedance
H/L High/low
HSI Horizontal situation indicator
HUD Heads-up display
Hz Hertz
IAC Integrated avionics computer
IAPS Integrated avionics processor system
IAS Indicated airspeed or Integrated avionics system
IDG Integrated drive generator
IDS Integrated display system
IEEE Institute of Electrical and Electronics Engineers
IF Intermediate frequency
IFR Instrument flight rules
IGN Ignition
IIS Integrated instrument system
ILS Instrument landing system
IMA Integrated modularized avionics
IND L Indicator light
INST Instrument
INSTR Instrument
INTCON Interconnect
INTFC Interface
INTPH Interphone
INTR Interrogation
INV Inverter
I/O Input/output
IR ILS receiver
KCCD Keyboard and cursor control device
kHz Kilohertz
kV Kilovolts
kVA Kilovoltamperes
kVAR Kilovoltampere reactive
LAAS Local area augmentation system
L-Band Radio frequency band (390 to 1550 MHz)
LCD Liquid-crystal display
LD Load
LED Light-emitting diode
LF (lf) Low frequency (30 to 300 kHz)

LO Z Low impendance
LOC Localizer
LRU Line replaceable unit
LS Loudspeaker
LT Light
LTS Lights
LVDT Linear variable differential transducer
MBA Marker-beacon antenna
MCDP Maintenance control and display panel
MCDU Multipurpose control and display unit
MEG or MEGA Million
MEL Minimum equipment list
MEM Memory
MF (mf) Medium frequency (300 kHz to 3 MHz)
MFD Multifunction display
MHZ Megahertz
MIC Microphone
MILLI One one-thousandth (0.001)
MKR BCN Marker beacon
MSEC (ms) Milliseconds
MSG Message
MTBF Mean time before failure
μ Micro
MUX Multiplexer
mV Millivolts
NAV Navigation
NC Normally closed; not connected; no connection
ND Navigational display
NDB Nondirectional beacon
NEG Negative
NSEC (ns) Nanoseconds
NTSB National Transportation Safety Board
NVM Nonvolatile memory
OC Overcurrent
OF Overfrequency
OIT Onboard maintenance terminal
OVV or OV Overvoltage
OVVCO or OVCO Overvoltage cutout
PA Passenger address; power amplifier
PDMC Power distribution maintenance computer
PEDEC Primary electrical power distribution center
PFD Primary flight display
PMAT Portable maintenance access terminal
PMG Permanent-magnet generator
POS Positive
POT Potentiometer
PR Power relay
PRL Parallel
PROM Programmable read-only memory
PROX Proximity
P-S Parallel to series
PSEU Proximity switch electronic unit
PWR Power
PWR SPLY Power supply
QTY Quantity
RA Radio altitude or Resolution advisory
RAD Radio
RAM Random-access memory
RAT Ram air turbine
RCL Recall
RCVR Receiver
RCVR/XMTR Receiver/transmitter
RF (rf) Radio frequency
RLS Remote light sensor
RMI Radio magnetic indicator
rpm Revolution per minute
RS-232 Recommended Standard #232
r-t Receiver-transmitter
RVDT Rotary variable differential transducer
SAT Static air temperature
SATCOM Satellite communication
SCR Silicon controlled rectifier
SDI Source destination identifier
SELCAL Selective calling system
SEPDC Secondary Electrical Power Distribution Centers
SER DL Serial data link
SG Symbol generator or Starter generator
SITA Société International de Telecommunications Aeronautiques
SMD Surface mounted device
SNR Signal-to-noise ratio
SOL Solenoid
SPDB Secondary power distribution box
SPKR Speaker
SQL Squelch
SRM Switched reluctance motor
SSB Single sideband
SSM Sign status matrix
STAT INV Static inverter
STBY Standby
SW Switch
SWAMP Severe wind and moisture problem
SYM GEN Symbol generator
TA Traffic advisory
TAT True air temperature
TAWS Terrain awareness warning system
TBDP Tie bus differential protection
TCAS Traffic alert and collision avoidance system
TDR Time domain reflectometer
TFR Transfer

TFT Thin-film transistor
TMC Thrust management computer
TMS Thrust management system
TMSP Thrust mode select panel
T-R Transformer-rectifier
TRU Transformer-rectifier unit
TSO Technical standard order
TXPDR Transponder
UBR Utility bus relay
UF Underfrequency
UHF Ultrahigh frequency (300 MHz to 3 GHz)
UNDF Underfrequency
UNDV Undervoltage
US Underspeed
USB (μs) Upper sideband
USEC Microseconds
UV Undervoltage
V Volts; voltage; vertical; valve
V ac or Vac Volts alternating current
V dc or Vdc Volts direct current
VA Voltamperes
VAC Volts alternating current
VAR Voltampere reactive
VDC Volts direct current
VFG Variable frequency generator
VFR Visual flight rules
VHF (vhf) Very high frequency (30 to 300 MHz)
VLJ Very light jets
VLSI Very large-scale integration
VOR VHF omnirange
VORTAC VOR tactical air navigation
VR Voltage regulator
VRLA Valve-regulated lead–acid (a type of battery)
VRMS Volts root mean square
W Watts
WAAS Wide area augmentation system
WARN Warning
WCP Weather radar control panel
WEA Weather
WPT Waypoint
WX (WXR) Weather radar
XCVR Transceiver
XDCR Transducer
XFMR Transformer
XFR Transfer
XMIT Transmit
XMTR Transmitter
XPDR Transponder
YD Yaw damper

Glossary

Accelerate. To change velocity; increase or decrease speed.

Accelerometer. A device for sensing or measuring acceleration and converting it into an electrical signal.

Acceptor. An impurity atom in a semiconductor material that will receive, or accept, electrons. Germanium with an acceptor impurity is called *p*-type germanium because it has a positive nature.

Actuator. A hydraulic, electric, or pneumatic device used to operate a mechanism by remote control.

Alignment, electrical. The tuning of electronic components in a particular circuit so that all portions of the circuit will respond to the correct frequency.

Alternating current (ac as adjective). An electric current that periodically changes direction and constantly changes in magnitude.

Alternation. The part of an ac cycle during which current is flowing in one direction; one half-cycle.

Alternator. An electric generator designed to produce alternating current.

Alternator control unit. A solid-state voltage regulator containing current and voltage sensors.

Ammeter. An instrument used to measure current flow.

Ampere (A). The basic unit of current flow. One A is the amount of current that flows when an emf of 1 V is applied to a circuit with a resistance of 1 Ω. One coulomb per second.

Ampere-hour (Ah). Quantity of electricity that has passed through a circuit when a current of 1 A has flowed for 1 h. Current (in amperes) × time (in hours) = ampere-hours.

Ampere-turn. The magnetizing force produced by a current of 1 A flowing through one turn of a coil. Ampere-turns = amperes × number of turns of wire in the coil.

Amplification. The increase of power, current, or voltage in an electronic circuit.

Amplifier. An electronic circuit that produces amplification.

Amplitude modulation (AM). Modulation of a carrier wave in which the modulating signal changes the amplitude of the carrier in proportion to the strength of the modulating signal.

Analog. Infinitely variable, or relating to an electric circuit that operates with infinite possible input or output signals.

Angular velocity. Time rate of change of an angle rotated around an axis in degrees per second or degrees per minute.

Anode. The positive electrode of a battery; the electrode of an electron tube, diode, or electroplating cell to which a positive voltage is applied.

Antenna. A device designed to radiate or intercept electromagnetic waves.

Apparent power. The power consumed by the resistance, inductance, and capacitance in an ac circuit.

Armature. In a dc generator or motor, the rotating member. In an ac generator the armature is stationary and is acted upon by the rotating field produced by the rotor. The moving element acted upon by the magnetic field in a relay is also called the armature.

ARINC 664. Ethernet-type data bus standards are used by various manufacturers; similar to the IEEE (Institute of Electrical and Electronics Engineers) 802.3 Standard.

Armature reaction. The interaction of the armature field with the main field of generator or motor, resulting in distortion of the main field.

Atom. The smallest possible particle of an element.

Attenuation. A reduction in the strength of a signal, the flow of current, flux, or other energy in an electronic system.

Audio frequency (AF as adjective). A frequency in the audible range, from about 35 to 20 000 Hz.

Automatic direction finder (ADF). A radio receiver utilizing a directional loop antenna that enables the receiver to indicate the direction from which a radio signal is being received; also called a *radio compass*.

Automatic flight control system (AFCS). A flight control system incorporating an automatic pilot with additional systems such as a VOR coupler, an ILS approach coupler, and an internal navigation system that is fully automatic, so the aircraft can be flown in a completely automatic mode.

Automatic frequency control (AFC). A circuit arrangement that maintains the frequency of the system within specified limits.

Automatic pilot. A system installed in an airplane or missile that senses derivations in the flight path and moves the control surface to maintain the selected flight path.

Automatic volume control (AVC). A circuit arrangement in which the dc component of the detector output in a radio receiver controls the bias of the RF tubes, thus regulating their output to maintain a reasonably constant volume.

Avionics. A generic term for aircraft electronics equipment. A contraction of *aviation electronics.*

Avionics full-duplex switched Ethernet (AFDX). An Airbus Industries proprietary data bus specification similar to ARINC 664.

Avionics standard communication bus (ASCB). A digital data transfer bus, used to transmit serial data.

Azimuth. Angular distance measured on a horizontal circle in a clockwise direction from either north or south.

Ballast. A circuit element designed to stabilize current flow.

Ballast transformer. A transformer specifically designed to power fluorescent lights.

Band. A range of frequencies.

Band-pass filter. A filter circuit that passes frequencies within a specific band and attenuates frequencies outside the band.

Band-reject filter. A circuit designed to reject a certain band of frequencies and attenuate all frequencies outside that band.

Bandwidth. The difference between the maximum and minimum frequencies in a band.

Base. The terminal of a transistor to which the controlling current is applied.

Battery. A group of voltaic cells connected together in series to produce a desired voltage and current capacity. Typical batteries utilize primary cells, secondary cells, and photovoltaic cells.

Bias. A voltage applied to the control element of a transistor to establish the correct operating point.

Binary system. A number system using only two symbols, 0 and 1, and having 2 as a base. In the decimal system, 10 symbols are used, and the base is 10.

Binary-coded decimal (BCD). A numbering system where four-binary bits are used to represent a decimal number.

Bit. Used to indicate a number in the binary system (1 or 0).

BITE. Built-in test equipment designed to monitor and test aircraft systems.

Black box. A slang term used to refer to a complex electric component or line replaceable unit (LRU).

Bonding. The connecting together of metal structures with electric conductors, thus establishing a uniform electric potential among all the parts bonded together.

Breakdown voltage. In a capacitor, the voltage at which the dielectric is ruptured; in a gas tube, the voltage level at which the gas becomes ionized and starts to conduct.

Brush. A device designed to provide an electric contact between a stationary conductor and a rotating element.

Buffer amplifier. An amplifier in a transmitter circuit designed to isolate the oscillator section from the power section, thus preventing a frequency shift.

Bus bar. A power distribution point to which a number of circuits may be connected. It often consists of a solid metal strip in which a number of terminals are installed.

Bus tie. An electric solenoid used to connect two bus bars.

Byte. A group of binary digits handled as a unit or word.

Cable. A group of insulated electric conductors, usually covered with rubber or plastic to form a flexible transmission line.

Capacitance (*C*). The property enabling two adjacent conductors separated by an insulating medium to store an electric charge. The unit of capacitance is the farad.

Capacitive reactance. The reaction, or actual, effect of capacitance in an ac circuit. The equation is $X_C = \frac{1}{2\pi fC}$, where X_C is capacitive reactance in ohms, f is frequency in hertz, and C is the capacitance in farads.

Capacitor. A device consisting of conducting plates separated by a dielectric and used to introduce capacitance into a circuit.

Capacity. A battery or cell's total available current. Typically measured in ampere-hours for aircraft storage batteries.

Carrier wave. A radio-frequency electromagnetic wave used to convey intelligence impressed upon it by modulation.

Cathode. (1) The negative electrode of a battery; (2) the negative terminal of a diode.

Cathode-ray tube (CRT). A special type of electron tube in which a stream of electrons from an electron gun impinges upon a phosphorescent screen, thus producing a bright spot on the screen. The electron beam is deflected electrically or magnetically to produce patterns on the screen.

Cell. A combination of two electrodes surrounded by an electrolyte for the purpose of producing voltage.

Characteristic curve. A graph that shows the performance of a transistor under various operating conditions.

Charge. A quantity of electricity. A charge is negative when it consists of a number of electrons greater than the number normally held by the material when it is in a neutral condition. The charge is positive when there is a deficiency of electrons.

Choke coil. An inductance coil designed to provide a high reactance to certain frequencies and generally used to block or reduce currents at these frequencies.

Circuit. Conductors connected together to provide one or more complete electrical paths.

Circuit breaker. A device that automatically opens a circuit if the current flow increases beyond an established limit.

Circuit protection. The provision of devices in an electric circuit to prevent excessive current flow. These devices may be fuses, circuit breakers, current limiters, or sensing relays.

Circular mil (cmil). The cross-sectional area of a circle having a diameter of 1 mil (0.001 in.). The circular mil is used to indicate the size of electric wire.

Closed-circuit voltage. The voltage in a system with a load connected.

Clutch. A mechanical device used to connect or disconnect a motor or some other driving unit and the driven unit.

Coaxial cable. A pair of concentric conductors. The inner conductor is supported by insulation that holds it in the center of the outer conductor. A coaxial cable is normally used to conduct HF currents.

Coil. One or more turns of a conductor designed for use in a circuit to produce inductance or an electromagnetic field.

Collector. The section of a transistor that carries the controlled current.

Color code. A system of colors used to indicate component values or to identify wires and terminals.

Commutator. A rotating contact device in the armature of a dc generator or motor; in effect, it changes the ac current flowing in the armature windings to a dc current in the external circuit.

Compass. A device used to determine direction on the earth's surface. A magnetic compass utilizes the earth's magnetic field to establish direction.

Compound. A chemical combination of two or more different elements.

Compound winding. A combination of series and parallel or shunt windings to provide the magnetic field for a generator or motor.

Conductance. The reciprocal of resistance.

Conductor. A material through which an electric current can pass easily.

Conduit. A metallic tubular sheath through which insulated conductors are run. The conduit provides mechanical protection and electric or magnetic shielding for the conductors.

Constant-speed drive (CSD). A unit used in conjunction with ac alternators to produce a constant-frequency ac voltage.

Continuity tester. A device designed to test the electrical continuity of a conductor or circuit. A battery and light, or other some other indicating unit, connected in series or an ohmmeter may serve as a continuity tester.

Continuous wave (CW). An RF carrier wave whose successive oscillations are identical in magnitude and frequency.

Control circuit. Any one of a variety of circuits designed to exercise control of an operating device by performing counting, timing, switching, and other operations.

Copper loss. The energy lost to heat due to the resistance of the wire in an electric motor.

Corona loss. Power loss due to the ionization of gas adjacent to a high-potential conductor.

Cosine. The ratio of the side adjacent to an acute angle of a right triangle to the hypotenuse.

Coulomb (C). The international coulomb is a unit of electric charge consisting of approximately 6.28×10^{18} electrons. The absolute coulomb is slightly greater than the international coulomb; that is, 1 absolute coulomb = 1.000 165 international coulomb.

Counter electromotive force (cemf). A voltage developed in the armature of a motor that opposes the applied emf. The same principle applied to any inductor through which an alternating current is flowing.

Coupling. Energy transfer between elements or circuits of an electronic system.

Cross modulation. The modulation of a desired signal by an unwanted signal, resulting in two signals in the output.

Crystal. A solid body with symmetrically arranged plane surfaces. In electronic systems, crystals are used as rectifiers, semiconductors, transistors, and frequency controllers and to produce oscillatory voltages.

Crystal diode. A diode constructed from a crystal semiconductor material such as silicon or germanium.

Current. The movement of electricity through a conductor, i.e., the flow of electrons through a conductor.

Current limiter. A device installed in a circuit to prevent current from increasing above a specified limit.

Cutoff. The point at which an operation stops because a cutoff condition has been reached.

Cycle. A complete sequence of events in a recurrent series of similar periods.

D-sub connector. Connectors that contain two or more parallel rows of pins or sockets surrounded by a D-shaped metal housing.

Damping. The decay in amplitude or strength of an oscillatory current when energy is not introduced to replace that lost through circuit resistance.

D'Arsonval meter movement. A meter movement consisting of a movable coil suspended on pivots between the poles of a permanent magnet.

Data bus. The communication link between two or more computer systems or subsystems.

Data bus standards. A set of rules used to describe both the hardware and software of a digital data transfer system.

Decade. A series of quantities in multiples of 10; for example, 10, 100, 1000, 10000.

Decibel (dB). One-tenth of a bel.

Decimal system. A number system using 10 figures to represent the quantities 0 through 9.

Decoupling. The process of eliminating electrical or magnetic coupling between units in an electronic system.

Deflection. The movement of an electron beam up and down or sideways in response to an electric or magnetic field in a cathode-ray tube.

Delta connection. A method of connecting three components to form a three-sided circuit, usually drawn as a triangle, hence the term *delta*. Delta (Δ) is the Greek letter corresponding to the English D.

Demodulation. The recovery of the AF signal from an RF carrier wave. Also called *detection*.

Detector. That portion of an electronic circuit that demodulates, or detects, a signal.

Deviation, compass. The error in a magnetic compass due to construction, installation, and nearby magnetic materials.

Diac. A negative-resistance breakdown diode, constructed in both unidirectional and bidirectional forms.

Dielectric. An insulating material used to separate the plates of a capacitor.

Dielectric constant. A measure of the effectiveness of a dielectric for holding a charge in a capacitor. Air is given a dielectric constant of 1, and mica has a dielectric constant of 5.8; hence a capacitor having mica as the dielectric has 5.8 times the capacitance of the same capacitor having a dielectric of air.

Differentiating circuit. A circuit that produces an output voltage proportional to the rate of change of the input.

Digital. Relating to an electric circuit with a finite number of possible inputs and outputs.

Diode. A semiconductor device with only a cathode and an anode; used as a rectifier and a detector.

Dipole antenna. An antenna consisting of two equal lengths of wire or some other conductor extending in opposite directions from the input point. Each section of the dipole is approximately one-quarter wavelength.

Direct current (dc as adjective). An electric current that flows continuously in one direction.

Directional gyro. A direction-indicating instrument that utilizes a gyroscope to hold the moving element in a fixed position relative to a directional reference.

Discriminator. A circuit whose output polarity and magnitude are determined by the variations of the input phase or frequency.

Distance-measuring equipment (DME). An electronic system used with radio navigation equipment to provide an indication of the distance to a specific point.

Distortion. Undesirable change in the waveform of the output of a circuit compared with the waveform of the input.

Donor. An impurity used in a semiconductor to provide free electrons as current carriers. A semiconductor with a donor impurity is of the *n* type.

Doppler effect. The effect noted as one moves toward or away from the source of a sound-wave or electromagnetic-wave propagation. Moving toward the source results in receiving a higher-frequency sound or signal than the source is emitting, and moving away from the source results in receiving a lower-frequency sound or signal.

Downlink. The radio transmission path downward from the aircraft to the earth.

Duplexer. A circuit that makes it possible to use the same antenna for both transmitting and receiving without allowing excessive power to flow to the receiver.

Dynamometer. A type of electric measuring instrument involving a reaction between a magnetic field and electromagnetic forces.

Eddy currents. Currents induced in the cores of coils, transformers, and armatures by the changing magnetic fields associated with their operation. These currents cause great losses of energy. For this reason such cores are composed of insulated laminations that limit the current paths.

Effective value. A term used to indicate the actual working value of an alternating current based on its heating effect. Also called the *root-mean-square (rms) value*. It is equal to $1/\sqrt{2}$ times the maximum value in a sinusoidal current.

Electret. A dielectric body in which a permanent state of electric polarization has been set up. Also, the material of which an electret is composed.

Electricity. In general terms, electricity may be said to consist of positive or negative charges at rest or in motion.

Electrode. A terminal element in an electric device or circuit. Some typical electrodes include the plates in a storage battery, the elements in an electron tube, and the carbon rods in an arc light.

Electrolysis. The process of decomposing a chemical compound by means of an electric current.

Electrolyte. Any solution that conducts an electric current.

Electromagnet. A magnet formed when an iron core is placed in a current-carrying coil.

Electromagnetic induction. The transfer of electric energy from one conductor to another by means of a moving electromagnetic field. A voltage is produced in a conductor as the magnetic lines of force cut or link with the conductor. The value of the voltage produced by electromagnetic induction is proportional to the number of lines of force cut per second. When 100 000 000 lines of force are cut per second, an emf of 1 V will be induced.

Electromagnetism. The magnetism produced by the flow of electric current.

Electromotive force (emf). The force that causes current to move through a conductor. The unit of measurement for emf is the volt; hence emf is often called *voltage*.

Electron. A negatively charged nonnuclear particle that orbits around the nucleus of an atom. Generally speaking, an electron may be considered a carrier of electric current through a conductor. An electron at rest has a mass of 9.107×10^{-28} g and a charge of 1.6×10^{-19} C.

Electron gun. The combination of an electron-emitting cathode with accelerating anodes and beam-forming electrodes to produce the electron beam in a CRT.

Electron tube. A device consisting of an evacuated or gas-filled envelope containing electrodes for the purpose of controlling electron flow. The electrodes are usually a cathode (electron emitter), a plate (anode), and one or more grids.

Electrostatic field. The field of electric force existing in the area around and between any two oppositely charged bodies.

Element. Any substance that cannot be changed to another substance except by nuclear disintegration. There are more than 100 known elements.

Emission, electronic. The freeing of electrons from the surface of a material, usually produced by heat.

Emitter. A section of a transmitter that carries current from both the base and collector circuits.

End systems. Computerized LRUs which transmit/receive data in an Ethernet-type data bus system.

Envelope protection. Software programming designed into an autoflight system to ensure that the aircraft never exceeds the operational limits and enters into an unsafe configuration such as a stall.

Equalizing circuit. A circuit in a multiple-generator voltage regulator system that tends to equalize the current output of the generators by controlling the field currents of several generators.

ESDS (electrostatic discharge sensitive). Components that are sensitive to damage from static electric charges.

Excitation. The application of electric current to the field windings of a generator to produce a magnetic field.

Fading. A decrease in the strength of a received radio signal.

Farad (F). The unit of capacitance; the capacitance of a capacitor that will store 1 C of electricity when an emf of 1 V is applied.

Feedback. A portion of the output signal of a circuit returned to the input. Positive feedback occurs when the feedback signal is in phase with the input signal. Negative feedback occurs when the feedback signal is 180° out of phase with the input signal.

Ferromagnetic materials. Magnetic materials composed largely of iron.

Fidelity. The degree of similarity between the input and output waveforms of an electronic circuit.

Field. A space where magnetic or electric lines of force exist.

Field coil. A winding or coil used to produce a magnetic field.

Field frame. The main structure of a generator or motor within which are mounted the field poles and windings.

Filament. The heated element in an electric lightbulb.

Filter. A circuit arranged to pass certain frequencies while attenuating all others. A high-pass filter passes high frequencies and attenuates low frequencies; a low-pass filter passes low frequencies and attenuates high frequencies.

Flux. Electrostatic or magnetic lines of force.

Flux gate. An electromagnetic sensing device that determines the direction of the earth's magnetic field and thus produces magnetic-direction information for navigation systems.

Flywheel effect. The characteristic of a parallel *LC* circuit that permits a continuing flow of current, even though only small pulses of energy are applied to the circuit.

Forward bias. A voltage applied to a semiconductor that creates a low resistance within that semiconductor.

Free electrons. Those electrons so loosely bound in the outer shells of some atoms that they are able to move from atom to atom when an emf is applied to the material.

Frequency. The number of complete cycles of a periodic process per second. In electricity the unit of frequency is the hertz.

Frequency counters. Instruments used to determine (count) the number of electrical pulses (frequency) of a given voltage.

Frequency modulation (FM). Modulation of a carrier wave by causing changes in carrier frequency that are proportional to the amplitude of the modulating signal.

Frequency multiplier. A circuit designed to double, triple, or quadruple the frequency of a signal by harmonic conversion.

Fuse. A metal link that melts when overheated by excess current; used to break an electric circuit whenever the load becomes excessive.

Gain. The increase in signal power through a circuit.

Gate. An electronic switching circuit commonly employed in digital electronics to produce required outputs in response to particular inputs. The outputs are either "on" or "off" to produce the binary digits 1 and 0. Also, the control circuit built into various semiconductor devices.

Gauss (G). The unit of magnetic flux density equal to 1 Mx (line of force) per square centimeter.

Generator. A rotating machine designed to produce a certain type and quantity of voltage and current.

Generator control unit (GCU). A solid-state device that controls generator output parameters.

Gimbal. A mechanism consisting of a pair of rings, one ring pivoted within the other and the outer ring supported on pivots 90° from the inner-ring pivots. A gimbal is often used to support a rotating mass gyroscope.

Glide slope. A directed radio beam emanating from a glide slope transmitter located near the runway of an instrumented airport; it provides a reference for guiding an airplane vertically to the runway.

Global Positioning System (GPS). A navigation system that employs satellite transmission signals to determine the aircraft's location.

Ground. (1) An electrical connection to the earth; (2) a common connecting device for the zero-potential side of the circuits in an electrical or electronic system; (3) the accidental connection of a hot conductor to the ground (a hot conductor is one whose potential differs from ground potential).

Ground wave. That portion of a radio wave that travels to the receiver along the surface of the earth.

Growler. An electromagnetic device that develops a strong alternating field by which armatures may be tested.

Guidance. The control of a spacecraft or aircraft while in flight.

Gyroscope. A comparatively heavy wheel mounted on a spinning axis that is free to rotate about one or both of two axes perpendicular to each other and to the spinning axis. The gyroscope is used to sense directional changes and to develop signals for operating automatic pilots and inertial navigation systems.

Harmonics. Multiples of a base frequency.

Harness. A bundle of wires typically routed between various sections of an aircraft.

Heat sink. A metallic surface designed to dissipate heat from electronic components.

Henry (H). The unit of inductance. It is the amount of inductance in a coil that will induce an emf of 1 V in the coil when the current flow is changing at the rate of 1 A/s.

Hertz (Hz). The unit of frequency. One hertz equals 1 cps.

Heterodyne. The process of mixing two frequencies to produce both sum and difference frequencies. The principle is used in superheterodyne receivers.

Hexadecimal. A base 16 numbering system used for a variety of computer functions due to their ability to represent large number values.

Hexadecimal notation. A base 16 number represented by a four-bit binary group often referred to simply as Hex or Hexadecimal.

High-intensity radiated field (HIRF). A form of electromagnetic energy which can cause failure of sensitive electronic systems.

High-pass filter. An *LC* filter designed to pass high frequencies and block low frequencies.

Horizontal-situation indicator (HSI). A flight instrument that provides the pilot with information regarding heading, course, glide slope deviation, and course deviation, as well as other data regarding aircraft position.

Horsepower (hp). A common unit of mechanical power. The time rate of work that will raise 550 lb through a vertical distance of 1 ft in 1 s; also, 33 000 ft · lb/min. One horsepower is equal to 746 W of electric power.

Hot-wire meter. An electric instrument for measuring alternating current. A wire is heated by the current flow, and the expansion of the wire is used to provide movement for the indicating needle.

Hydrometer. A calibrated float used to determine the specific gravity of a liquid.

Hypotenuse. The side of a right triangle opposite the right angle.

Hysteresis. The ability of a magnetic material to withstand changes in its magnetic state. When a magnetomotive force (mmf) is applied to such a material, the magnetization lags the mmf because of a resistance to change in orientation of the particles involved.

Ignition. Pertaining to engines, the introduction of an electric spark into a combustion chamber to fire the fuel-air mixture.

Image frequency. A frequency produced by the heterodyne action of an oscillator in a superheterodyne receiver. An image frequency is produced when an unwanted signal is mixed with the oscillator frequency; the frequency of the unwanted signal is such that a difference frequency (the image frequency) is produced that is equal to the intermediate frequency of the receiver.

Impedance (*Z*). The combined effect of resistance, capacitive reactance, and inductive reactance in an ac circuit. *Z* is measured in ohms.

Inductance (*L*). The ability of a coil or conductor to oppose a change in current flow (*see* **Henry**).

Inductance coil. A coil designed to introduce inductance into a circuit.

Induction motor. An ac motor in which the rotating field produced by the stator induces a current and an opposing field in the rotor. The reaction of the fields creates the rotation force.

Inductive reactance (X_L). The effect of inductance in an ac circuit. The equation for inductive reactance is $X_L = 2\pi fL$. X_L is measured in ohms.

Inductor. An inductance coil.

Inertia. The tendency of a mass to remain at rest or to continue in motion in the same direction.

Inertial navigation. The navigation of a missile or airplane by means of a device that senses changes of direction or acceleration and automatically corrects deviations from the planned course.

Inertial reference systems (IRS). A combination of laser gyros and accelerometers are used to measure angular rates and accelerations and used for aircraft navigation.

Instrument landing system (ILS). A radio guidance and communications system designed to guide aircraft through approaches, letdowns, and landings under instrument flying conditions.

Insulator. A material that will not conduct current to an appreciable degree.

Integrated circuit (IC). A microminiature circuit incorporated on a very small chip of semiconductor material through solid-state technology. A number of circuit elements such as transistors, diodes, resistors, and capacitors are built into the semiconductor chip by means of photography, etching, and diffusion.

Internal resistance. Prevalent in nickel-cadmium batteries; an overtemperature condition created by a chemical reaction within the cells of the battery.

Interphone. A communication system used by flight crew members and ground service personnel.

Interpoles. Small magnetic poles inserted between the main field poles of a generator or motor in series with the load circuit to compensate for the effect of armature reaction.

Inverter. A mechanical or electronic device that converts direct current into alternating current. Also, a binary digital circuit element or circuit with one input and one output. The output state is always the inverse (opposite) of the input state.

Ion. An atom or molecule that has lost one or more electrons (positive ion) or one that has one or more extra electrons (negative ion).

I/O. Input/output.

Ionization. The process of creating ions by either chemical or electrical means.

JFET. *Junction field-effect transistor.* A semiconductor that alters current flow as a function of voltage applied to the gate connection.

Joule (J). A unit of electric energy or work equivalent to the work done in maintaining a current of 1 A against a resistance of 1 Ω for 1 s; 1 J = 0.737 32 ft·lb.

Jumper. A short conductor usually used to make a temporary connection between two terminals.

Junction box. An enclosure used to house and protect terminal strips and other circuit components.

Junction transistor. A transistor consisting of a single crystal of *p*- or *n*-type germanium between two electrodes of the opposite type. The center layer is the base and forms junctions with the emitter and collector.

Keying. The process of modulating a CW carrier wave with a key circuit to provide interruptions in the carrier in the form of dots and dashes for code transmission.

Kilo. A prefix meaning 1000; for example, kilocycle, kilovolt, kilowatt.

Kinetic energy. The energy that a body possesses as a result of its motion. It is equal to $\frac{1}{2}MV^2$, where M is mass and V is velocity.

LASCR. An SCR that is activated by light.

***LC* circuit.** A circuit network containing inductance and capacitance.

Lead-acid cell. A secondary cell that produces voltage using an acidic electrolyte and lead-compound electrodes.

Least significant bit. In a numerical series of bits (1s and 0s)—the bit farthest to the right has the least significance.

Least significant digit. In a numerical series of digits—the digit farthest to the right has the least significance.

Lenz's law. A law stated by H. F. E. Lenz in 1833 to the effect that an induced current in a conductor is always in such a direction that its field opposes the change in the field causing the induced current.

Light-emitting diode (LED). A semiconductor that utilizes a light-producing material such as gallium phosphide. The material produces light when an electric current is passed through it in a certain direction. LEDs are often used for digital displays.

Limit switch. A switch designed to stop an actuator at the limit of its movement.

Load factor. The ratio of average load to greatest load.

Local oscillator. The internal-oscillator section of a superheterodyne circuit.

Localizer. That section of an ILS that produces the directional reference beam.

Logic circuit. A circuit designed to operate according to the fundamental laws of logic.

Logic gates. Fundamental circuits used to manipulate electrons. Typically, several logic gates are contained within one integrated circuit or microprocessor.

Logic monitor. An instrument used to measure logic levels (1 or 0) of an integrated circuit.

Logic probe. An instrument used to measure logic levels (1 or 0) of a digital circuit.

Loop. A control circuit consisting of a sensor, a controller, an actuator, a controlled unit, and a follow-up or feedback to the sensor; also, any closed electronic circuit including a feedback signal that is compared with the reference signal to maintain a desired condition.

Loop antenna. A bidirectional antenna consisting of one or more complete turns of wire in a coil.

Low-pass filter. A filter circuit designed to pass LF signals and attenuate HF signals.

Mach number. The ratio of actual speed to the speed of sound. An object moving at the speed of sound has a Mach number of 1.

Magnet. A solid material that has the property of attracting substances containing iron.

Magnetic field. A space where magnetic lines of force exist.

Magneto. A special type of electric generator having a permanent magnet or magnets to provide the field.

Magnetometer. The electronic compass, often called a remote compass or slaved compass system, containing an electronic unit that measures the earth's magnetic flux.

Magnetron tube. A special electron tube for use in microwave systems. It uses strong magnetic and electric fields and tuned cavities to produce microwave amplification.

Marker beacon. A radio navigation aid used in the approach zone of an instrumented airport. As the airplane crosses over the marker-beacon transmitter, the pilot receives an accurate indication of the airplane's distance from the runway through the medium of a flashing light and an aural signal.

Master switch. A switch designed to control all electric power to all circuits in a system.

Matter. That which has substance and occupies space, material.

Maxwell (Mx). A unit of magnetic flux; one magnetic line of force.

Mega. A prefix meaning *one million*; for example, megahertz, megohm.

Mho. A unit of conductance, the reciprocal of ohm.

Microfarad (μF). One-millionth of a farad.

Microphone. A device for converting sound waves into electric impulses.

Microprocessor. (1) An integrated circuit (IC) that can be programmed to perform a variety of desired functions. The circuit contains an arithmetic-logic unit, a controller, some registers, and possibly other elements. (2) A complex digital circuit that performs specific tasks similar to a miniature computer.

Microsecond (μs). One-millionth of a second.

Microswitch. A spring-loaded switch requiring very small force to trip the switch contacts.

Microwave. An electromagnetic wave with a length of less than 10 m; i.e., it has a frequency of 30 MHz or more.

Microwave landing system (MLS). A radio landing system for aircraft that utilizes microwave frequencies for the transmission of guidance and control signals.

Mil. One-thousandth of an inch.

Milli. A prefix meaning *one-thousandth;* for example, milliammeter, milliampere, millihenry.

Minimum equipment list (MEL). A detailed list of all necessary equipment and under what specific conditions the aircraft can be dispatched.

Mixer. A circuit in which two frequencies are combined to produce sum and difference frequencies (*see also* **Heterodyne** and **Beat frequency oscillator**).

Mode A. An airborne transponder that provides a pilot-selected (nonaltitude) 4096 code reply when interrogated by a ground-based secondary surveillance radar (SSR) or a TCAS.

Mode C. An airborne transponder that provides a reply that includes aircraft altitude information when interrogated by an SSR or a TCAS.

Mode S. An airborne transponder that replies to discrete aircraft address interrogations, mode A and C interrogations from ground SSR stations, and airborne TCAS-equipped aircraft.

Modulation. The impressing of an information signal on a carrier wave.

Modulator. That portion of a transmitter circuit that modulates the carrier wave.

Molecule. The smallest particle of a substance that can exist in a free state and maintain its chemical properties.

The more electric airplane. A design concept that incorporates more electrical systems in order to reduce the number of hydraulic, pneumatic, and other mechanical systems on modern aircraft.

MOSFET. A metal-oxide silicon field-effect transistor.

Most significant bit. In a numerical series of bits (1s and 0s)—the bit farthest to the left has the most significance.

Most significant digit. In a numerical series of digits—the digit farthest to the left has the most significance.

Motor, electric. A rotating device for converting electric energy into mechanical energy.

Multimeter. A combination instrument designed to measure a variety of electrical quantities.

Multivibrator. A special type of relaxation oscillator circuit designed to produce nonlinear signals such as square waves and sawtooth waves.

Mutual inductance. The inductance of a voltage in one coil due to the field produced by an adjacent coil. Inductive coupling is accomplished through the mutual inductance of two adjacent coils.

Neutron. A neutral particle found in the nucleus of an atom.

Nickel-cadmium cell. A secondary or primary cell that produces voltage using a nickel compound for the positive electrode and a cadmium compound for the negative electrode.

North pole. The north-seeking pole of a magnet.

Null. An indicated low or zero point in a radio signal.

Octal notation. A numbering system where three-bit groups are used to represent a specific octal number.

Octal notation system. A number system that consists of one or more digit groups used to represent a base 8 number.

Ohm (Ω). The unit of resistance that limits the current to 1 A when an emf of 1 V is applied.

Ohmmeter. An electric measuring instrument designed to measure resistance in ohms.

Ohm's law. A law of current flow stated by Georg S. Ohm as follows: One volt of electrical pressure is required to force 1 A of current through 1 Ω of resistance; also, the current in a circuit is directly proportional to the voltage and inversely proportional to the resistance. The equation for Ohm's law may be expressed as $I = E/R$, $R = E/I$, or $E = IR$.

Open circuit. A circuit with an unwanted disconnection, infinite resistance.

Open-circuit voltage. The voltage in a circuit with a load disconnected (open circuit).

Optoelectronics. Electronic systems that utilize light-emitting and light-sensitive devices such as light-emitting diodes (LEDs) and phototransistors for control and operation.

Oscillator. An electronic circuit that produces alternating currents with frequencies determined by the inductance and capacitance in the circuit.

Oscilloscope. An electronic device utilizing a CRT for observing electrical signals.

Parallel circuit. A circuit in which there are two or more paths for the current connected to the same two power terminals.

Parallel electrical system. A power distribution system in which all operating generators are connected to one bus bar.

Parity bit. A specific bit assigned in a digital data specification that is used to check for errors in data transmission.

Peak inverse voltage (PIV). The maximum voltage that may be applied safely to a semiconductor device in the direction inverse to normal current flow.

Peak voltage. The maximum level of available voltage.

Peripheral. A device used to send information to or receive information from a computer.

Permeability (μ). The property of a magnetic substance determining the flux density produced in the substance by a magnetic field of a given intensity. The equation is $\mu = B/H$, where B is flux density in gauss and H is the field intensity in oersteds. The permeability of air is 1.

Phase angle. The angular difference between two sinusoidal waveforms. When the voltage of an ac signal leads the current by 10°, there is a phase angle of 10° between the voltage and the current.

Phase inverter. An electronic circuit whose output is 180° out of phase with the input.

Photodiode. A semiconductor that becomes conductive or produces voltage when exposed to light.

Photolithography. A process used to imprint circuits on silicon wafers. The silicon wafers are assembled into integrated circuits (ICs).

Physical layer. The hardware including the data bus, connectors, switches, and LRU circuitry in an Ethernet-type data bus system.

Picofarad (pF). One-trillionth of a farad, or one-millionth of a microfarad.

Piezoelectric effect. The property of certain crystals enabling them to generate an electrostatic voltage between opposite faces when subjected to mechanical pressure. Conversely, the crystal will expand or contract if subjected to a strong electrical potential.

Pitch. The rotation of an aircraft about its lateral axis.

Placard. A label placed on or near an aircraft component containing information necessary for flight safety.

Plan position indicator (PPI). A radar system component for presenting a map-like display of the search area on the screen of a CRT.

Polarity. (1) The nature of the electric charge on each of two terminals between which there is a potential difference; (2) the difference in the nature of the magnetic effect exhibited by the two poles of a magnet.

Potential difference (PD). The voltage existing between two terminals or two points of differing potential.

Potentiometer. A variable resistor often used as a voltage divider.

Potting. The process of encapsulating electric wires and components in a plastic or similar material.

Power. The rate of doing work (*see also* **Horsepower**).

Power factor. In ac circuits, the ratio of true power to apparent power. Also, a multiplier equal to the cosine of the phase angle (θ) between the current and voltage.

Power supply. The part of a circuit that supplies the filament and plate voltages for the operation of the circuit.

Primary cell. A voltaic cell whose chemical action destroys some of the active elements in the cell, thus making it impossible or impractical to recharge the cell.

Primary winding. The input winding of a transformer.

Proton. A positively charged particle found in the nucleus of an atom.

Proximity sensor. A solid-state component able to detect the presence of nearby objects without any physical contact often used to determine the position of moving components, such as flaps, cargo doors, and landing gear.

Pulse generator. An electronic circuit designed to produce sharp pulses of voltage.

***Q* factor.** The "figure of merit" or "quality" of an inductance coil. The equation for the Q of a coil is $Q = X_L/R = 2\pi L/R$.

Radar (radio detecting and ranging). Radio equipment that utilizes reflected pulse signals to locate and determine the distance to any reflecting object within its range.

Radar mile. The time required for a radar pulse to travel a distance of 1 nmi and return to the radar receiver; approximately 12.4 μs.

Radio frequency (RF as adjective). A frequency above the audible range, usually above 20 000 Hz.

Rate gyro. A gyro unit whose output is proportional to the rate of changing direction.

Radome. A nonmetallic cover used to protect the antenna assembly of a radar system.

Rate signal. Any signal proportional to a rate of change.

***RC* circuit.** A circuit containing both resistance and capacitance.

***RC* time constant.** The time required to charge a capacitor to 63.2 percent of its full-charge state through a given resistance.

Reactive power. The power consumed by the inductive and capacitive reactances in an ac circuit.

Recommended Standard number 232 (RS-232). A data bus standard developed as a common interface between various units of a standard personal computer system and adapted for aircraft use.

Rectification. The conversion of alternating current into direct current by means of a rectifier.

Rectifier. A device that permits current to flow in one direction only.

Relaxation oscillator. An oscillator circuit in which an *RC* circuit determines the frequency of oscillation. The output is a sawtooth or rectangular wave.

Relay. An electromagnetic device having a fixed core and a pivoting mechanical linkage. An electric switch operated by an electromagnet.

Reluctance. The property of a material that opposes the passage of magnetic flux lines through it.

Residual magnetism. The magnetism that remains in a de-energized electromagnet.

Resistance. That property of a conductor that tends to hold, or restrict, the flow of an electric current.

Resistor. A circuit element possessing a finite amount of resistance.

Resonance. A condition in an *LC* circuit in which capacitive reactance and inductive reactance are equal.

Reverse bias. A voltage applied to a semiconductor that creates a high resistance within that semiconductor.

Reverse-current cutout relay. A relay incorporated into a generator circuit to disconnect the generator from the battery when battery voltage is greater than generator voltage.

Rheostat. A variable resistor.

Ring laser rate sensor (laser gyro). A solid-state angular rate sensor that employs laser beams and photosensors to detect motion.

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Ripple. A small periodic variation in the voltage level of a dc power supply.

Roll. The rotation of an airplane or missile about its longitudinal axis.

Rotor. The rotating part of an electric machine.

Sawtooth wave. The output of a relaxation oscillator, rising slowly and then dropping sharply to zero to form wave shapes resembling the teeth of a saw.

Schematic diagram. A graphic representation of an electric circuit.

Schottky diode. A specialty high-speed diode with a low forward voltage drop. Due to the high switching speeds of a Schottky diode, they are use in high-speed circuitry and radio frequency (RF) devices such as switched-mode power supply, mixers, and detectors.

Scope. A contraction of *oscilloscope*. Also used to designate the CRT used in radar.

Secondary cell. An electrolytic voltaic cell capable of being repeatedly charged and discharged.

Secondary coil. The output winding of a transformer.

Selcal. A contraction of *selective calling;* refers to an automatic signaling system used in aircraft to notify the pilot that the aircraft is receiving a call.

Selectivity. The ability of a radio receiver to tune in desired signals and tune out undesired signals.

Self-inductance. The property of a single conductor or a coil that causes it to induce a voltage in itself whenever there is a change of current flow.

Silicon-controlled rectifier (SCR). A semiconductor rectifier that is controlled by means of a gate signal.

Sensitivity. A measure of the ability of a radio receiver to receive very weak signals.

Sensor. A sensing unit used to actuate signal-producing devices in response to changes in physical conditions.

Series circuit. A circuit in which the current flows through all the circuit elements via a single path.

Servo. An actuating device that feeds back an indication of its output or movement to the controlling unit, where it is compared with a reference at the input. Any difference between the input and output is used to produce the required control.

Shielding. Metal covers placed around electric and electronic devices to prevent the intrusion of external electrostatic and electromagnetic fields.

Short circuit. A circuit with an extra, unwanted connection.

Shunt. A calibrated resistor connected across an electric device to bypass a portion of the current.

Sideband. The band of frequencies on each side of the carrier frequency produced by modulation.

Signal. The electric current, voltage, or waves constituting the inputs and outputs of electric or electronic circuits or devices. A signal may be the electric energy carrying information, or it may be the information itself.

Signal generator. A test unit designed to produce reference electrical signals that may be applied to electronic circuits for testing purposes.

Sine curve or wave. A graphical representation of a wave proportional in magnitude to the sine of its angular displacement; hence the sine wave is most useful in representing ac values.

Skin effect. The tendency of HF alternating currents to flow in the outer portion of a conductor.

Skip distance. The distance from a transmitter to the point where the reflected sky wave first reaches the earth.

Sky wave. That portion of a radio wave frequency spectrum that is transmitted in a straight path or reflected off the ionosphere.

Slip rings. Conducting rings used with brushes to conduct electric current to or from a rotating unit.

Solenoid. An electromagnetic device having a movable core. An electrically operated switch.

Solid-state. An adjective used to describe electric devices that use a solid material, such as silicon or germanium, to control current flow.

Space wave. That portion of a radio wave frequency that is capable of traveling through the ionosphere.

Split-bus electrical system. A power distribution system containing two isolated bus bars.

Split-field motor. A motor containing two separate field windings: one for clockwise rotation, one for counterclockwise rotation.

Split-phase motor. An ac motor that utilizes an inductor or a capacitor to shift the phase of the current in one of two field windings. This causes the resultant field to have a relational effect.

Square mil (mil^2). An area equivalent to a square having sides 1 mil (0.001 in.) in length.

Square wave. An electric wave having a square shape.

Squat switch. A switch activated by the compression of a landing gear strut.

Squirrel-cage rotor. A rotor for a brushless ac motor.

Standing waves. Stationary waves occurring on an antenna or a transmission line as a result of two waves, identical in amplitude and frequency, traveling in opposite directions along the conductor.

Starter-generator. A unit typically used on turbine engines to provide starting torque and generating electric power.

Static air temperature (SAT). The temperature of the undisturbed air surrounding the aircraft.

Static electricity. Electric charges that are at rest.

Stator. The stationary winding of a rotating ac machine.

Strobe light. A high-intensity flashing light created by a high voltage discharged into a gaseous flashtube.

Substrate. The semiconductor material upon which diffused and epitaxially deposited regions are formed to construct diodes, transistors, and similar devices.

Superheterodyne. A radio receiver using the heterodyne principle to produce an intermediate frequency (IF).

Sweep. The horizontal deflection of the electron beam in a CRT.

Switch. A device for opening and closing an electric circuit.

Synchro. A device for transmitting indications of angular position from one point to another.

Synchronous motor. An ac motor whose rotor is synchronized with the rotating field produced by the stator. The speed of rotation is always in time with the frequency of the applied alternating current.

Tachometer. An instrument designed to indicate the rpm of a rotating device.

Tank circuit. A parallel resonant circuit including an inductance and a capacitance.

TCAS. *Traffic alert and collision avoidance system.* An airborne system that interrogates mode A, C, and S transponders in nearby aircraft and uses the replies to identify and display potential and predicted collision threats.

Terminal. A connection fitting attached to the end of a circuit element.

Terminal strip. An insulated strip with terminal posts to provide a convenient junction point for a group of separate circuits.

Thermionic. Describes electron emission caused by heat.

Thermocouple. A junction of two dissimilar metals that generates a small current when exposed to heat.

Thin-film transistor (TFT). A modern flat panel display is comprised of thousands of tiny liquid crystals. Each connected in what is known as an active matrix. The active matrix uses TFTs to turn on/off each LCD at the appropriate time.

Three-phase system. An ac electrical system consisting of three conductors, each carrying a current 120° out of phase. Three-phase systems are used extensively in modern electrical and electronic actuating systems.

Thyristor. A four-layer (*pnpn*) semiconductor device with two, three, or four external terminals. Current flow through a thyristor may be controlled by one or more gates, by light, or by voltage applied between the two main terminals.

Transducer. A calibrated device that measures one form of energy and converts it into voltage.

Transceiver. A unit serving as both a receiver and a transmitter.

Transformer. A device used to increase or decrease the voltage in an ac circuit. It couples electric energy between circuits by means of mutual inductance.

Transformer-rectifier. A unit that contains both a transformer and a rectifier circuit.

Transistor. A semiconductor device, usually made of a germanium or silicon crystal, used to rectify or amplify an electric signal.

Transmission line. A conductor for radio waves, usually used to conduct RF energy from the output of a transmitter to the antenna.

Transmitter. An electronic system designed to produce modulated RF carrier waves to be radiated by an antenna; also, an electric device used to collect quantita[illegible] mation at one point and send it to a remote ind[illegible] trically.

Transponder. An airbone receiver-transmitter designed to aid air traffic control personnel in tracking aircraft during flight.

Triac. A thyristor that provides bilateral operation. It is equivalent to two silicon controlled rectifiers in inverse parallel connection. It is described as a bidirectional triode thyristor and is controlled by a gate circuit.

Trigger pulse. An electric pulse applied to certain electronic-circuit elements to start an operation.

True air temperature (TAT). The temperature of the air as it is compressed by the moving aircraft.

True power. The power consumed by the resistance in an ac circuit.

Tuning. The process of adjusting circuits to resonance at a particular frequency.

Turn-and-bank indicator. A gyro-operated instrument designed to show the pilot of an airplane the rate of turn. It also has a curved tube containing a ball to show whether the airplane is correctly banked.

Ultrahigh frequency (UHF). A radio frequency between 300 and 3000 MHz.

Uplink. The radio transmission path upward from the earth to the aircraft.

Vacuum tube. An electron tube with an evacuated envelope.

Valence orbit. The outermost orbit (shell) of an atom.

Valve-regulated lead-acid (VRLA) battery. A rechargeable secondary lead-acid battery commonly known as a *sealed battery* and is found in many modern aircraft; two common categories, *the absorbed glass mat* (AGM) battery and the *gel battery* (gel cell).

Vector. A quantity having both magnitude and direction.

Velocity. A measure of speed with direction.

Very high frequency (VHF). A frequency between 30 and 300 MHz.

Very low frequency (VLF). A frequency between 3 and 30 kHz.

VHF omnirange (VOR). An electronic air navigation system that provides accurate direction information in relation to a certain ground station.

Video. A term describing electronic circuit components controlling or producing the visual signals displayed on a CRT.

Virtual link. The ability for a smart switch to make data routing decisions in an Ethernet-type data bus system.

Virtual link ID. A digital identifier used to direct all data packets within an Ethernet-type data network.

Volt. The unit of emf or voltage.

Voltamperes. Product of voltage and current in a circuit.

Voltage divider. A resistance arranged with connections (taps) to provide for the removal of voltages of any desired level. A potentiometer is often used as a variable voltage divider.

Voltage drop. The electrical pressure drop created by current traveling through a resistance.

Voltage regulator. A circuit that maintains a constant-level voltage supply despite changes in input voltage or load.

Voltmeter. A voltage-measuring instrument.

Volume control. The circuit in a receiver or amplifier that varies loudness.

Watt (W). The unit of electric power. In a dc circuit, power (in watts) = volts × amperes, or $P(W) = EI$.

Watthour (Wh). The commercial unit of electric energy; watthours = watts × hours.

Wattmeter. An instrument for measuring electric power.

Waveguide. A hollow metallic tube designed to carry electromagnetic energy at extremely high frequencies.

Wavelength (λ). The distance between points of identical phase in a radio wave. The equation for wavelength is λ (lambda) = 300 000 000/*f*, where λ is wavelength in meters and *f* is frequency in hertz.

Weather mapping system. A device used to detect server weather conditions by measuring the amount and intensity of static electrical discharge within a storm.

Word. A category of digital data.

Yaw. Rotation of an aircraft about its vertical axis; turning to the right or left.

Zener diode. A diode that can be made to conduct in the reverse-biased mode at a precisely defined voltage. This allows the diode to be used as a precision voltage reference. The Zener diode has become the heart of virtually all modern voltage control circuits or solid-state voltage regulators.

Index

FIGURE 3-18 A 24-V lead-acid aircraft battery with self-contained battery box.

(a)

(b)

FIGURE 4-24 A typical crimped installation: (a) step one, prepare wire for installation; (b) step two, compress ring terminal using tool.

FIGURE 4-31 Common aircraft connectors.

(a)

FIGURE 4-34 Common steps used during the crimping process. (a) Select the correct crimping tool and adaptors for the wire and pin being crimped. (e) Completely compress (squeeze) handles until tool automatically releases. (*Daniels Manufacturing Corporation.*)

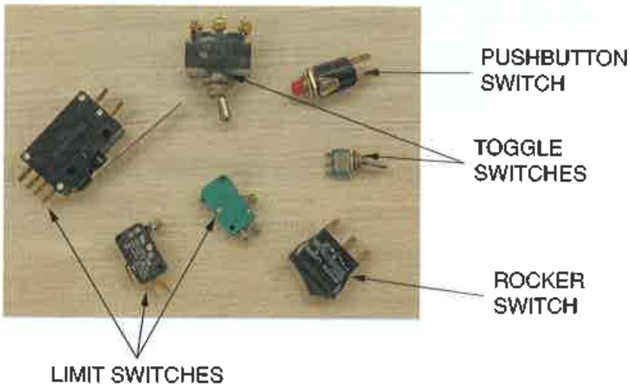

FIGURE 6-3 Common switch designs.

FIGURE 6-85 A modern instrument panel replaces conventional instruments with multiple flat panel displays.

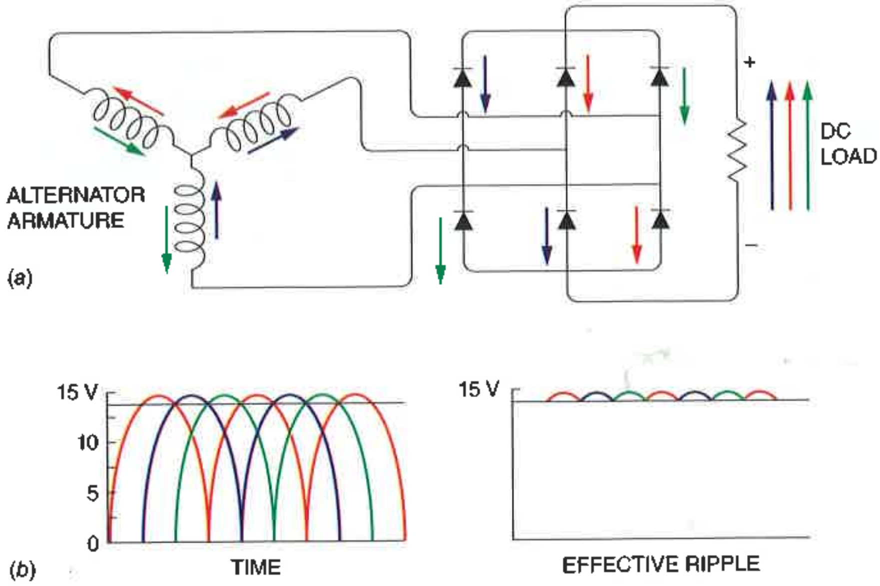

FIGURE 11-6 Rectification of a three-phase current.

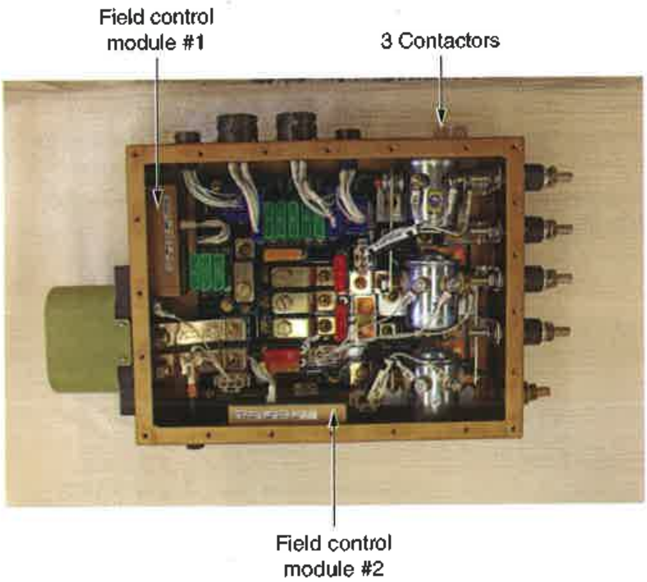

FIGURE 11-21 Cirrus aircraft master control unit (MCU).

FIGURE 12-7 Cirrus SR20 instrument panel.

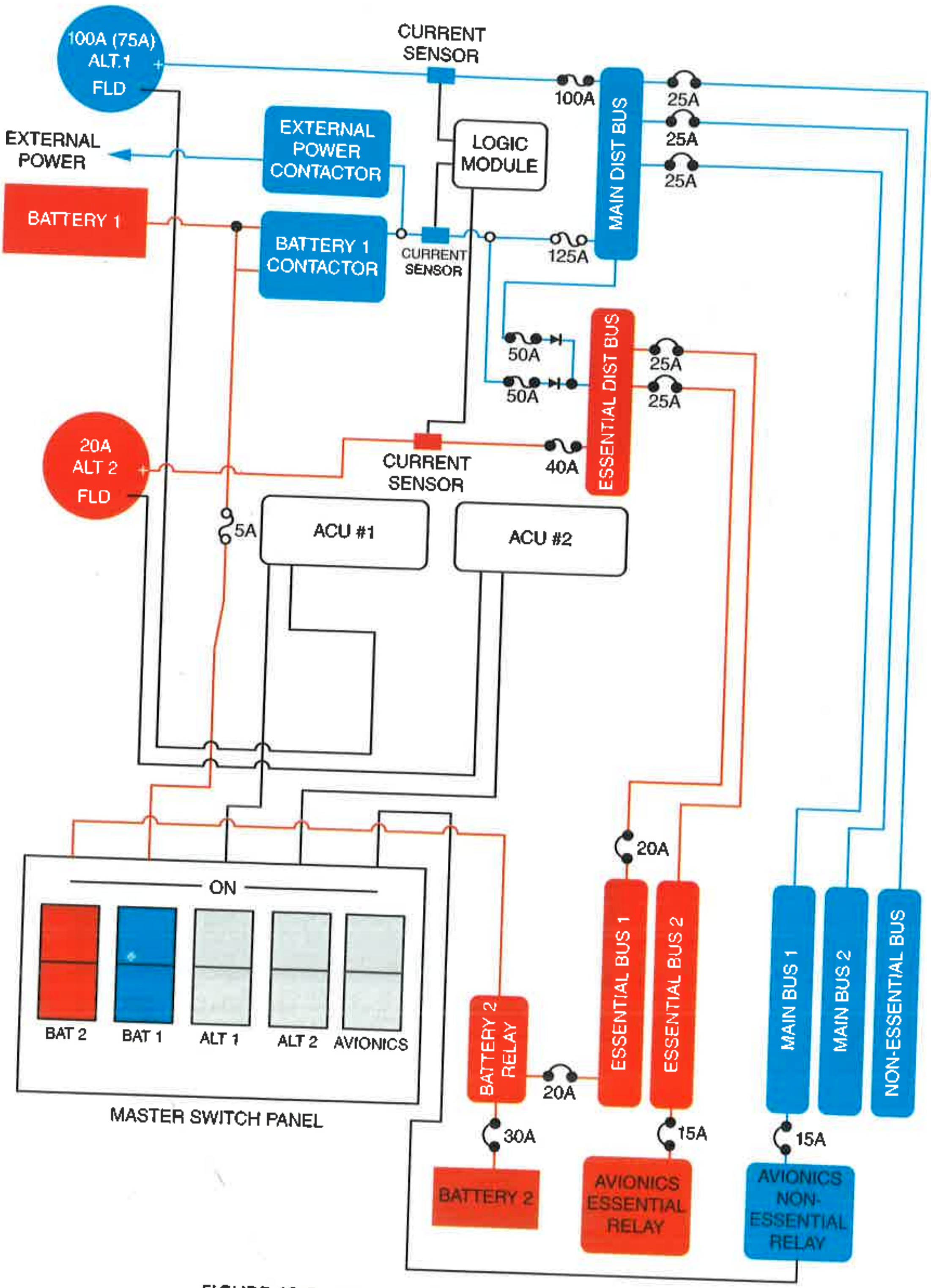

FIGURE 12-8 Cirrus SR20 power distribution system.

FIGURE 12-15 A typical ground (negative voltage) distribution point found on a composite aircraft.

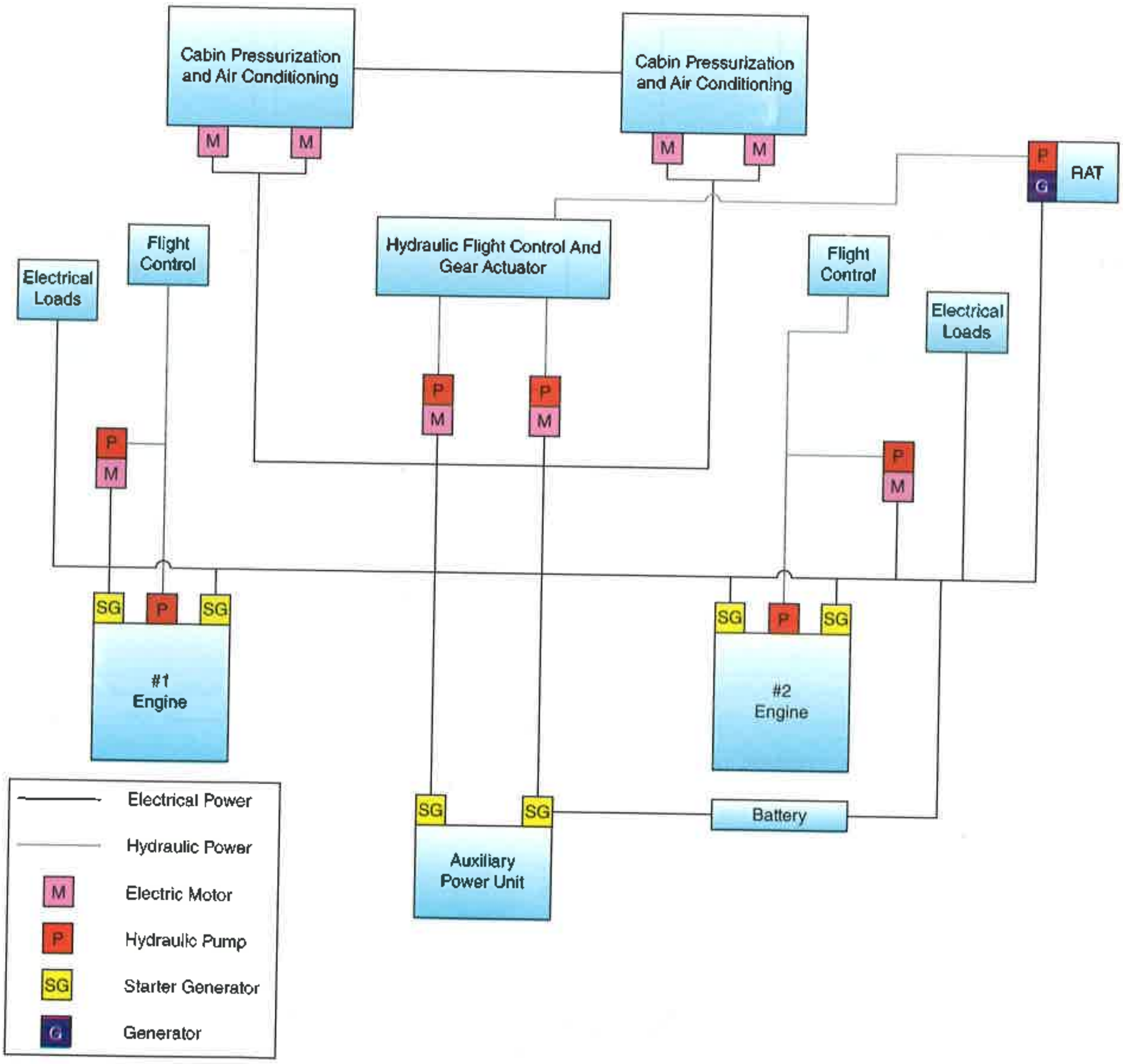

FIGURE 12-28 Boeing 787 power distribution system.

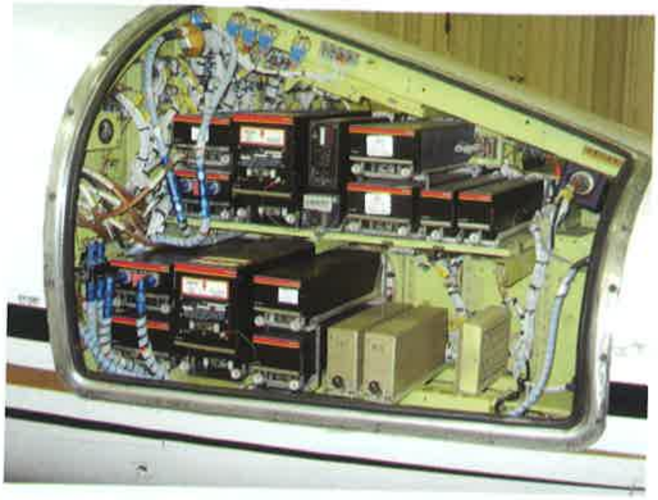

FIGURE 13-1 Forward equipment bay in the nose of a light jet aircraft.

FIGURE 13-10 Caution data shown on a modern flat panel display.

FIGURE 13-32 Digital multimeter connected to the terminals of a solenoid circuit to measure voltage.

FIGURE 14-49 Modern digital aircraft radio: (*a*) internal circuitry showing surface mounted integrated circuits; (*b*) digital display panel.

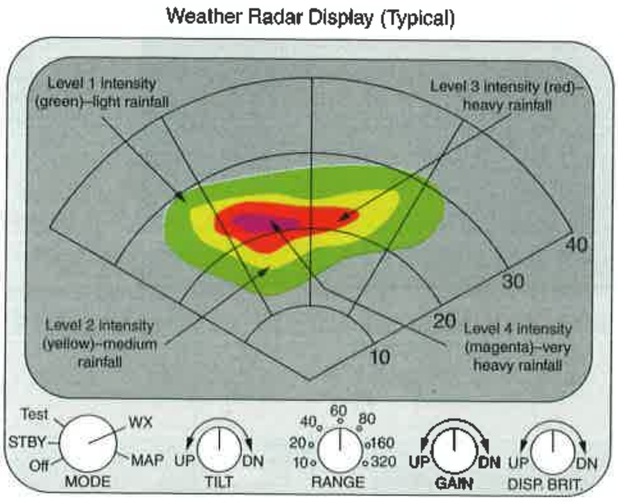

FIGURE 16-9 A typical color radar display. The range markings are typically white or blue. Level 1 storm activity (light rain), green; Level 2 storm activity (moderate rain), yellow; Level 3 storm activity (heavy rain), red; turbulence (extreme storm activity), magenta.

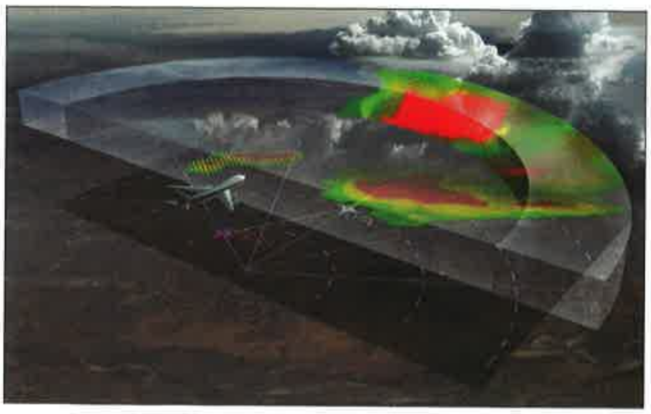

FIGURE 16-20 3-D aircraft weather radar. (*Honeywell.*)

FIGURE 16-21 The RDT-4000 IntuVue 3-D radar system for a Boeing 737. (*Honeywell.*)

FIGURE 17-28 The AV80R portable multifunction display designed for light aircraft. (*Bendix King, by Honeywell.*)

FIGURE 17-32 Airbus A-380 flight deck. (*Airbus S.A.S.*)

FIGURE 17-47 Control display unit (CDU).

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9 789339 204945

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Cover design: Thomas De Pierro