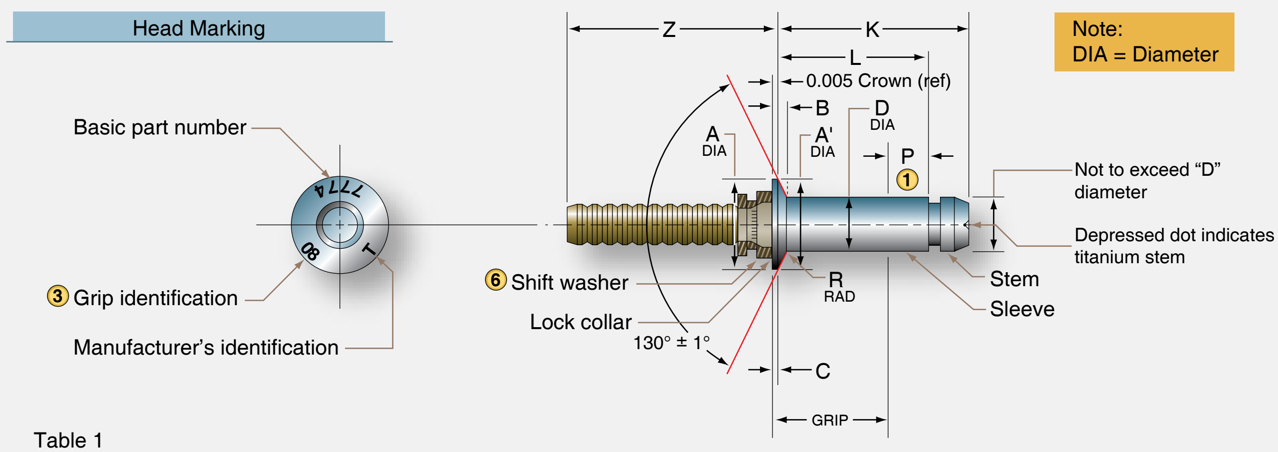


Table 1

Dia. Dash No.	D ± 0.001 (6)	A Max	A' Min	B Max	P Max	R Max	Z Min	Hole Limits	Installed Strength (Lb) (4)	
									Single Shear Minimum (5)	Tensile Minimum
–05	0.163	0.333	0.296	0.039	0.215	0.025	0.844	0.164/0.167	1980	900
–06	0.198	0.386	0.342	0.043	0.250	0.025	0.875	0.199/0.202	2925	1400
–06	0.259	0.507	0.463	0.057	0.305	0.030	1.000	0.260/0.263	5005	2100

Table 2

Grip Dash No.	Grip Limits				–05 Diameter		Grip Limits				–06 Diameter		–08 Diameter	
	Overlap Min	1/16 Range (4)		Overlap Max			Overlap Min	1/16 Range (4)		Overlap Max				
		Min	Max		L Ref	K Max		Min	Max		L Ref	K Max	L Ref	K Max
–02	—	0.094	0.157	0.173	0.336	0.476	—	0.120	0.157	0.173	0.355	0.521	—	—
–03	0.146	0.154	0.220	0.236	0.398	0.536	(9)	0.156	0.220	0.236	0.417	0.584	0.479	0.645
–04	0.209	0.219	0.282	0.298	0.460	0.602	0.203	0.219	0.282	0.298	0.480	0.647	0.541	0.708
–05	0.271	0.281	0.345	0.361	0.523	0.664	0.265	0.281	0.345	0.361	0.542	0.709	0.604	0.770
–06	0.334	0.344	0.407	0.423	0.585	0.727	0.328	0.344	0.407	0.423	0.605	0.772	0.666	0.833
–07	0.396	0.406	0.470	0.486	0.648	0.789	0.390	0.406	0.470	0.486	0.667	0.834	0.729	0.895
–08	0.459	0.469	0.532	0.548	0.710	0.852	0.453	0.469	0.532	0.548	0.730	0.897	0.791	0.958
–09	0.521	0.531	0.595	0.611	0.773	0.914	0.515	0.531	0.595	0.611	0.792	0.959	0.854	1.020
–10	0.584	0.594	0.657	0.673	0.835	0.977	0.578	0.594	0.657	0.673	0.855	1.022	0.916	1.083
–11	0.646	0.656	0.720	0.736	0.898	1.039	0.640	0.656	0.720	0.736	0.917	1.084	0.979	1.145
–12	0.709	0.719	0.782	0.798	0.960	1.102	0.703	0.719	0.782	0.798	0.980	1.147	1.041	1.208

Figure 7-83. *Cherry's titanium Maxibolt.*

The large footprint enables distribution of the joint preload over a larger area, virtually eliminating the possibility of delaminating the composite structure. The shear strength of the Accu-Lok™ is 95 KSI, and it is available in 100° flush head, 130° flush head, and protruding head styles. A similar fastener designed by Monogram is called the Radial-Lok®. *[Figure 7-84]*

Fiberlite

The fiberlite fastening system uses composite materials for a wide range of aerospace hardware. The strength of fiberlite fasteners is equivalent to aluminum at two-thirds the weight. The composite fastener provides good material compatibility with carbon fiber and fiberglass.

Screws & Nutplates in Composite Structures

The use of screws and nutplates in place of Hi-Loks® or blind fasteners is recommended if a panel must be removed periodically for maintenance. Nutplates used in composite structures usually require three holes: two for attachment of the nutplate and one for the removable screw, although rivetless nut plates and adhesive bonded nutplates are available that do not require drilling and countersinking two extra holes.

Machining Processes & Equipment

Drilling

Hole drilling in composite materials is different from drilling

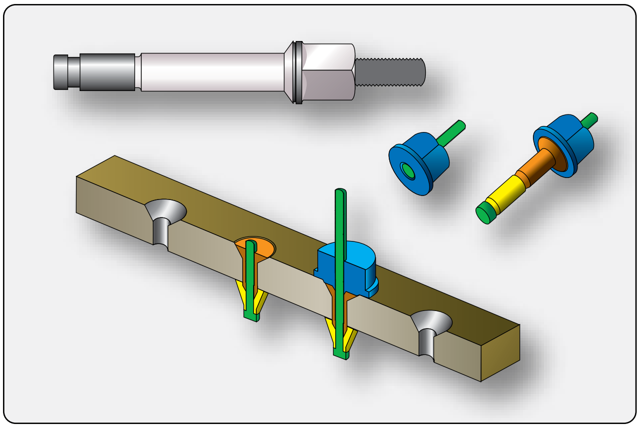


Figure 7-84. *Accu-Lok ™ installation.*

holes in metal aircraft structures. Different types of drill bits, higher speeds, and lower feeds are required to drill precision holes. Structures made from carbon fiber and epoxy resin are very hard and abrasive, requiring special flat flute drills or similar four-flute drills. Aramid fiber (Kevlar®)/epoxy composites are not as hard as carbon but are difficult to drill unless special cutters are used because the fibers tend to fray or shred unless they are cut clean while embedded in the epoxy. Special drill bits with clothes pin points and fish-tail points have been developed that slice the fibers prior to pulling them out of the drilled hole. If the Kevlar®/epoxy part is sandwiched between two metal parts, standard twist drills can be used.

Equipment

Air-driven tools are used for drilling holes in composite materials. Drill motors with free speed of up to 20,000 rpm are used. A general rule for drilling composites is to use high speed and a low feed rate (pressure). Drilling equipment with a power feed control produces better hole quality than drill motors without power feed control. Drill guides are recommended, especially for thicker laminates.

Do not use standard twist drill bits for drilling composite structures. Standard high-speed steel is unacceptable, because it dulls immediately, generates excessive heat, and causes ply delamination, fiber tear-out, and unacceptable hole quality.

Drill bits used for carbon fiber and fiberglass are made from diamond-coated material or solid carbide because the fibers are so hard that standard high-speed steel (HSS) drill bits do not last long. Typically, twist drills are used, but brad point drills are also available. The Kevlar® fibers are not as hard as carbon, and standard HSS drill bits can be used. The hole quality can be poor if standard drill bits are used and the preferred drill style is the sickle-shaped Klenk drill. This drill first pulls on the fibers and then shears them, which results in a better quality hole. Larger holes can be cut with diamond-coated hole saws or fly cutters, but only use fly cutters in a drill press, and not in a drill motor. *[Figures 7-85, 7-86,* and *7-87]*

Processes & Precautions

Composite materials are drilled with drill motors operating between 2,000 and 20,000 rpm and a low feed rate. Drill motors with a hydraulic dash pod or other type of feed control are preferred because they restrict the surging of the drill as it exits the composite materials. This reduces breakout damage and delaminations. Parts made from tape products are especially susceptible to breakout damage; parts made

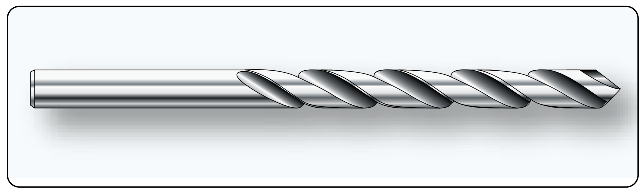


Figure 7-85. *Klenk-type drill for drilling Kevlar®.*

Figure 7-86. *Drilling and cutting tools for composite materials.*

Figure 7-87. *Autofeed drill.*

from fabric material have experienced less damage. The composite structure needs to be backed with a metal plate or sheet to avoid breakout. Holes in composite structures are often predrilled with a small pilot hole, enlarged with a diamond-coated or carbide drill bit and reamed with a carbide reamer to final hole size.

Back counterboring is a condition that can occur when carbon/epoxy parts mate metal substructure parts. The back edge of the hole in the carbon/epoxy part can be eroded or radiused by metal chips being pulled through the composite. The condition is more prevalent when there are gaps between the parts or when the metal debris is stringy rather than small chips. Back counterboring can be minimized or eliminated by changing feeds and speeds, cutter geometry, better part clamp-up adding a final ream pass, using a peck drill, or combination of these.

When drilling combinations of composite parts with metal parts, the metal parts may govern the drilling speed. For example, even though titanium is compatible with carbon/epoxy material from a corrosion perspective, lower drilling speeds are required in order to ensure no metallurgical damage occurs to the titanium. Titanium is drilled with low speed and high feed. Drill bits suitable for titanium might not be suitable for carbon or fiberglass. Drill bits that are used for drilling titanium are often made from cobalt-vanadium; drill bits used for carbon fiber are made from carbide or are diamond coated to increase drill life and to produce an accurate hole. Small-diameter high-speed steel drill bits, such as No. 40 drill, which are used to manually drill pilot holes, are typically used because carbide drills are relatively brittle and are easily broken. The relatively low cost of these small HSS drill bits offsets the limited life expectancy. High-speed steel drill bits may last for only one hole.

The most common problem with carbide cutters used in hand-drill operations is handling damage (chipped edges) to the cutters. A sharp drill with a slow constant feed can produce a 0.1 mm (0.004-inch) tolerance hole through carbon/epoxy plus thin aluminum, especially if a drill guide is used. With hard tooling, tighter tolerances can be maintained. When the structure under the carbon/epoxy is titanium, drills can pull titanium chips through the carbon/epoxy and enlarge the hole. In this case, a final ream operation may be required to hold tight hole tolerances. Carbide reamers are needed for holes through carbon/epoxy composite structure. In addition, the exit end of the hole needs good support to prevent splintering and delaminations when the reamer removes more than about 0.13 mm (0.005-inch) on the diameter. The support can be the substructure or a board held firmly against the back surface. Typical reaming speeds are about one-half of the drilling speed.

Cutting fluids are not normally used or recommended for drilling thin (less than 6.3 mm, or 0.25-inch thick) carbon/epoxy structures. It is good practice to use a vacuum while drilling into composite materials to prevent carbon dust from freely floating around the work area.

Countersinking

Countersinking a composite structure is required when flush head fasteners are to be installed in the assembly. For metallic structures, a 100° included angle shear or tension head fastener has been the typical approach. In composite structures, two types of fasteners are commonly used: a 100° included angle tension head fastener or a 130° included angle head fastener. The advantage of the 130° head is that the fastener head can have about the same diameter as a tension head 100° fastener with the head depth of a shear-type head 100° fastener. For seating flush fasteners in composite parts, it is recommended that the countersink cutters be designed to produce a controlled radius between the hole and the countersink to accommodate the head-to-shank fillet radius on the fasteners. In addition, a chamfer operation or a washer may be required to provide proper clearance for protruding head fastener head-to-shank radii. Whichever head style is used, a matching countersink/chamfer must be prepared in the composite structure.

Carbide cutters are used for producing a countersink in carbon/epoxy structure. These countersink cutters usually have straight flutes similar to those used on metals. For Kevlar® fiber/epoxy composites, S-shaped positive rake cutting flutes are used. If straight-fluted countersink cutters are used, a special thick tape can be applied to the surface to allow for a clean cutting of the Kevlar® fibers, but this is not as effective as the S-shaped fluted cutters. Use of a piloted countersink cutter is recommended because it ensures better concentricity between the hole and the countersink and decreases the possibility of gaps under the fasteners due to misalignment or delaminations of the part.

Use a microstop countersink gauge to produce consistent countersink wells. Do not countersink through more than 70 percent of the skin depth because a deeper countersink well reduces material strength. When a piloted countersink cutter is used, the pilot must be periodically checked for wear, as wear can cause reduction of concentricity between the hole and countersink. This is especially true for countersink cutters with only one cutting edge. For piloted countersink cutters, position the pilot in the hole and bring the cutter to full rpm before beginning to feed the cutter into the hole and preparing the countersink. If the cutter is in contact with the composite before triggering the drill motor, you may get splintering.

Cutting Processes & Precautions

Cutters that work well for metals would either have a short life or produce a poorly cut edge if used for composite materials. The cutters that are used for composites vary with the composite material that is being cut. The general rule for cutting composites is high speed and slow feed.

- Carbon fiber reinforced plastics: Carbon fiber is very hard and quickly wears out high speed steel cutters. For most trimming and cutting tasks, diamond grit cutters are best. Aluminum-oxide or silicon-carbide sandpaper or cloth is used for sanding. Silicon-carbide lasts longer then aluminum-oxide. Router bits can also be made from solid carbide or diamond coated.
- Glass fiber reinforced plastics: Glass fibers, like carbon, are very hard and quickly wear out high-speed steel cutters. Fiberglass is drilled with the same type and material drill bits as carbon fiber.
- Aramid (Kevlar®) fiber-reinforced plastics: Aramid fiber is not as hard as carbon and glass fiber, and cutters made from high-speed steel can be used. To prevent loose fibers at the edge of aramid composites, hold the part and then cut with a shearing action. Aramid composites need to be supported with a plastic backup plate. The aramid and backup plate are cut through at the same time. Aramid fibers are best cut by being held in tension and then sheared. There are specially shaped cutters that pull on the fibers and then shear them. When using scissors to cut aramid fabric or prepreg, they must have a shearing edge on one blade and a serrated or grooved surface on the other. These serrations hold the material from slipping. Sharp blades should always be used as they minimize fiber damage. Always clean the scissor serrations immediately after use so the uncured resin does not ruin the scissors.

Always use safety glasses and other protective equipment when using tools and equipment.

Cutting Equipment

The bandsaw is the equipment that is most often used in a repair shop for cutting composite materials. A toothless carbide or diamond-coated saw blade is recommended. A typical saw blade with teeth does not last long if carbon fiber or fiberglass is cut. *[Figure 7-88]* Air-driven hand tools, such as routers, saber saws, die grinders, and cut-off wheels can be used to trim composite parts. Carbide or diamond-coated cutting tools produce a better finish and they last much longer. Specialized shops have ultrasonic, waterjet, and laser cutters. These types of equipment are numerical controlled (NC) and produce superior edge and hole quality. A waterjet cutter cannot be used for honeycomb structure because it introduces water in the part. Do not cut anything else on equipment that is used for composites because other materials can contaminate the composite material.

Prepreg materials can be cut with a CNC Gerber table. The use of this equipment speeds up the cutting process and optimizes the use of the material. Design software is available that calculates how to cut plies for complex shapes. *[Figures 7-89]*

Repair Safety

Advanced composite materials including prepreg, resin systems, cleaning solvents, and adhesives could be hazardous, and it is important that you use personal protection equipment. It is important to read and understand the Safety Data Sheets (SDS) and handle all chemicals, resins, and fibers correctly. The SDS lists the hazardous chemicals in the material system, and it outlines the hazards. The material could be a respiratory irritant or carcinogenic, or another kind of dangerous substance.

Figure 7-88. *Bandsaw.*

Figure 7-89. *Gerber cutting table.*

Eye Protection

Always protect eyes from chemicals and flying objects. Wear safety glasses at all times and, when mixing or pouring acids, wear a face shield. Never wear corrective contact lenses in a shop, even with safety glasses. Some of the chemical solvents can melt the lenses and damage eyes. Dust can also get under the lenses, causing damage.

Respiratory Protection

Do not breathe carbon fiber dust and always ensure that there is a good flow of air where the work is performed. Always use equipment to assist in breathing when working in a confined space. Use a vacuum near the source of the dust to remove the dust from the air. When sanding or applying paint, you need a dust mask or a respirator. A properly fitted dust mask provides the protection needed. For application of paints, a sealed respirator with the correct filters or a fresh air supply respirator is required.

Downdraft Tables

A downdraft table is an efficient and economical device for protecting workers from harmful dust caused by sanding and grinding operations. The tables are also useful housekeeping tools because the majority of particulate material generated by machining operations is immediately collected for disposal. Downdraft tables should be sized and maintained to have an average face velocity between 100 and 150 cubic feet per minute. The downdraft table draws contaminants like dust and fibers away from the operator's material. Downdraft tables should be monitored and filters changed on a regular basis to provide maximum protection and particulate collection.

Skin Protection

During composite repair work, protect your skin from hazardous materials. Chemicals could remain on hands that burn sensitive skin. Always wear gloves and clothing that offer protection against toxic materials. Use only approved gloves that protect skin and do not contaminate the composite material. Always wash hands prior to using the toilet or eating. Damaged composite components should be handled with care. Single fibers can easily penetrate the skin, splinter off, and become lodged in the skin.

Fire Protection

Most solvents are flammable. Close all solvent containers and store in a fireproof cabinet when not in use. Make sure that solvents are kept away from areas where static electricity can occur. Static electricity can occur during sanding operations or when bagging material is unrolled. It is preferable to use air-driven tools. If electric tools are used, ensure that they are the enclosed type. Do not mix too much resin. The resin could overheat and start smoking caused by the exothermic process. Ensure that a fire extinguisher is always nearby.

Transparent Plastics

Plastics cover a broad field of organic synthetic resin and may be divided into two main classifications: thermoplastics and thermosetting plastics.

a. Thermoplastics—may be softened by heat and can be dissolved in various organic solvents. Acrylic plastic is commonly used as a transparent thermoplastic material for windows, canopies, etc. Acrylic plastics are known by the trade names of Lucite® or Plexiglas® and by the British as Perspex®, and meet the military specifications of MIL-P-5425 for regular acrylic and MIL-P-8184 for craze-resistant acrylic.

b. Thermosetting plastics—do not soften appreciably under heat but may char and blister at temperatures of 240–260 °C (400–500 °F). Most of the molded products of synthetic resin composition, such as phenolic, urea-formaldehyde, and melamine formaldehyde resins, belong to the thermosetting group. Once the plastic becomes hard, additional heat does not change it back into a liquid as it would with a thermoplastic.

Optical Considerations

Scratches and other types of damage that obstruct the vision of the pilots are not acceptable. Some types of damage might be acceptable at the edges of the windshield.

Identification

Storage & Handling

Because transparent thermoplastic sheets soften and deform when they are heated, they must be stored where the temperature never becomes excessive. Store them in a cool, dry location away from heating coils, radiators, or steam pipes, and away from such fumes as are found in paint spray booths or paint storage areas.

Keep paper-masked transparent sheets out of the direct rays of the sun, because sunlight accelerates deterioration of the adhesive, causing it to bond to the plastic, and making it difficult to remove.

Store plastic sheets with the masking paper in place, in bins that are tilted at a 10° angle from the vertical to prevent buckling. If the sheets are stored horizontally, take care to avoid getting dirt and chips between them. Stacks of sheets must never be over 18 inches high, with the smallest sheets stacked on top of the larger ones so there is no unsupported overhang. Leave the masking paper on the sheets as long as possible, and take care not to scratch or gouge the sheets by sliding them against each other or across rough or dirty tables.

Store formed sections with ample support so they do not lose their shape. Vertical nesting should be avoided. Protect formed parts from temperatures higher than 120 °F (49 °C), and leave their protective coating in place until they are installed on the aircraft.

Forming Procedures & Techniques

Transparent acrylic plastics get soft and pliable when they are heated to their forming temperatures and can be formed to almost any shape. When they cool, they retain the shape to which they were formed. Acrylic plastic may be cold-bent into a single curvature if the material is thin and the bending radius is at least 180 times the thickness of the sheet. Cold bending beyond these limits impose so much stress on the surface of the plastic that tiny fissures or cracks, called crazing, form.

Heating

Wear cotton gloves when handling the plastic to eliminate finger marks on the soft surface. Before heating any transparent plastic material, remove all of the masking paper and adhesive from the sheet. If the sheet is dusty or dirty, wash it with clean water and rinse it well. Dry the sheet thoroughly by blotting it with soft absorbent paper towels.

For the best results when hot forming acrylics, adhere to the temperatures recommended by the manufacturer. Use a forced-air oven that can operate over a temperature range of 120–374 °F (49–190 °C). If the part gets too hot during the forming process, bubbles may form on the surface and impair the optical qualities of the sheet.

For uniform heating, it is best to hang the sheets vertically by grasping them by their edges with spring clips and suspending the clips in a rack. *[Figure 7-90]* If the piece is too small to hold with clips, or if there is not enough trim area, lay the sheets on shelves or racks covered with soft felt or flannel. Be sure there is enough open space to allow the air to circulate around the sheet and heat it evenly.

Small forming jobs, such as landing light covers, may be heated in a kitchen baking oven. Infrared heat lamps may be used if they are arranged on 7- to 8-inch centers and enough of them are used in a bank to heat the sheet evenly. Place the lamps about 18-inches from the material.

Never use hot water or steam directly on the plastic to heat it because this likely causes the acrylic to become milky or cloudy.

Forms

Heated acrylic plastic molds with almost no pressure, so the forms used can be of very simple construction. Forms made of pressed wood, plywood, or plaster are adequate to form simple curves, but reinforced plastic or plaster may be needed to shape complex or compound curves. Since hot plastic conforms to any waviness or unevenness, the form used must be completely smooth. To ensure this, sand the form and cover it with soft cloth, such as outing flannel or billiard felt. The mold should be large enough to extend beyond the trim line of the part, and provisions should be made for holding the hot plastic snug against the mold as it cools.

A mold can be made for a complex part by using the damaged part itself. If the part is broken, tape the pieces together, wax or grease the inside so the plaster does not stick to it, and support the entire part in sand. Fill the part with plaster and allow it to harden, and then remove it from the mold. Smooth out any roughness and cover it with soft cloth. It is now ready to use to form the new part.

Forming Methods

Simple Curve Forming

Heat the plastic material to the recommended temperature, remove it from the heat source, and carefully drape it over the prepared form. Carefully press the hot plastic to the form and either hold or clamp the sheet in place until it cools. This process may take from 10–30 minutes. Do not force cool it.

Compound Curve Forming

Compound curve forming is normally used for canopies or complex wingtip light covers, and it requires a great deal of specialized equipment. There are four commonly used methods, each having its advantages and disadvantages.

Stretch Forming

Preheated acrylic sheets are stretched mechanically over the form in much the same way as is done with the simple curved

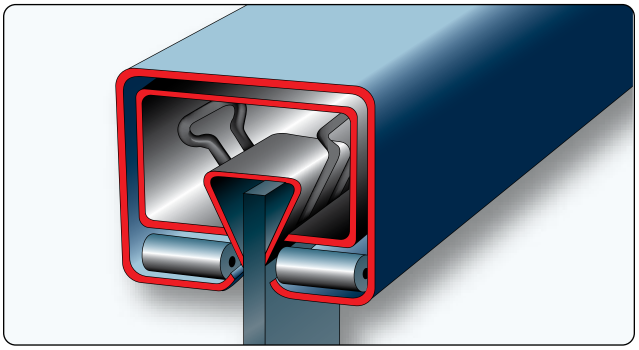


Figure 7-90. *Hanging an acrylic sheet.*

piece. Take special care to preserve uniform thickness of the material, since some parts must stretch more than others.

Male & Female Die Forming

Male and female die forming requires expensive matching male and female dies. The heated plastic sheet is placed between the dies that are then mated. When the plastic cools, the dies are opened.

Vacuum Forming Without Forms

Many aircraft canopies are formed by this method. In this process, a panel, which has cut into it the outline of the desired shape, is attached to the top of a vacuum box. The heated and softened sheet of plastic is then clamped on top of the panel. When the air in the box is evacuated, the outside air pressure forces the hot plastic through the opening and forms the concave canopy. It is the surface tension of the plastic that shapes the canopy.

Vacuum Forming With a Female Form

If the shape needed is other than that which would be formed by surface tension, a female mold, or form must be used. It is placed below the plastic sheet and the vacuum pump is connected. When air from the form is evacuated, the outside air pressure forces the hot plastic sheet into the mold and fills it.

Sawing & Drilling

Sawing

Several types of saws can be used with transparent plastics; however, circular saws are the best for straight cuts. The blades should be hollow ground or have some set to prevent binding. After the teeth are set, they should be side dressed to produce a smooth edge on the cut. Band saws are recommended for cutting flat acrylic sheets when the cuts must be curved or where the sheet is cut to a rough dimension to be trimmed later. Close control of size and shape may be obtained by band sawing a piece to within 1⁄16-inch of the desired size, as marked by a scribed line on the plastic, and then sanding it to the correct size with a drum or belt sander.

Drilling

Unlike soft metal, acrylic plastic is a very poor conductor of heat. Make provisions for removing the heat when drilling. Deep holes need cooling, and water-soluble cutting oil is a satisfactory coolant since it has no tendency to attack the plastic.

The drill used on acrylics must be carefully ground and free from nicks and burrs that would affect the surface finish. Grind the drill with a greater included angle than would be used for soft metal. The rake angle should be zero in order to scrape, and not cut. The length of the cutting edge (and hence the width of the lip) can be reduced by increasing the included angle of the drill. *[Figure 7-91]* Whenever holes are drilled completely through acrylic, the standard twist drills should be modified to a 60° tip angle, the cutting edge to a zero rake angle, and the back lip clearance angle increased to 12-15°. Drills specially modified for drilling acrylic are available from authorized distributors and dealers.

The patented Unibit® is good for drilling small holes in aircraft windshields and windows. *[Figure 7-92]* It can cut holes from ⅛ to ½-inch in 1⁄32-inch increments and produces good smooth holes with no stress cracks around their edges.

Cementing

Polymerizable cements are those in which a catalyst is added to an already thick monomer-polymer syrup to promote rapid hardening. Cement PS-30® and Weld-On 40® are polymerizable cements of this type. They are suitable for cementing all types of plexiglas acrylic cast sheet and parts molded from plexiglas molding pellets. At room temperature, the cements harden (polymerize) in the container in about 45 minutes after mixing the components. They harden more rapidly at higher temperatures. The cement joints are usually hard enough for handling within 4 hours after assembly. The joints may be machined within 4 hours after assembly, but it is better to wait 24 hours.

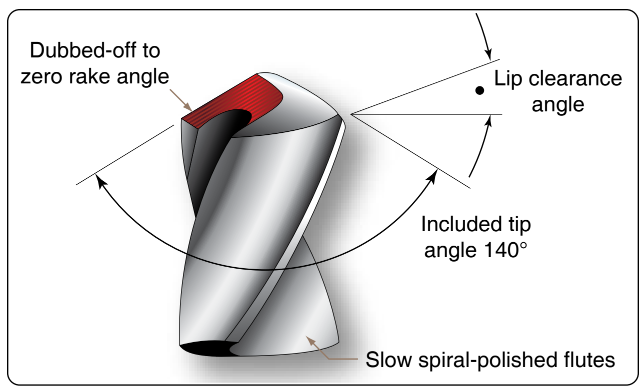


Figure 7-91. *Drill with an included angle of 140° is used to drill acrylic plastics.*

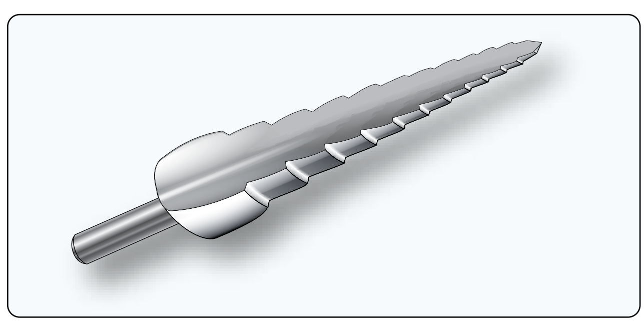


Figure 7-92. *Unibit® drill for drilling acrylic plastics.*

Application of Cement

PS-30® and Weld-On 40® joints retain excellent appearance and color stability after outdoor exposure. These cements produce clear, transparent joints and should be used when the color and appearance of the joints are important.

PS-30® and Weld-On 40® should be used at temperatures no lower than 65 °F. If cementing is done in a room cooler than 65 °F, it requires a longer time to harden and the joint strength is reduced.

The cement should be prepared with the correct proportions of components as given in the manufacturer's instructions and thoroughly mixed, making sure neither the mixing container nor mixing paddle adds color or effects the hardening of the cement. Clean glass or polyethylene mixing containers are preferred. Because of their short pot life (approximately 45 minutes), Cement PS-30® and Weld-On 40® must be used quickly once the components are mixed. Time consumed in preparation shortens the effective working time, making it necessary to have everything ready to be cemented before the cements are mixed. For better handling, pour cement within 20 minutes of mixing. For maximum joint strength, the final cement joint should be free of bubbles. It is usually sufficient to allow the mixed cement to stand for 10 minutes before cementing to allow bubbles to rise to the surface. The gap joint technique can only be used with colorless plexiglas acrylic or in cases where joints are hidden. If inconspicuous joints in colored plexiglas acrylic are needed, the parts must be fitted closely, using closed V-groove, butt, or arc joints.

Cement forms, or dams, may be made with masking tape as long as the adhesive surface does not contact the cement. This is easily done with a strip of cellophane tape placed over the masking tape adhesive. The tape must be chosen carefully. The adhesive on ordinary cellophane tape prevents the cure of PS-30® and Weld-On 40®. Before actual fabrication of parts, sample joints should be tried to ensure that the tape system used does not harm the cement. Since it is important for all of the cement to remain in the gap, only contact pressure should be used.

Bubbles tend to float to the top of the cement bead in a gap joint after the cement is poured. These cause no problem if the bead is machined off. A small wire (not copper) or similar object may be used to lift some bubbles out of the joint; however, the cement joint should be disturbed as little as possible.

Polymerizable cements shrink as the cement hardens. Therefore, the freshly poured cement bead should be left above the surfaces being cemented to compensate for the shrinkage. If it is necessary for appearances, the bead may be machined off after the cement has set.

Repairs

Whenever possible, replace, rather than repair, extensively damaged transparent plastic. A carefully patched part is not the equal of a new section, either optically or structurally. At the first sign of crack development, drill a small hole with a #30 or a ⅛-inch drill at the extreme ends of the cracks. *[Figure 7-93]* This serves to localize the cracks and to prevent further splitting by distributing the strain over a large area. If the cracks are small, stopping them with drilled holes usually suffices until replacement or more permanent repairs can be made.

Cleaning

Plastics have many advantages over glass for aircraft use, but they lack the surface hardness of glass and care must be exercised while servicing the aircraft to avoid scratching or otherwise damaging the surface. Clean the plastic by washing it with plenty of water and mild soap, using a clean, soft, grit-free cloth, sponge, or bare hands. Do not use gasoline, alcohol, benzene, acetone, carbon tetrachloride, fire extinguisher or deicing fluids, lacquer thinners, or window

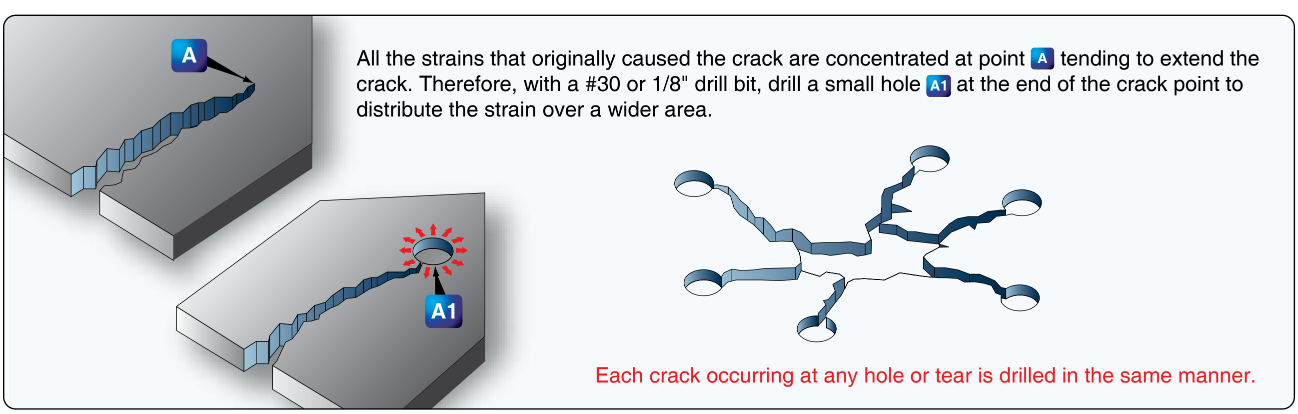


Figure 7-93. *Stop drilling of cracks.*

cleaning sprays. These soften the plastic and cause crazing.

Plastics should not be rubbed with a dry cloth since it is likely to cause scratches and to build up an electrostatic charge that attracts dust particles to the surface. If, after removing dirt and grease, no great amount of scratching is visible, finish the plastic with a good grade of commercial wax. Apply the wax in a thin even coat and bring to a high polish by rubbing lightly with a soft cloth.

Polishing

Do not attempt hand polishing or buffing until the surface is clean. A soft, open-type cotton or flannel buffing wheel is suggested. Minor scratches may be removed by vigorously rubbing the affected area by hand, using a soft clean cloth dampened with a mixture of turpentine and chalk, or by applying automobile cleanser with a damp cloth. Remove the cleaner and polish with a soft, dry cloth. Acrylic and cellulose acetate plastics are thermoplastic. Friction created by buffing or polishing too long in one spot can generate sufficient heat to soften the surface. This condition produces visual distortion and should be avoided.

Windshield Installation

Use material equivalent to that originally used by the manufacturer of the aircraft for replacement panels. There are many types of transparent plastics on the market. Their properties vary greatly, particularly expansion characteristics, brittleness under low temperatures, resistance to discoloration when exposed to sunlight, surface checking, etc. Information on these properties is in MIL-HDBK-17, Plastics for Flight Vehicles, Part II Transparent Glazing Materials. These properties are considered by aircraft manufacturers in selecting materials to be used in their designs and the use of substitutes having different characteristics may result in subsequent difficulties.

Installation Procedures

When installing a replacement panel, use the same mounting method employed by the manufacturer of the aircraft. While the actual installation varies from one type of aircraft to another, consider the following major principles when installing any replacement panel.

1. Never force a plastic panel out of shape to make it fit a frame. If a replacement panel does not fit easily into the mounting, obtain a new replacement or heat the whole panel and re-form. When possible, cut and fit a new panel at ordinary room temperature.
2. In clamping or bolting plastic panels into their mountings, do not place the plastic under excessive compressive stress. It is easy to develop more than 1,000 psi on the plastic by overtorquing a nut and bolt. Tighten each nut to a firm fit, and then back the nut off one full turn (until they are snug and can still be rotated with the fingers).
3. In bolted installations, use spacers, collars, shoulders, or stop-nuts to prevent tightening the bolt excessively. Whenever such devices are used by the aircraft manufacturer, retain them in the replacement installation. It is important that the original number of bolts, complete with washers, spacers, etc., be used. When rivets are used, provide adequate spacers or other satisfactory means to prevent excessive tightening of the frame to the plastic.
4. Mount plastic panels between rubber, cork, or other gasket material to make the installation waterproof, to reduce vibration, and to help to distribute compressive stresses on the plastic.
5. Plastics expand and contract considerably more than the metal channels in which they are mounted. Mount windshield panels to a sufficient depth in the channel to prevent it from falling out when the panel contracts at low temperatures or deforms under load. When the manufacturer's original design permits, mount panels to a minimum depth of 1⅛-inches, and with a clearance of ⅛-inch between the plastic and bottom of the channel.
6. In installations involving bolts or rivets, make the holes through the plastic oversize by ⅛-inch and center so that the plastic does not bind or crack at the edge of the holes. The use of slotted holes is also recommended.

Chapter 8
Aircraft Painting & Finishing

Introduction

Paint, or more specifically its overall color and application, is usually the first impression that is transmitted to someone when they look at an aircraft for the first time. Paint makes a statement about the aircraft and the person who owns or operates it. The paint scheme may reflect the owner's ideas and color preferences for an amateur-built aircraft project, or it may be colors and identification for the recognition of a corporate or air carrier aircraft.

Paint is more than aesthetics; it affects the weight of the aircraft and protects the integrity of the airframe. The topcoat finish is applied to protect the exposed surfaces from corrosion and deterioration. Also, a properly painted aircraft is easier to clean and maintain because the exposed surfaces are more resistant to corrosion and dirt, and oil does not adhere as readily to the surface.

A wide variety of materials and finishes are used to protect and provide the desired appearance of the aircraft. The term "paint" is used in a general sense and includes primers, enamels, lacquers, and the various multipart finishing formulas. Paint has three components: resin as coating material, pigment for color, and solvents to reduce the mix to a workable viscosity.

Internal structure and unexposed components are finished to protect them from corrosion and deterioration. All exposed surfaces and components are finished to provide protection and to present a pleasing appearance. Decorative finishing includes trim striping, the addition of company logos and emblems, and the application of decals, identification numbers, and letters.

Finishing Materials

A wide variety of materials are used in aircraft finishing. Some of the more common materials and their uses are described in the following paragraphs.

Acetone

Acetone is a fast-evaporating colorless solvent. It is used as an ingredient in paint, nail polish, and varnish removers. It is a strong solvent for most plastics and is ideal for thinning fiberglass resin, polyester resins, vinyl, and adhesives. It is also used as a superglue remover. Acetone is a heavy-duty degreaser suitable for metal preparation and removing grease from fabric covering prior to doping. It should not be used as a thinner in dope because of its rapid evaporation, which causes the doped area to cool and collect moisture. This absorbed moisture prevents uniform drying and results in blushing of the dope and a flat no-gloss finish.

Alcohol

Butanol, or butyl alcohol, is a slow-drying solvent that can be mixed with aircraft dope to retard drying of the dope film on humid days, thus preventing blushing. A mixture of dope solvent containing 5 to 10 percent of butyl alcohol is usually sufficient for this purpose. Butanol and ethanol alcohol are mixed together in ratios ranging from 1:1 to 1:3 to use to dilute wash coat primer for spray applications because the butyl alcohol retards the evaporation rate.

Ethanol or denatured alcohol is used to thin shellac for spraying and as a constituent of paint and varnish remover. It can also be used as a cleaner and degreaser prior to painting.

Isopropyl, or rubbing alcohol, can be used as a disinfectant. It is used in the formulation of oxygen system cleaning solutions. It can be used to remove grease pencil and permanent marker from smooth surfaces, or to wipe hand or fingerprint oil from a surface before painting.

Benzene

Benzene is a highly flammable, colorless liquid with a sweet odor. It is a product used in some paint and varnish removers. It is an industrial solvent that is regulated by the Environmental Protection Agency (EPA) because it is an extremely toxic chemical compound when inhaled or absorbed through the skin. It has been identified as a Class A carcinogen known to cause various forms of cancer. It should be avoided for use as a common cleaning solvent for paint equipment and spray guns.

Methyl Ethyl Ketone (MEK)

Methyl ethyl ketone (MEK), also referred to as 2-Butanone, is a highly flammable, liquid solvent used in paint and varnish removers, paint and primer thinners, in surface coatings, adhesives, printing inks, as a catalyst for polyester resin hardening, and as an extraction medium for fats, oils, waxes, and resins. Because of its effectiveness as a quickly evaporating solvent, MEK is used in formulating high solids coatings that help to reduce emissions from coating operations. Persons using MEK should use protective gloves and have adequate ventilation to avoid the possible irritation effects of skin contact and breathing of the vapors.

Methylene Chloride

Methylene chloride is a colorless, volatile liquid completely miscible with a variety of other solvents. It is widely used in paint strippers and as a cleaning agent/degreaser for metal parts. It has no flash point under normal use conditions and can be used to reduce the flammability of other substances.

Toluene

Referred to as toluol or methylbenzene, toluene is a clear, water-insoluble liquid with a distinct odor similar to that of benzene. It is a common solvent used in paints, paint thinners, lacquers, and adhesives. It has been used as a paint remover in softening fluorescent-finish, clear-topcoat sealing materials. It is also an acceptable thinner for zinc chromate primer. It has been used as an antiknocking additive in gasoline. Prolonged exposure to toluene vapors should be avoided because it may be linked to brain damage.

Turpentine

Turpentine is obtained by distillation of wood from certain pine trees. It is a flammable, water-insoluble liquid solvent used as a thinner and quick-drier for varnishes, enamels, and other oil-based paints. Turpentine can be used to clean paint equipment and paint brushes used with oil-based paints.

Mineral Spirits

Sometimes referred to as white spirit, Stoddard solvent, or petroleum spirits, mineral spirits is a petroleum distillate used as a paint thinner and mild solvent. The reference to the name Stoddard came from a dry cleaner who helped to develop it in the 1920s as a less volatile dry cleaning solvent and as an alternative to the more volatile petroleum solvents that were being used for cleaning clothes. It is the most widely used solvent in the paint industry, used in aerosols, paints, wood preservatives, lacquers, and varnishes. It is also commonly used to clean paint brushes and paint equipment. Mineral spirits are used in industry for cleaning and degreasing machine tools and parts because it is very effective in removing oils and greases from metal. It has low odor, is less flammable, and less toxic than turpentine.

Naphtha

Naphtha is one of a wide variety of volatile hydrocarbon mixtures that is sometimes processed from coal tar but more often derived from petroleum. Naphtha is used as a solvent for various organic substances, such as fats and rubber, and in the making of varnish. It is used as a cleaning fluid and is incorporated into some laundry soaps. Naphtha has a low flashpoint and is used as a fuel in portable stoves and lanterns. It is sold under different names around the world and is known as white gas, or Coleman fuel, in North America.

Linseed Oil

Linseed oil is the most commonly used carrier in oil paint. It makes the paint more fluid, transparent, and glossy. It is used to reduce semipaste oil colors, such as dull black stenciling paint and insignia colors, to a brushing consistency. Linseed oil is also used as a protective coating on the interior of metal tubing. Linseed oil is derived from pressing the dried ripe flax seeds of the flax plant to obtain the oil and then using a process called solvent extraction. Oil obtained without the solvent extraction process is marketed as flaxseed oil. The term "boiled linseed oil" indicates that it was processed with additives to shorten its drying time.

A note of caution is usually added to packaging of linseed oil with the statement, "Risk of Fire from Spontaneous Combustion Exists with this Product." Linseed oil generates heat as it dries. Oily materials and rags must be properly disposed after use to eliminate the possible cause of spontaneous ignition and fire.

Thinners

Thinners include a plethora of solvents used to reduce the viscosity of any one of the numerous types of primers, subcoats, and topcoats. The types of thinner used with the various coatings is addressed in other sections of this chapter.

Varnish

Varnish is a transparent protective finish primarily used for finishing wood. It is available in interior and exterior grades. The exterior grade does not dry as hard as the interior grade, allowing it to expand and contract with the temperature changes of the material being finished. Varnish is traditionally a combination of a drying oil, a resin, and a thinner or solvent. It has little or no color, is transparent, and has no added pigment. Varnish dries slower than most other finishes. Resin varnishes dry and harden when the solvents in them evaporate. Polyurethane and epoxy varnishes remain liquid after the evaporation of the solvent but quickly begin to cure through chemical reactions of the varnish components.

Primers

The importance of primers in finishing and protection is generally misunderstood and underestimated because it is invisible after the topcoat finish is applied. A primer is the foundation of the finish. Its role is to bond to the surface, inhibit corrosion of metal, and provide an anchor point for the finish coats. It is important that the primer pigments be either anodic to the metal surface or passivate the surface should moisture be present. The binder must be compatible with the finish coats. Primers on nonmetallic surfaces do not require sacrificial or passivating pigments. Some of the various primer types are discussed below.

Wash Primers

Wash primers are water-thin coatings of phosphoric acid in solutions of vinyl butyral resin, alcohol, and other ingredients. They are very low in solids with almost no filling qualities. Their functions are to passivate the surface, temporarily provide corrosion resistance, and provide an adhesive base for the next coating, such as a urethane or epoxy primer. Wash primers do not require sanding and have high-corrosion protection qualities. Some have a very small recoat time frame that must be considered when painting larger aircraft. The manufacturers' instructions must be followed for satisfactory results.

Red Iron Oxide

Red oxide primer is an alkyd resin-based coating that was developed for use over iron and steel located in mild environmental conditions. It can be applied over rust that is free of loose particles, oil, and grease. It has limited use in the aviation industry.

Gray Enamel Undercoat

This is a single component, nonsanding primer compatible with a wide variety of topcoats. It fills minor imperfections, dries fast without shrinkage, and has high-corrosion resistance. It is a good primer for composite substrates.

Urethane

This is a term that is misused or interchanged by painters and manufacturers alike. It is typically a two-part product that uses a chemical activator to cure by linking molecules together to form a whole new compound. Polyurethane is commonly used when referring to urethane, but not when the product being referred to is acrylic urethane.

Urethane primer, like the urethane paint, is also a two-part product that uses a chemical activator to cure. It is easy to sand and fills well. The proper film thickness must be observed, because it can shrink when applied too heavily. It is typically applied over a wash primer for best results. Special precautions must be taken by persons spraying because the activators contain isocyanates (discussed further in the Protective Equipment section at the end of this chapter).

Epoxy

Epoxy is a synthetic, thermosetting resin that produces tough, hard, chemical-resistant coatings and adhesives. It uses a catalyst to chemically activate the product, but it is not classified as hazardous because it contains no isocyanates. Epoxy can be used as a nonsanding primer/sealer over bare metal and it is softer than urethane, so it has good chip resistance. It is recommended for use on steel tube frame aircraft prior to installing fabric covering.

Zinc Chromate

Zinc chromate is a corrosion-resistant pigment that can be added to primers made of different resin types, such as epoxy, polyurethane, and alkyd. Older type zinc chromate is distinguishable by its bright yellow color when compared to the light green color of some of the current brand primers. Moisture in the air causes the zinc chromate to react with the metal surface, and it forms a passive layer that prevents corrosion. Zinc chromate primer was, at one time, the standard primer for aircraft painting. Environmental concerns and new formula primers have all but replaced it.

Identification of Paints

Dope

When fabric-covered aircraft ruled the sky, dope was the standard finish used to protect and color the fabric. The dope imparted additional qualities of increased tensile strength, airtightness, weather-proofing, ultraviolet (UV) protection, and tautness to the fabric cover. Aircraft dope is essentially a colloidal solution of cellulose acetate or nitrate combined with plasticizers to produce a smooth, flexible, homogeneous film.

Dope is still used on fabric covered aircraft as part of a covering process. However, the type of fabric being used to cover the aircraft has changed. Grade A cotton or linen was the standard covering used for years, and it still may be used if it meets the requirements of the Federal Aviation Administration (FAA), Technical Standard Order (TSO) C-15d/AMS 3806c.

Polyester fabric coverings now dominate in the aviation industry. These new fabrics have been specifically developed for aircraft and are far superior to cotton and linen. The protective coating and topcoat finishes used with the Ceconite® polyester fabric covering materials are part of a Supplemental Type Certificate (STC) and must be used as specified when covering any aircraft with a Standard Airworthiness Certificate. The Ceconite® covering procedures use specific brand name, nontautening nitrate and butyrate dope as part of the STC.

The Poly-Fiber® system also uses a special polyester fabric covering as part of its STC, but it does not use dope. All the liquid products in the Poly-Fiber® system are made from vinyl, not from cellulose dope. The vinyl coatings have several real advantages over dope: they remain flexible, they do not shrink, they do not support combustion, and they are easily removed from the fabric with MEK, which simplifies most repairs.

Synthetic Enamel

Synthetic enamel is an oil-based, single-stage paint (no clear coat) that provides durability and protection. It can be mixed with a hardener to increase the durability and shine while decreasing the drying time. It is one of the more economical types of finish.

Lacquers

The origin of lacquer dates back thousands of years to a resin obtained from trees indigenous to China. In the early 1920s, nitrocellulose lacquer was developed from a process using cotton and wood pulp.

Nitrocellulose lacquers produce a hard, semiflexible finish that can be polished to a high sheen. The clear variety yellows as it ages, and it can shrink over time to a point that the surface crazes. It is easy to spot repair because each new coat of lacquer softens and blends into the previous coat. This was one of the first coatings used by the automotive industry in mass production, because it reduced finishing times from almost two weeks to two days.

Acrylic lacquers were developed to eliminate the yellowing problems and crazing of the nitrocellulose lacquers. General Motors started using acrylic lacquer in the mid-1950s, and they used it into the 1960s on some of their premium model cars. Acrylics have the same working properties but dry to a less brittle and more flexible film than nitrocellulose lacquer.

Lacquer is one of the easiest paints to spray, because it dries quickly and can be applied in thin coats. However, lacquer is not very durable; bird droppings, acid rain, and gasoline spills actually eat down into the paint. It still has limited use on collector and show automobiles because they are usually kept in a garage, protected from the environment.

The current use of lacquer for an exterior coating on an aircraft is almost nonexistent because of durability and environmental concerns. Upwards of 85 percent of the volatile organic compounds (VOCs) in the spray gun ends up in the atmosphere, and some states have banned its use.

There are some newly developed lacquers that use a catalyst, but they are used mostly in the woodworking and furniture industry. They have the ease of application of nitrocellulose lacquer with much better water, chemical, and abrasion resistance. Additionally, catalyzed lacquers cure chemically, not solely through the evaporation of solvents, so there is a reduction of VOCs released into the atmosphere. It is activated when the catalyst is added to the base mixture.

Polyurethane

Polyurethane is at the top of the list when compared to other coatings for abrasion-, stain-, and chemical-resistant properties. Polyurethane was the coating that introduced the wet look. It has a high degree of natural resistance to the damaging effects of UV rays from the sun. Polyurethane is usually the first choice for coating and finishing the corporate and commercial aircraft in today's aviation environment.

Urethane Coating

The term urethane applies to certain types of binders used for paints and clear coatings. (A binder is the component that holds the pigment together in a tough, continuous film and provides film integrity and adhesion.) Typically, urethane is a two-part coating that consists of a base and catalyst that, when mixed, produces a durable, high-gloss finish that is abrasion- and chemical-resistant.

Acrylic Urethanes

Acrylic simply means plastic. It dries to a harder surface but is not as resistant to harsh chemicals as polyurethane. Most acrylic urethanes need additional UV inhibitors added when subject to the UV rays of the sun.

Methods of Applying Finish

There are several methods of applying aircraft finish. Among the most common are dipping, brushing, and spraying.

Dipping

The application of finishes by dipping is generally confined to factories or large repair stations. The process consists of dipping the part to be finished in a tank filled with the finishing material. Primer coats are frequently applied in this manner.

Brushing

Brushing has long been a satisfactory method of applying finishes to all types of surfaces. Brushing is generally used for small repair work and on surfaces where it is not practicable to spray paint.

The material to be applied should be thinned to the proper consistency for brushing. A material that is too thick has a tendency to pull or rope under the brush. If the materials are too thin, they are likely to run or not cover the surface adequately. Proper thinning and substrate temperature allows the finish to flow-out and eliminates the brush marks.

Spraying

Spraying is the preferred method for a quality finish. Spraying is used to cover large surfaces with a uniform layer of material, which results in the most cost effective method of application. All spray systems have several basic similarities. There must be an adequate source of compressed air, a reservoir or feed tank to hold a supply of the finishing material, and a device for controlling the combination of the air and finishing material ejected in an atomized cloud or spray against the surface to be coated.

A self-contained, pressurized spray can of paint meets the above requirements and satisfactory results can be obtained painting components and small areas of touchup. However, the aviation coating materials available in cans is limited, and this chapter addresses the application of mixed components through a spray gun.

There are two main types of spray equipment. A spray gun with an integral paint container is adequate for use when painting small areas. When large areas are painted, pressure-feed equipment is more desirable since a large supply of finishing material can be applied without the interruption of having to stop and refill a paint container. An added bonus is the lighter overall weight of the spray gun and the flexibility of spraying in any direction with a constant pressure to the gun.

The air supply to the spray gun must be entirely free of water or oil in order to produce the optimum results in the finished product. Water traps, as well as suitable filters to remove any trace of oil, must be incorporated in the air pressure supply line. These filters and traps must be serviced on a regular basis.

Finishing Equipment

Paint Booth

A paint booth may be a small room in which components of an aircraft are painted, or it can be an aircraft hangar big enough to house the largest aircraft. Whichever it is, the location must be able to protect the components or aircraft from the elements. Ideally, it would have temperature and humidity controls; but, in all cases, the booth or hangar must have good lighting, proper ventilation, and be dust free.

A simple paint booth can be constructed for a small aircraft by making a frame out of wood or polyvinyl chloride (PVC) pipe. It needs to be large enough to allow room to walk around and maneuver the spray gun. The top and sides can be covered with plastic sheeting stapled or taped to the frame. An exhaust fan can be added to one end with a large air-conditioning filter placed on the opposite end to filter incoming air. Lights should be large enough to be set up outside of the spray booth and shine through the sheeting or plastic windows. The ideal amount of light would be enough to produce a glare off of all the surfaces to be sprayed. This type of temporary booth can be set up in a hangar, a garage, or outside on a ramp, if the weather and temperature are favorable.

Normally, Environmental Protection Agency (EPA) regulations do not apply to a person painting one airplane. However, anyone planning to paint an aircraft should be aware that local clean air regulations may be applicable to an airplane painting project. When planning to paint an aircraft at an airport, it would be a good idea to check with the local airport authority before starting.

Air Supply

The air supply for paint spraying using a conventional siphon feed spray gun should come from an air compressor with a storage tank big enough to provide an uninterrupted supply of air with at least 90 pounds per square inch (psi) providing 10 cubic feet per minute (CFM) of air to the spray gun.

The compressor needs to be equipped with a regulator, water trap, air hose, and an adequate filter system to ensure that clean, dry, oil-free air is delivered to the spray gun.

If using one of the newer high-volume low-pressure (HVLP) spray guns and using a conventional compressor, it is better to use a two-stage compressor of at least a 5 horsepower (hp) that operates at 90 psi and provides 20 CFM to the gun. The key to the operation of the newer HVLP spray guns is the air volume, not the pressure.

If purchasing a new complete HVLP system, the air supply is from a turbine compressor. An HVLP turbine has a series of fans, or stages, that move a lot of air at low pressure. More stages provide greater air output (rated in CFM), which means better atomization of the coating being sprayed. The intake air is also the cooling air for the motor. This air is filtered from dirt and dust particles prior to entering the turbine. Some turbines also have a second filter for the air supply to the spray gun. The turbine does not produce oil or water to contaminate the air supply, but the air supply from the turbine heats up, causing the paint to dry faster, so you may need an additional length of hose to reduce the air temperature at the spray gun.

Spray Equipment

Air Compressors

Piston–type compressors are available with one-stage and multiple-stage compressors, various size motors, and various size supply tanks. The main requirement for painting is to ensure the spray gun has a continuous supplied volume of air. Piston-type compressors compress air and deliver it to a storage tank. Most compressors provide over 100 psi, but only the larger ones provide the volume of air needed for an uninterrupted supply to the gun. The multistage compressor is a good choice for a shop when a large volume of air is needed for pneumatic tools. When in doubt about the size of the compressor, compare the manufacturer's specifications and get the largest one possible. *[Figure 8-1]*

Large Coating Containers

For large painting projects, such as spraying an entire aircraft, the quantity of mixed paint in a pressure tank provides many advantages. The setup allows a greater area to be covered without having to stop and fill the cup on a spray gun. The painter is able to keep a wet paint line, and more material is applied to the surface with less overspray. It provides the flexibility of maneuvering the spray gun in any position without the restriction and weight of an attached paint cup. Remote pressure tanks are available in sizes from 2 quarts to over 60 gallons. *[Figure 8-2]*

System Air Filters

The use of a piston-type air compressor for painting requires that the air supply lines include filters to remove water and oil. A typical filter assembly is shown in *Figure 8-3*.

Miscellaneous Painting Tools & Equipment

Some tools that are available to the painter include:

- Masking paper/tape dispenser that accommodates various widths of masking paper. It includes a masking tape dispenser that applies the tape to one edge of the paper as it is rolled off to facilitate one person applying the paper and tape in a single step.
- Electronic and magnetic paint thickness gauges to measure dry paint thickness.
- Wet film gauges to measure freshly applied wet paint.
- Infrared thermometers to measure coating and substrate surfaces to verify that they fall in the recommended temperature range prior to spraying.

Figure 8-1. *Standard air compressor.*

Figure 8-2. *Pressure paint tank.*

Spray Guns

A top quality spray gun is a key component in producing a quality finish in any coating process. It is especially important when painting an aircraft because of the large area and varied surfaces that must be sprayed.

When spray painting, it is of utmost importance to follow the manufacturer's recommendations for correct sizing of the air cap, fluid tip, and needle combinations. The right combination provides the best coverage and the highest quality finish in the shortest amount of time.

All of the following examples of the various spray guns

Figure 8-3. *Air line filter assembly.*

(except the airless) are of the air atomizing type. They are the most capable of providing the highest quality finish.

Siphon-Feed Gun

The siphon-feed gun is a conventional spray gun familiar to most people, with a one quart paint cup located below the gun. Regulated air passes through the gun and draws (siphons) the paint from the supply cup. This is an external mix gun, which means the air and fluid mix outside the air cap. This gun applies virtually any type coating and provides a high quality finish. *[Figure 8-4]*

Gravity-Feed Gun

A gravity-feed gun provides the same high-quality finish as a siphon-feed gun, but the paint supply is located in a cup on top of the gun and supplied by gravity. The operator can make fine adjustments between the atomizing pressure and fluid flow and utilize all material in the cup. This also is an external mix gun. *[Figure 8-5]*

The HVLP production spray gun is an internal mix gun. The air and fluid is mixed inside the air cap. Because of the low pressure used in the paint application, it transfers at least 65 percent and upwards of 80 percent of the finish material to the surface. HVLP spray guns are available with a standard cup located underneath or in a gravity-feed model with the cup on top. The sample shown can be connected with hoses to a remote paint material container holding from 2 quarts to 60 gallons. *[Figure 8-6]*

Because of more restrictive EPA regulations, and the fact that more paint is being transferred to the surface with less waste from overspray, a large segment of the paint and coating industry is switching to HVLP spray equipment.

Figure 8-4. *Siphon-feed spray gun.*

Figure 8-5. *Gravity-feed spray gun.*

Figure 8-6. *A high-volume, low-pressure (HVLP) spray gun.*

Airless spraying does not directly use compressed air to atomize the coating material. A pump delivers paint to the spray gun under high hydraulic pressure (500 to 4,500 psi) to atomize the fluid. The fluid is then released through an orifice in the spray nozzle. This system increases transfer efficiency and production speed with less overspray than conventional air atomized spray systems. It is used for production work but does not provide the fine finish of air atomized systems. *[Figure 8-7]*

Fresh Air Breathing Systems

Fresh air breathing systems should be used whenever coatings are being sprayed that contain isocyanides. This includes all polyurethane coatings. The system incorporates a high-capacity electric air turbine that provides a constant source of fresh air to the mask. The use of fresh air breathing systems is also highly recommended when spraying chromate primers and chemical stripping aircraft. The system provides cool filtered breathing air with up to 200 feet of hose, which allows the air pump intake to be placed in an area of fresh air, well outside of the spraying area. *[Figure 8-8]*

Figure 8-8. *Breathe-Cool II® supplied air respirator system with Tyvek® hood.*

A charcoal-filtered respirator should be used for all other spraying and sanding operations to protect the lungs and respiratory tract. The respirator should be a double-cartridge, organic vapor type that provides a tight seal around the nose and mouth. The cartridges can be changed separately, and should be changed when detecting odor or experiencing nose or throat irritation. The outer prefilters should be changed if experiencing increased resistance to breathing. *[Figure 8-9]*

Figure 8-9. *Charcoal-filtered respirator.*

Viscosity Measuring Cup

This is a small cup with a long handle and a calibrated orifice in the bottom that allows the liquid in the cup to drain out at a specific timed rate. Coating manufacturers recommend spraying their product at a specific pressure and viscosity. That viscosity is determined by measuring the efflux (drain) time of the liquid coating through the cup orifice. The time (in seconds) is listed on most paint manufacturers' product/technical data pages. The measurement determines if the mixed coating meets the recommended viscosity for spraying.

There are different manufacturers of the viscosity measuring devices, but the most common one listed and used for spray painting is known as a Zahn cup. The orifice number must correspond to the one listed on the product/technical data sheet. For most primers and topcoats, the #2 or #3 Zahn cup is the one recommended. *[Figure 8-10]*

To perform an accurate viscosity measurement, it is very important that the temperature of the sample material be within the recommended range of 73.5 °F ± 3.5 °F (23 ºC ± 2 ºC), and then proceed as follows:

Figure 8-7. *Airless spray gun.*

Figure 8-10. *A Zahn cup viscosity measuring cup.*

1. Thoroughly mix the sample with minimum bubbles.
2. Dip the Zahn cup vertically into the sample being tested, totally immersing the cup below the surface.
3. With a stopwatch in one hand, briskly lift the cup out of the sample. As the top edge of the cup breaks the surface, start the stopwatch.
4. Stop the stopwatch when the first break in the flow of the liquid is observed at the orifice exit. The number in seconds is referred to as the efflux time.
5. Record the time on the stopwatch and compare it to the coating manufacturer's recommendation. Adjust the viscosity, if necessary, but be aware not to thin the coating below recommendations that could result in the release of VOCs into the atmosphere above the regulated limitations.

Mixing Equipment

Use a paint shaker for all coatings within 5 days of application to ensure the material is thoroughly mixed. Use a mechanical paint stirrer to mix larger quantities of material. If a mechanical stirrer is driven by a drill, the drill should be pneumatic, instead of electric. The sparks from an electric drill can cause an explosion from the paint vapors.

Preparation

Surfaces

The most important part of any painting project is the preparation of the substrate surface. It takes the most work and time, but with the surface properly prepared, the results are a long-lasting, corrosion-free finish. Repainting an older aircraft requires more preparation time than a new paint job because of the additional steps required to strip the old paint, and then clean the surface and crevices of paint remover. Paint stripping is discussed in another section of this chapter.

It is recommended that all the following procedures be performed using protective clothing, rubber gloves, and goggles, in a well-ventilated area, at temperatures between 68 °F and 100 °F.

Aluminum surfaces are the most common on a typical aircraft. The surface should be scrubbed with Scotch-Brite® pads using an alkaline aviation cleaner. The work area should be kept wet and rinsed with clean water until the surface is water break free. This means that there are no beads or breaks in the water surface as it flows over the aluminum surface.

The next step is to apply an acid etch solution to the surface. Following manufacturers' suggestions, this is applied like a wash using a new sponge and covering a small area while keeping it wet and allowing it to contact the surface for between 1 and 2 minutes. It is then rinsed with clean water without allowing the solution to dry on the surface. Continue this process until all the aluminum surfaces are washed and rinsed. Extra care must be taken to thoroughly rinse this solution from all the hidden areas that it may penetrate. It provides a source for corrosion to form if not completely removed.

When the surfaces are completely dry from the previous process, the next step is to apply Alodine® or another type of an aluminum conversion coating. This coating is also applied like a wash, allowing the coating to contact the surface and keeping it wet for 2 to 5 minutes without letting it dry. It then must be thoroughly rinsed with clean water to remove all chemical salts from the surface. Depending on the brand, the conversion coating may color the aluminum a light gold or green, but some brands are colorless. When the surface is thoroughly dry, the primer should be applied as soon as possible as recommended by the manufacturer.

The primer should be one that is compatible with the topcoat finish. Two-part epoxy primers provide excellent corrosion resistance and adhesion for most epoxy and urethane surfaces and polyurethane topcoats. Zinc chromate should not be used under polyurethane paints.

Composite surfaces that need to be primed may include the entire aircraft if it is constructed from those materials, or they may only be components of the aircraft, such as fairings, radomes, antennas, and the tips of the control surfaces.

Epoxy sanding primers have been developed that provide an excellent base over composites and can be finish sanded with 320 grit using a dual action orbital sander. They are compatible with two-part epoxy primers and polyurethane topcoats.

Topcoats must be applied over primers within the recommended time window, or the primer may have to be scuff sanded before the finish coat is applied. Always follow the recommendations of the coating manufacturer.

Primer & Paint

Purchase aircraft paint for the aviation painting project. Paint manufacturers use different formulas for aircraft and automobiles because of the environments they operate in. The aviation coatings are formulated to have more flexibility and chemical resistance than the automotive paint.

It is also highly recommended that compatible paints of the same brand are used for the entire project. The complete system (of a particular brand) from etching to primers and reducers to the finish topcoat are formulated to work together. Mixing brands is a risk that may ruin the entire project.

When purchasing the coatings for a project, always request a manufacturer's technical or material data and safety data sheets, for each component used. Before starting to spray, read the sheets. If the manufacturer's recommendations are not followed, a less than satisfactory finish or a hazard to personal safety or the environment may result. It cannot be emphasized enough to follow the manufacturer's recommendations. The finished result is well worth the effort.

Before primer or paint is used for any type application, it must be thoroughly mixed. This is done so that any pigment that may have settled to the bottom of the container is brought into suspension and distributed evenly throughout the paint. Coatings now have shelf lives listed in their specification sheets. If a previously opened container is found to have a skin or film formed over the primer or paint, the film must be completely removed before mixing. The material should not be used if it has exceeded its shelf life and/or has become thick or jelled.

Mechanical shaking is recommended for all coatings within 5 days of use. After opening, a test with a hand stirrer should be made to ensure that all the pigment has been brought into suspension. Mechanical stirring is recommended for all two-part coatings. When mixing any two-part paint, the catalyst/activator should always be added to the base or pigmented component. The technical or material data sheet of the coating manufacturer should be followed for recommended times of induction (the time necessary for the catalyst to react with the base prior to application). Some coatings do not require any induction time after mixing, and others need 30 minutes of reaction time before being applied.

Thinning of the coating material should follow the recommendations of the manufacturer. The degree of thinning depends on the method of application. For spray application, the type of equipment, air pressure, and atmospheric conditions guide the selection and mixing ratios for the thinners. Because of the importance of accurate thinning to the finished product, use a viscosity measuring (flow) cup. Material thinned using this method is the correct viscosity for the best application results.

Thin all coating materials and mix in containers separate from the paint cup or pot. Then, filter the material through a paint strainer recommended for the type coating you are spraying as you pour it into the cup or supply pot.

Spray Gun Operation

Adjusting the Spray Pattern

To obtain the correct spray pattern, set the recommended air pressure on the gun, usually 40 to 50 psi for a conventional gun. Test the pattern of the gun by spraying a piece of masking paper taped to the wall. Hold the gun square to the wall approximately 8 to 10 inches from the surface. (With hand spread, it is the distance from the tip of the thumb to the tip of the little finger.)

All spray guns (regardless of brand name) have the same type of adjustments. The upper control knob proportions the air flow, adjusting the spray pattern of the gun. *[Figure 8-11]* The lower knob adjusts the fluid passing the needle, which in turn controls the amount or volume of paint being delivered through the gun.

Pull the trigger lever fully back. Move the gun across the paper, and alternately adjust between the two knobs to obtain a spray fan of paint that is wet from top to bottom (somewhat like the pattern at dial 10.) Turning in (to the right) on the lower, or fluid knob, reduces the amount of paint going through the gun. Turning out increases the volume of paint. Turning out (to the left) on the upper, or pattern control knob, widens the spray pattern. Turning in reduces it to a cone shape (as shown with dial set at 0).

Once the pattern is set on the gun, the next step is to follow the correct spraying technique for applying the coating to the surface.

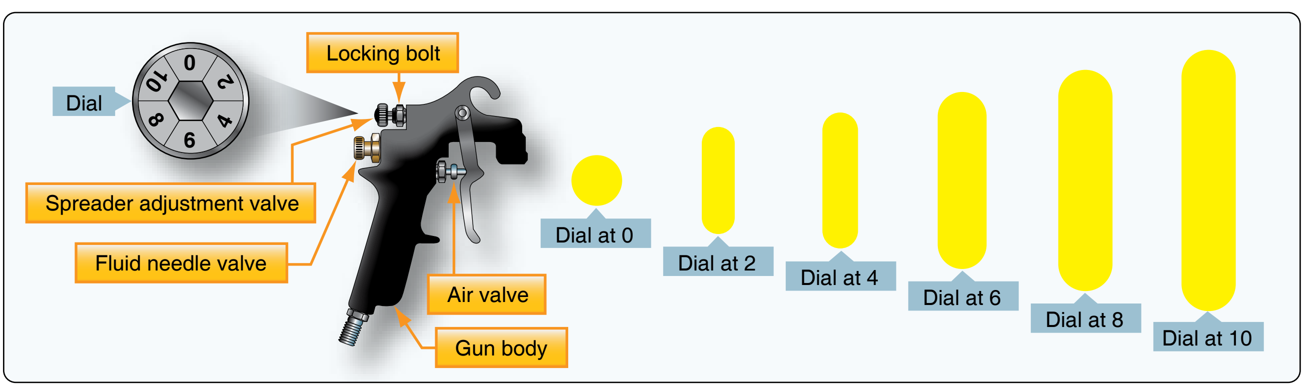


Figure 8-11. *Adjustable spray pattern.*

Applying the Finish

If the painter has never used a spray gun to apply a finish coat of paint, and the aircraft has been completely prepared, cleaned, primed, and ready for the topcoat, they may need to pause for some practice. Reading a book or an instruction manual is a good start as it provides the basic knowledge about the movement of the spray gun across the surface. Also, if available, the opportunity to observe an aircraft being painted is well worth the time.

At this point in the project, the aircraft has already received its primer coats. The difference between the primer and the finish topcoat is that the primer is flat (no gloss) and the finish coat has a glossy surface (some more than others, depending on the paint). The flat finish of the primer is obtained by paying attention to the basics of trigger control distance from the surface and consistent speed of movement of the spray gun across the surface.

Primer is typically applied using a crosscoat spray pattern. A crosscoat is one pass of the gun from left to right, followed by another pass moving up and down. The starting direction does not matter as long as the spraying is accomplished in two perpendicular passes. The primer should be applied in light coats as cross-coating is the application of two coats of primer.

Primer does not tend to run because it is applied in light coats. The gloss finish requires a little more experience with the gun. A wetter application produces the gloss, but the movement of the gun, overlap of the spray pattern, and the distance from the surface all affect the final product. It is very easy to vary one or another, yielding runs or dry spots and a less than desirable finish. Practice not only provides some experience, but also provides the confidence needed to produce the desired finish.

Start the practice by spraying the finish coat material on a flat, horizontal panel. The spray pattern has been already adjusted by testing it on the masking paper taped to the wall. Hold the gun 8–10 inches away from and perpendicular to the surface. Pull the trigger enough for air to pass through the cap and start a pass with the gun moving across the panel. As it reaches the point to start painting, squeeze the trigger fully back and continue moving the gun about one foot per second across the panel until the end is reached. Then, release the trigger enough to stop the paint flow but not the air flow. *[Figure 8-12]*

The constant air flow through the gun maintains a constant pressure, rather than a buildup of pressure each time that the trigger is released. This would cause a buildup of paint at the end of each pass, causing runs and sags in the finish. Repeat the sequence of the application, moving back in the opposite direction and overlapping the first pass by 50 percent. This is accomplished by aiming the center of the spray pattern at the outer edge of the first pass and continuing the overlap with each successive pass of the gun.

Once the painter has mastered spraying a flat horizontal panel, practice next on a panel that is positioned vertically against a wall. This is the panel that shows the value of applying a light

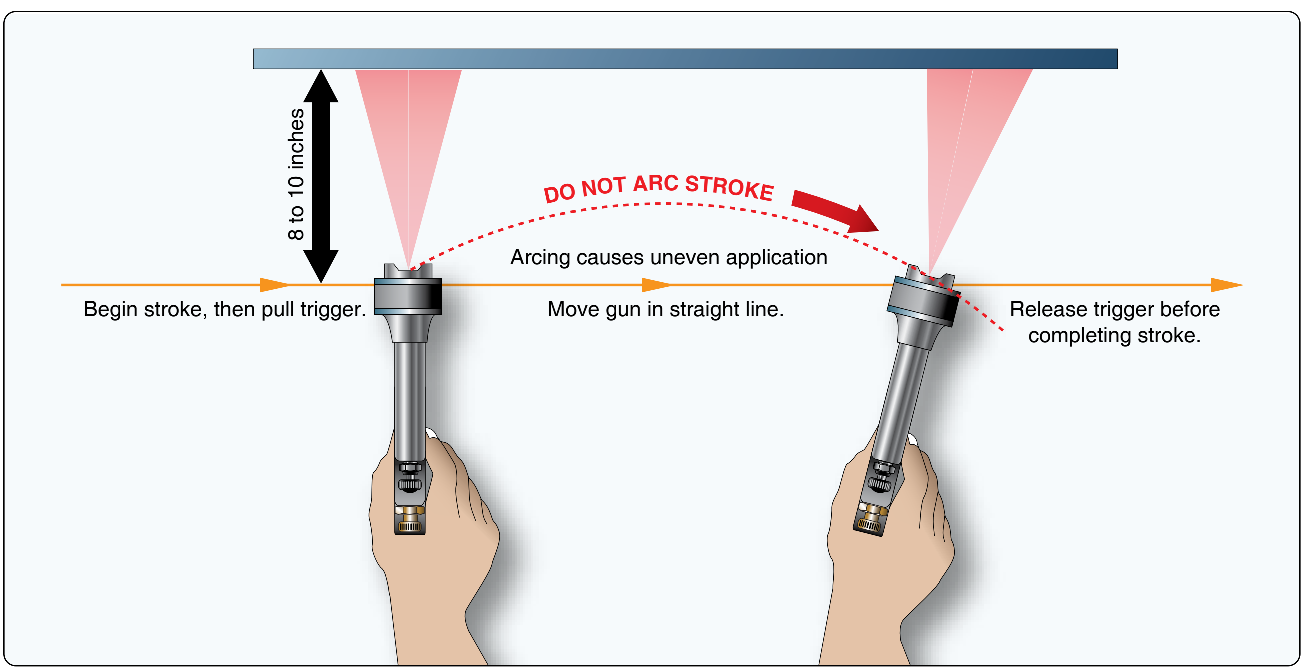


Figure 8-12. *Proper spray application.*

tack coat before spraying on the second coat. The tack coat holds the second coat from sagging and runs. Practice spraying this test panel both horizontally with overlapping passes and then rotate the air cap 90° on the gun and practice spraying vertically with the same 50 percent overlapping passes.

Practice cross-coating the paint for an even application. Apply two light spray passes horizontally, overlapping each by 50 percent, and allowing it to tack. Then, spray vertically with overlapping passes, covering the horizontal sprayed area. When practice results in a smooth, glossy, no-run application on the vertical test panel, you are ready to try your skill on the actual project.

Common Spray Gun Problems

A quick check of the spray pattern can be verified before using the gun by spraying some thinner or reducer, compatible with the finish used, through the gun. It is not of the same viscosity as the coating, but it indicates if the gun is working properly before the project is started.

If the gun is not working properly, use the following information to troubleshoot the problem:

- A pulsating, or spitting, fan pattern may be caused by a loose nozzle, clogged vent hole on the supply cup, or the packing may be leaking around the needle.
- If the spray pattern is offset to one side or the other, the air ports in the air cap or the ports in the horns may be plugged.
- If the spray pattern is heavy on the top or the bottom, rotate the air cap 180°. If the pattern reverses, the air cap is the problem. If it stays the same, the fluid tip or needle may be damaged.
- Other spray pattern problems may be a result of improper air pressure, improper reducing of the material, or wrong size spray nozzle.

Sequence for Painting a Single-Engine or Light Twin Airplane

As a general practice on any surface being painted, spray each application of coating in a different direction to facilitate even and complete coverage. After you apply the primer, apply the tack coat and subsequent top coats in opposite directions, one coat vertically and the next horizontally, as appropriate.

Start by spraying all the corners and gaps between the control surfaces and fixed surfaces. Paint the leading and trailing edges of all surfaces. Spray the landing gear and wheel wells, if applicable, and paint the bottom of the fuselage up the sides to a horizontal break, such as a seam line. Paint the underside of the horizontal stabilizer. Paint the vertical stabilizer and the rudder, and then move to the top of the horizontal stabilizer. Spray the top and sides of the fuselage down to the point of the break from spraying the underside of the fuselage. Then, spray the underside of the wings. Complete the job by spraying the top of the wings.

The biggest challenge is to control the overspray and keep the paint line wet. The ideal scenario would be to have another experienced painter with a second spray gun help with the painting. It is much easier to keep the paint wet and the job is completed in half the time.

Common Paint Troubles

Common problems that may occur during the painting of almost any project but are particularly noticeable and troublesome on the surfaces of an aircraft include poor adhesion, blushing, pinholes, sags and/or runs, "orange peel," fisheyes, sanding scratches, wrinkling, and spray dust.

Poor Adhesion

- Improper cleaning and preparation of the surface to be finished.
- Application of the wrong primer.
- Incompatibility of the topcoat with the primer. *[Figure 8-13]*
- Improper thinning of the coating material or selection of the wrong grade reducer.
- Improper mixing of materials.
- Contamination of the spray equipment and/or air supply.

Correction for poor adhesion requires a complete removal of the finish, a determination and correction of the cause, and a complete refinishing of the affected area.

Figure 8-13. *Example of poor adhesion.*

Blushing

Blushing is the dull milky haze that appears in a paint finish. *[Figure 8-14]* It occurs when moisture is trapped in the paint. Blushing forms when the solvents quickly evaporate from the sprayed coating, causing a drop in temperature that is enough to condense the water in the air. It usually forms when the humidity is above 80 percent. Other causes include:

- Incorrect temperature (below 60 °F or above 95 °F).
- Incorrect reducer (fast drying) being used.
- Excessively high air pressure at the spray gun.

If blushing is noticed during painting, a slow-drying reducer can sometimes be added to the paint mixture, and then the area resprayed. If blushing is found after the finish has dried, the area must be sanded down and repainted.

Pinholes

Pinholes are tiny holes, or groups of holes, that appear in the surface of the finish as a result of trapped solvents, air, or moisture. *[Figure 8-15]* Examples include:

- Contaminants in the paint or air lines.
- Poor spraying techniques that allow excessively heavy or wet paint coats, which tend to trap moisture or solvent under the finish.
- Use of the wrong thinner or reducer, either too fast by quick drying the surface and trapping solvents or too slow and trapping solvents by subsequent topcoats.

If pinholes occur during painting, the equipment and painting technique must be evaluated before continuing. When dry, sand the surface smooth and then repaint.

Figure 8-15. *Example of pinholes.*

Sags & Runs

Sags and runs are usually caused by applying too much paint to an area, by holding the spray gun too close to the surface, or moving the gun too slowly across the surface. *[Figure 8-16]* Other causes include:

- Too much reducer in the paint (too thin).
- Incorrect spray gun setting of air-paint mixture.

Sags and runs can be avoided by following the recommended thinning instructions for the coatings being applied and taking care to use the proper spray gun techniques, especially on vertical surfaces and projected edges. Dried sags and runs must be sanded out and the surface repainted.

Orange Peel

"Orange peel" refers to the appearance of a bumpy surface, much like the skin of an orange. *[Figure 8-17]* It can be the result of a number of factors with the first being the improper adjustment of the spray gun. Other causes include:

Figure 8-14. *Example of blushing.*

Figure 8-16. *Example of sags and runs.*

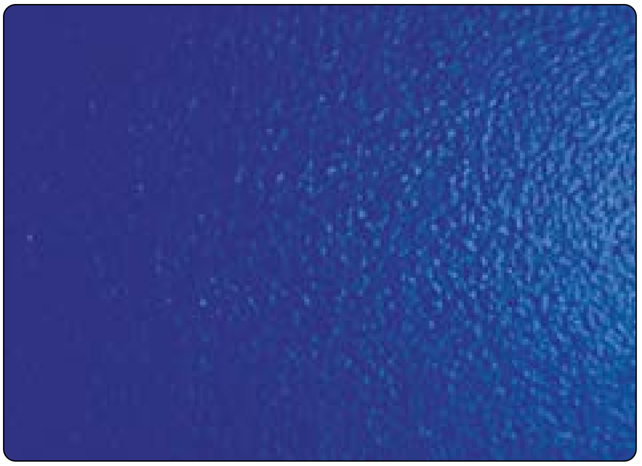


Figure 8-17. *Example of orange peel.*

- Not enough reducer (too thick) or the wrong type reducer for the ambient temperature.
- Material not uniformly mixed.
- Forced drying method, either with fans or heat, is too quick.
- Too little flash time between coats.
- Spray painting when the ambient or substrate temperature is either too hot or too cold.

Light orange peel can be wet sanded or buffed out with polishing compound. In extreme cases, it has to be sanded smooth and resprayed.

Fisheyes

Fisheyes appear as small holes in the coating as it is being applied, which allows the underlying surface to be seen. *[Figure 8-18]* Usually, it is due to the surface not being cleaned of all traces of silicone wax. If numerous fisheyes appear when spraying a surface, stop spraying and clean off all the wet paint. Then, thoroughly clean the surface to remove all traces of silicone with a silicone wax remover.

The most effective way to eliminate fisheyes is to ensure that the surface about to be painted is clean and free from any type of contamination. A simple and effective way to check this is referred to as a water break test. Using clean water, spray, pour, or gently hose down the surface to be painted. If the water beads up anywhere on the surface, it is not clean. The water should flatten out and cover the area with an unbroken film.

If the occasional fisheye appears when spraying, wait until the first coat sets up and then add a recommended amount of fisheye eliminator to the subsequent finish coats. Fisheyes may appear during touchup of a repair. A coat of sealer may help, but a complete removal of the finish may be the only solution.

One last check before spraying is to ensure that the air compressor has been drained of water, the regulator cleaned, and the system filters are clean or have been replaced so that this source of contamination is eliminated.

Sanding Scratches

Sanding scratches appear in the finish paint when the surface has not been properly sanded and/or sealed prior to spraying the finish coats. *[Figure 8-19]* This usually shows up in nonmetal surfaces. Composite cowling, wood surfaces, and plastic fairings must be properly sanded and sealed before painting. The scratches may also appear if an overly rapid quick-drying thinner is used.

The only fix after the finish coat has set up is to sand down the affected areas using a finer grade of sandpaper, follow with a recommended sealer, and then repaint.

Wrinkling

Wrinkling is usually caused by trapped solvents and unequal drying of the paint finish due to excessively thick or solvent-

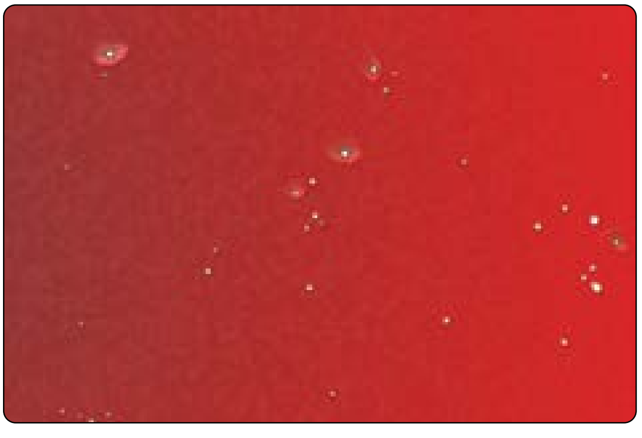


Figure 8-18. *Example of fisheyes.*

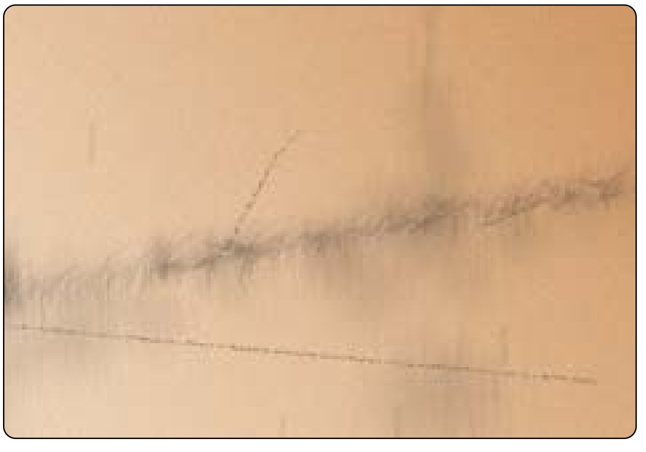


Figure 8-19. *Example of sanding scratches.*

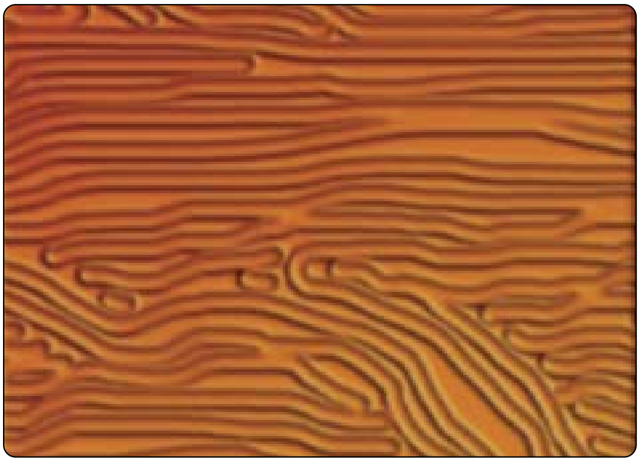


Figure 8-20. *Example of wrinkling.*

heavy paint coats. *[Figure 8-20]* Fast reducers can also contribute to wrinkling if the sprayed coat is not allowed to dry thoroughly. Thick coatings and quick-drying reducers allow the top surface of the coating to dry, trapping the solvents underneath. If another heavy coat is applied before the first one dries, wrinkles may result. It may also have the effect of lifting the coating underneath, almost with the same result as a paint stripper.

Rapid changes in ambient temperatures while spraying may cause an uneven release of the solvents, causing the surface to dry, shrink, and wrinkle. Making the mistake of using an incompatible thinner, or reducer, when mixing the coating materials may cause not only wrinkles but other problems as well. Wrinkled paint must be completely removed and the surface refinished.

Spray Dust

Spray dust is caused by the atomized spray particles from the gun becoming dry before reaching the surface being painted, thus failing to flow into a continuous film. *[Figure 8-21]* This may be caused by:

- Incorrect spray gun setting of air pressure, paint flow, or spray pattern.
- Spray gun being held too far from the surface.
- Material being improperly thinned or the wrong reducers being used with the finish coats.

The affected area needs to be sanded and recoated.

Painting Trim & Identification Marks

Masking & Applying the Trim

At this point in the project, the entire aircraft has been painted with the base color and all the masking paper and tape carefully removed. Refer again to the coating manufacturer's technical data sheet for "dry and recoat" times for the appropriate temperatures and "dry to tape" time that must elapse before safe application and removal of tape on new paint without it lifting.

Masking Materials

When masking for the trim lines, use 3M® Fine Line tape. It is solvent proof, available in widths of ⅛–1 inch and, when applied properly, produces a sharp edge paint line. A good quality masking tape should be used with masking paper to cover all areas not being trimmed to ensure the paper does not lift and allow overspray on the basecoat. Do not use newspaper to mask the work as paint penetrates newspaper. Using actual masking paper is more efficient, especially if used with a masking paper/tape dispenser as part of the finishing equipment.

Masking for the Trim

After the base color has dried and cured for the recommended time shown in the manufacturer's technical data sheet, the next step is to mask for the trim. The trim design can be simple, with one or two color stripes running along the fuselage, or it can be an elaborate scheme covering the entire aircraft. Whichever is chosen, the basic masking steps are the same.

If unsure of a design, there are numerous websites that provide the information and software to do a professional job. If electing to design a personalized paint scheme, the proposed design should be portrayed on a silhouette drawing of the aircraft as close to scale as possible. It is much easier to change a drawing than to remask the aircraft.

Start by identifying a point on the aircraft from which to

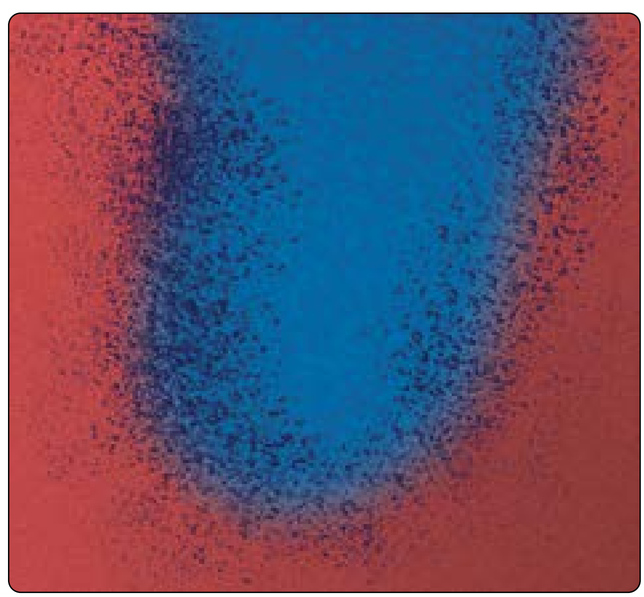


Figure 8-21. *Example of spray dust.*

initiate the trim lines using the Fine Line tape. If the lines are straight and/or have large radius curves, use ¾-inch or one-inch tape and keep it pulled tight. The wider tape is much easier to control when masking a straight line. Smaller radius curves may require ½-inch or even ¼-inch tape. Try and use the widest tape that lays flat and allows for a smooth curve. Use a small roller (like those used for wallpaper seams) to go back over and roll the tape edges firmly onto the surface to ensure they are flat.

Finish masking the trim lines on one side of the aircraft, to include the fuselage, vertical fin and rudder, the engine nacelles and wing(s). Once complete, examine the lines. If adjustments are needed to the placement or design, now is the time to correct it. With one side of the aircraft complete, the entire design and placement can be transferred to the opposite side.

Different methods can be employed to transfer the placement of the trim lines from one side of the aircraft to the other. One method is to trace the design on paper and then apply it to the other side, starting at the same point opposite the first starting point. Another method is to use the initial starting point and apply the trim tape using sheet metal or rivet lines as reference, along with measurements, to position the tape in the correct location.

When both sides are completed, a picture can be taken of each side and a comparison made to verify the tape lines on each side of the aircraft are identical.

With the Fine Line taping complete, some painters apply a sealing strip of ¾-inch or 1-inch masking tape covering half and extending over the outside edge of the Fine Line tape. This provides a wider area to apply the masking paper and adds an additional seal to the Fine Line tape. Now, apply the masking paper using 1-inch tape, placing half the width of the tape on the paper and half on the masked trim tape.

Use only masking paper made for painting and a comparable quality masking tape. With all the trim masking complete, cover the rest of the exposed areas of the aircraft to prevent overspray from landing on the base color. Tape the edges of the covering material to ensure the spray does not drift under it.

Now, scuff-sand all the area of trim to be painted to remove the gloss of the base paint. The use of 320-grit for the main area and a fine mesh Scotch-Brite pad next to the tape line should be sufficient. Then, blow all the dust and grit off the aircraft, and wipe down the newly sanded trim area with a degreaser and a tack cloth. Press or roll down the trim tape edges one more time before painting.

There are some various methods used by painters to ensure that a sharp defined tape line is attained upon removal of the tape. The basic step is to first use the 3M® Fine Line tape to mask the trim line. Some painters then spray a light coat of the base color or clear coat just prior to spraying the trim color. This will seal the tape edge line and ensure a clean sharp line when the tape is removed.

If multiple colors are used for the trim, cover the trim areas not to be sprayed with masking paper. When the first color is sprayed and dried, remove the masking paper from the next trim area to spray and cover the trim area that was first sprayed, taking care not to press the masking paper or tape into the freshly dried paint.

With all the trim completed, the masking paper should be removed as soon as the last trimmed area is dry to the touch. Carefully remove the Fine Line trim edge tape by slowly pulling it back onto itself at a sharp angle. Remove all trim and masking tape from the base coat as soon as possible to preclude damage to the paint.

As referenced previously, use compatible paint components from the same manufacturer when painting trim over the base color. This reduces the possibility of an adverse reaction between the base coat and the trim colors.

Display of Nationality & Registration Marks

The complete regulatory requirement for identification and marking of a U.S.-registered aircraft can be found in Title 14 of the Code of Federal Regulations (14 CFR), Part 45, Identification and Registration Marking.

In summary, the regulation states that the marks must:

- Be painted on the aircraft or affixed by other means to insure a similar degree of permanence;
- Have no ornamentation;
- Contrast in color with the background; and
- Be legible.

The letters and numbers may be taped off and applied at the same time and using the same methods as when the trim is applied, or they may be applied later as decals of the proper size and color.

Display of Marks

Each operator of an aircraft shall display on the aircraft marks consisting of the Roman capital letter "N" (denoting United States registration) followed by the registration number of the aircraft. Each suffix letter must also be a

Roman capital letter.

Location & Placement of Marks

On fixed-wing aircraft, marks must be displayed on either the vertical tail surfaces or the sides of the fuselage. If displayed on the vertical tail surfaces, they shall be horizontal on both surfaces of a single vertical tail or on the outer surfaces of a multivertical tail. If displayed on the fuselage surfaces, then horizontally on both sides of the fuselage between the trailing edge of the wing and the leading edge of the horizontal stabilizer. Exceptions to the location and size requirement for certain aircraft can be found in 14 CFR part 45.

On rotorcraft, marks must be displayed horizontally on both surfaces of the cabin, fuselage, boom, or tail. On airships, balloons, powered parachutes, and weight-shift control aircraft, display marks as required by 14 CFR part 45.

Size Requirements for Different Aircraft

Almost universally for U.S.-registered, standard certificated, fixed-wing aircraft, the marks must be at least 12 inches high. A glider may display marks at least 3 inches high.

In all cases, the marks must be of equal height, two-thirds as wide as they are high, and the characters must be formed by solid lines one-sixth as wide as they are high. The letters “M” and “W” may be as wide as they are high.

The spacing between each character may not be less than one-fourth of the character width. The marks required by 14 CFR part 45 for fixed-wing aircraft must have the same height, width, thickness, and spacing on both sides of the aircraft.

The marks must be painted or, if decalcomanias (decals), be affixed in a permanent manner. Other exceptions to the size and location of the marks are applicable to aircraft with Special Airworthiness certificates and those penetrating ADIZ and DEWIZ airspace. The current 14 CFR part 45 should be consulted for a complete copy of the rules.

Decals

Markings are placed on aircraft surfaces to provide servicing instructions, fuel and oil specifications, tank capacities, and to identify lifting and leveling points, walkways, battery locations, or any areas that should be identified. These markings can be applied by stenciling or by using decals.

Decals are used instead of painted instructions because they are usually less expensive and easier to apply. Decals used on aircraft are usually of three types: paper, metal, or vinyl film. These decals are suitable for exterior and interior surface application.

To assure proper adhesion of decals, clean all surfaces thoroughly with aliphatic naphtha to remove grease, oil, wax, or foreign matter. Porous surfaces should be sealed and rough surfaces sanded, followed by cleaning to remove any residue.

The instructions to be followed for applying decals are usually printed on the reverse side of each decal. A general application procedure for each type of decal is presented in the following paragraphs to provide familiarization with the techniques involved.

Paper Decals

Immerse paper decals in clean water for 1 to 3 minutes. Allowing decals to soak longer than 3 minutes causes the backing to separate from the decal while immersed. If decals are allowed to soak less than 1 minute, the backing does not separate from the decal.

Place one edge of the decal on the prepared receiving surface and press lightly, then slide the paper backing from beneath the decal. Perform any minor alignment with the fingers. Remove water by gently blotting the decal and adjacent area with a soft, absorbent cloth. Remove air or water bubbles trapped under the decal by wiping carefully toward the nearest edge of the decal with a cloth. Allow the decal to dry.

Metal Decals with Cellophane Backing

Apply metal decals with cellophane backing adhesive as follows:

1. Immerse the decal in clean, warm water for 1 to 3 minutes.
2. Remove it from the water and dry carefully with a clean cloth.
3. Remove the cellophane backing, but do not touch adhesive.
4. Position one edge of the decal on the prepared receiving surface. On large foil decals, place the center on the receiving surface and work outward from the center to the edges.
5. Remove all air pockets by rolling firmly with a rubber roller, and press all edges tightly against the receiving surface to ensure good adhesion.

Metal Decals With Paper Backing

Metal decals with a paper backing are applied similarly to those having a cellophane backing. However, it is not necessary to immerse the decal in water to remove the backing. It may be peeled from the decal without moistening. Follow the manufacturer’s recommendation for activation of the adhesive, if necessary, before application. The decal should be positioned and smoothed out following the procedures given for cellophane-backed decals.

Metal Decals with No Adhesive

Apply decals with no adhesive in the following manner:

1. Apply one coat of cement, Military Specification MIL-A-5092, to the decal and prepared receiving surface.
2. Allow cement to dry until both surfaces are tacky.
3. Apply the decal and smooth it down to remove air pockets.
4. Remove excess adhesive with a cloth dampened with aliphatic naphtha.

Vinyl Film Decals

To apply vinyl film decals, separate the paper backing from the plastic film. Remove any paper backing adhering to the adhesive by rubbing the area gently with a clean cloth saturated with water. Remove small pieces of remaining paper with masking tape.

1. Place vinyl film, adhesive side up, on a clean porous surface, such as wood or blotter paper.
2. Apply recommended activator to the adhesive in firm, even strokes to the adhesive side of decal.
3. Position the decal in the proper location, while adhesive is still tacky, with only one edge contacting the prepared surface.
4. Work a roller across the decal with overlapping strokes until all air bubbles are removed.

Removal of Decals

Paper decals can be removed by rubbing the decal with a cloth dampened with lacquer thinner. If the decals are applied over painted or doped surfaces, use lacquer thinner sparingly to prevent removing the paint or dope.

Remove metal decals by moistening the edge of the foil with aliphatic naphtha and peeling the decal from the adhering surface. Work in a well-ventilated area.

Vinyl film decals are removed by placing a cloth saturated with MEK on the decal and scraping with a plastic scraper. Remove the remaining adhesive by wiping with a cloth dampened with a dry-cleaning solvent.

Paint System Compatibility

The use of several different types of paint, coupled with several proprietary coatings, makes repair of damaged and deteriorated areas particularly difficult. Paint finishes are not necessarily compatible with each other. The following general rules for coating compatibility are included for information and are not necessarily listed in order of importance:

1. Old type zinc chromate primer may be used directly for touchup of bare metal surfaces and for use on interior finishes. It may be overcoated with wash primers if it is in good condition. Acrylic lacquer finishes do not adhere to this material.
2. Modified zinc chromate primer does not adhere satisfactorily to bare metal. It must never be used over a dried film of acrylic nitrocellulose lacquer.
3. Nitrocellulose coatings adhere to acrylic finishes, but the reverse is not true. Acrylic nitrocellulose lacquers may not be used over old nitrocellulose finishes.
4. Acrylic nitrocellulose lacquers adhere poorly to bare metal and both nitrocellulose and epoxy finishes. For best results, the lacquers must be applied over fresh, successive coatings of wash primer and modified zinc chromate. They also adhere to freshly applied epoxy coatings (dried less than 6 hours).
5. Epoxy topcoats adhere to any paint system that is in good condition, and may be used for general touchup, including touchup of defects in baked enamel coatings.
6. Old wash primer coats may be overcoated directly with epoxy finishes. A new second coat of wash primer must be applied if an acrylic finish is to be applied.
7. Old acrylic finishes may be refinished with new acrylic if the old coating is softened using acrylic nitrocellulose thinner before touchup.
8. Damage to epoxy finishes can best be repaired by using more epoxy, since neither of the lacquer finishes stick to the epoxy surface. In some instances, air-drying enamels may be used for touchup of epoxy coatings if edges of damaged areas are abraded with fine sandpaper.

Paint Touchup

Paint touchup may be required on an aircraft following repair to the surface substrate. Touchup may also be used to cover minor topcoat damage, such as scratches, abrasions, permanent stains, and fading of the trim colors. One of the first steps is to identify the paint that needs to be touched up.

Identification of Paint Finishes

Existing finishes on current aircraft may be any one of several types, a combination of two or more types, or combinations of general finishes with special proprietary coatings.

Any of the finishes may be present at any given time, and repairs may have been made using material from several different type coatings. Some detailed information for the identification of each finish is necessary to ensure the topcoat application does not react adversely with the undercoat. A simple test can be used to confirm the nature of the coatings present.

The following procedure aids in identification of the paint finish. Apply a coating of engine oil (MIL SPEC, MIL-PRF-7808, turbine oil, or equivalent) to a small area of the surface to be checked. Old nitrocellulose finishes soften within a period of a few minutes. Acrylic and epoxy finishes show no effects.

If still not identified, wipe a small area of the surface in question with a rag wet with MEK. The MEK picks up the pigment from an acrylic finish, but has no effect on an epoxy coating. Just wipe the surface, and do not rub. Heavy rubbing picks up even epoxy pigment from coatings that are not thoroughly cured. Do not use MEK on nitrocellulose finishes. *Figure 8-22* provides a solvent test to identify the coating on an aircraft.

Surface Preparation for Touchup

In the case of a repair and touchup, once the aircraft paint coating has been identified, the surface preparation follows some basic rules.

The first rule, as with the start of any paint project, is to wash and wipe down the area with a degreaser and silicone wax remover before starting to sand or abrade the area.

If a whole panel or section within a seam line can be refinished during a touchup, it eliminates having to match and blend the topcoat to an existing finish. The area of repair should be stripped to a seam line and the finish completely redone from wash primer to the topcoat, as applicable. The paint along the edge of the stripped area should be hand-sanded wet and feathered with a 320-grade paper.

For a spot repair that requires blending of the coating, an area about three times the area of the actual repair will need to be prepared for blending of the paint. If the damaged area is through the primer to the substrate, the repair area should be abraded with 320 aluminum oxide paper on a double-action (D/A) air sander. Then, the repair and the surrounding area should be wet sanded using the air sander fitted with 1500 wet paper. The area should then be wiped with a tack cloth prior to spraying.

Apply a crosscoat of epoxy primer to the bare metal area, following the material data sheet for drying and recoat times. Abrade the primer area lightly with 1500 wet or dry, and then abrade the unsanded area around the repair with cutting compound. Clean and wipe the area with a degreasing solvent, such as isopropyl alcohol, and then a tack cloth.

Mix the selected topcoat paint that is compatible for the repair. Apply two light coats over the sanded repair area, slightly extending the second coat beyond the first. Allow time for the first coat to flash before applying the second coat. Then, thin the topcoat by one-third to one-half with a compatible reducer and apply one more coat, extending beyond the first two coats. Allow to dry according to the material data sheet before buffing and polishing the blended area.

If the damage did not penetrate the primer, and only the topcoat is needed for the finish, complete the same steps that would follow a primer coat.

Paint touchup procedures generally are the same for almost

3–5 Minute Contact With Cotton Wad Saturated With Test Solvent									
Hitrate	Nitrate dope	Butyrate dope	Nitro-cellulose lacquer	Poly-tone Poly-brush Poly-spray	Synthetic enamel	Acrylic lacquer	Acrylic enamel	Urethane enamel	Epoxy paint
Methanol	S	IS	IS	IS	PS	IS	PS	IS	IS
Toluol (Toluene)	IS	IS	IS	S	IS	S	ISW	IS	IS
MEK (Methyl ethyl ketone)	S	S	S	S	ISW	S	ISW	IS	IS
Isopropanol	IS	IS	IS	IS	IS	S	IS	IS	IS
Methylene chloride	SS	VS	S	VS	ISW	S	ISW	ISW	ISW

IS – Insoluble
ISW – Insoluble, film wrinkles
PS – Penetrate film, slight softening without wrinkling
S – Soluble
SS – Slightly Soluble
VS – Very Soluble

Figure 8-22. *Chart for solvent testing of coating.*

any repair. The end result, however, is affected by numerous variables, which include the preparation, compatibility of the finishing materials, color match, selection of reducers and/or retarders based on temperature, and experience and expertise of the painter.

Stripping the Finish

The most experienced painter, the best finishing equipment, and newest coatings, do not produce the desired finish on an aircraft if the surface was not properly prepared prior to refinishing. Surface preparation for painting of an entire aircraft typically starts with the removal of the paint. This is done not only for the weight reduction that is gained by stripping the many gallons of topcoats and primers, but for the opportunity to inspect and repair corrosion or other defects uncovered by the removal of the paint.

Before any chemical stripping can be performed, all areas of the aircraft not being stripped must be protected. The stripper manufacturer can recommend protective material for this purpose. This normally includes all window material, vents and static ports, rubber seals and tires, and composite components that may be affected by the chemicals.

The removal of paint from an aircraft, even a small single-engine model, involves not only the labor but a concern for the environment. You should recognize the impact and regulatory requirements that are necessary to dispose of the water and coating materials removed from the aircraft.

Chemical Stripping

At one time, most chemical strippers contained methylene chloride, considered an environmentally acceptable chemical until 1990. It was very effective in removing multiple layers of paint. However, in 1990, it was listed as a toxic air contaminant that caused cancer and other medical problems and was declared a Hazardous Air Pollutant (HAP) by the EPA in the Clean Air Act Amendments of 1990.

Since then, other substitute chemical strippers were tested, from formic acid to benzyl alcohol. None of them were found to be particularly effective in removing multiple layers of paint. Most of them were not friendly to the environment.

One of the more recent entries into the chemical stripping business is an environmentally friendly product known as EFS-2500, which works by breaking the bond between the substrate and primer. This leads to a secondary action that causes the paint to lift both primer and top coat off the surface as a single film. Once the coating is lifted, it is easily removed with a squeegee or high-pressure water.

This product differs from conventional chemical strippers by not melting the coatings. Cleanup is easier, and the product complies with EPA rules on emissions. Additionally, it passed Boeing testing specifications related to sandwich corrosion, immersion corrosion, and hydrogen embrittlement. EFS-2500 has no chlorinated components, is non-acidic, nonflammable, nonhazardous, biodegradable, and has minimal to no air pollution potential.

The stripper can be applied using existing common methods, such as airless spraying, brushing, rolling, or immersion in a tank. It works on all metals, including aluminum, magnesium, cadmium plate, titanium, wood, fiberglass, ceramic, concrete, plaster, and stone.

Plastic Media Blasting (PMB)

Plastic media blasting (PMB) is one of the stripping methods that reduces and may eliminate a majority of environmental pollution problems that can be associated with the earlier formulations of some chemical stripping. PMB is a dry abrasive blasting process designed to replace chemical paint stripping operations. PMB is similar to conventional sand blasting except that soft, angular plastic particles are used as the blasting medium. The process has minimum effect on the surface under the paint because of the plastic medium and relatively low air pressure used in the process. The media, when processed through a reclamation system, can be reused up to 10 times before it becomes too small to effectively remove the paint.

PMB is most effective on metal surfaces, but it has been used successfully on composite surfaces after it was found to produce less visual damage than removing the paint by sanding.

New Stripping Methods

Various methods and materials for stripping paint and other coatings are under development and include:

- A laser stripping process used to remove coatings from composites.
- Carbon dioxide pellets (dry ice) used in conjunction with a pulsed flashlamp that rapidly heats a thin layer of paint, which is then blasted away by the ice pellets.

Safety in the Paint Shop

All paint booths and shops must have adequate ventilation systems installed that not only remove the toxic air but, when properly operating, reduce and/or eliminate overspray and dust from collecting on the finish. All electric motors used in the fans and exhaust system should be grounded and enclosed to eliminate sparks. The lighting systems and all bulbs should be covered and protected against breakage.

Proper respirators and fresh air breathing systems must be available to all personnel involved in the stripping and painting process. When mixing any paint or two-part coatings, eye protection and respirators should be worn.

An appropriate number and size of the proper class fire extinguishers should be available in the shop or hangar during all spraying operations. They should be weighed and certified, as required, to ensure they work in the event they are needed. Fireproof containers should be available for the disposal of all paint and solvent soaked rags.

Storage of Finishing Materials

All chemical components that are used to paint an aircraft burn in their liquid state. They should be stored away from all sources of heat or flames. The ideal place would be in fireproof metal cabinets located in a well-ventilated area.

Some of the finishing components have a shelf life listed in the material or technical data sheet supplied by the coating manufacturer. Those materials should be marked on the container, with a date of purchase, in the event that they are not used immediately.

Protective Equipment for Personnel

The process of painting, stripping, or refinishing an aircraft requires the use of various coatings, chemicals, and procedures that may be hazardous if proper precautions are not utilized to protect personnel involved in their use.

The most significant hazards are airborne chemicals inhaled either from the vapors of opened paint containers or atomized mist resulting from spraying applications. There are two types of devices available to protect against airborne hazards: respirators and forced-air breathing systems.

A respirator is a device worn over the nose and mouth to filter particles and organic vapors from the air being inhaled. The most common type incorporate double charcoal-filtered cartridges with replaceable dust filters that fits to the face over the nose and mouth with a tight seal. When properly used, this type of respirator provides protection against the inhalation of organic vapors, dust, mists of paints, lacquers, and enamels. A respirator does not provide protection against paints and coatings containing isocyanates (polyurethane paint).

A respirator must be used in an area of adequate ventilation. If breathing becomes difficult, there is a smell or taste of the contaminant(s), or an individual becomes dizzy or feels nauseous, they should leave the area and seek fresh air and assistance as necessary. Carefully read the warnings furnished with each respirator describing the limits and materials for which they provide protection.

A forced-air breathing system must be used when spraying any type of polyurethane or any coating that contains isocyanates. It is also recommended for all spraying and stripping of any type, whether chemical or media blasting. The system provides a constant source of fresh air for breathing, which is pumped into the mask through a hose from an electric turbine pump.

Protective clothing, such as Tyvek® coveralls, should be worn that not only protects personnel from the paint but also help keep dust off the painted surfaces. Rubber gloves must be worn when any stripper, etching solution, conversion coatings, and solvent is used.

When solvents are used for cleaning paint equipment and spray guns, the area must be free of any open flame or other heat source. Solvent should not be randomly sprayed into the atmosphere when cleaning the guns. Solvents should not be used to wash or clean paint and other coatings from bare hands and arms. Use protective gloves and clothing during all spraying operations.

In most states, there are Occupational Safety Hazard Administration (OSHA) regulations in effect that may require personnel to be protected from vapors and other hazards while on the job. In any hangar or shop, personnel must be vigilant and provide and use protection for safety.

Chapter 9

Aircraft Electrical System

Introduction

The satisfactory performance of any modern aircraft depends to a very great degree on the continuing reliability of electrical systems and subsystems. Improperly or carelessly installed or maintained wiring can be a source of both immediate and potential danger. The continued proper performance of electrical systems depends on the knowledge and technique of the mechanic who installs, inspects, and maintains the electrical system wires and cables.

Ohm's Law

Ohm's Law describes the basic mathematical relationships of electricity. The law was named after German Physicist George Simon Ohm (1789–1854). Basically, Ohm's Law states that the current (electron flow) through a conductor is directly proportional to the voltage (electrical pressure) applied to that conductor and inversely proportional to the resistance of the conductor. The unit used to measure resistance is called the ohm. The symbol for the ohm is the Greek letter omega (Ω). In mathematical formulas, the capital letter R refers to resistance. The resistance of a conductor and the voltage applied to it determine the number of amperes of current flowing through the conductor. Thus, 1 ohm of resistance limits the current flow to 1 ampere in a conductor to which a voltage of 1 volt is applied. The primary formula derived from Ohm's Law is: $E = I \times R$ (E = electromotive force measured in volts, I = current flow measured in amps, and R = resistance measured in ohms). This formula can also be written to solve for current or resistance:

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

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

Ohm's Law provides a foundation of mathematical formulas that predict how electricity responds to certain conditions. *[Figure 9-1]* For example, Ohm's Law can be used to calculate that a lamp of 12 Ohms (Ω) passes a current of 2 amps when connected to a 24-volt direct current (DC) power source.

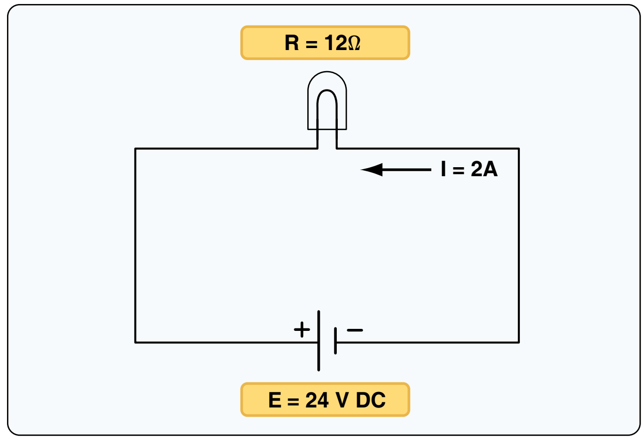


Figure 9-1. *Ohm's Law used to calculate how much current a lamp will pass when connected to a 24-volt DC power source.*

Example 1

A 28-volt landing light circuit has a lamp with 4 ohms of resistance. Calculate the total current of the circuit.

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

$$I = \frac{28 \text{ volts}}{4\Omega}$$

$$I = 7 \text{ amps}$$

Example 2

A 28-volt deice boot circuit has a current of 6.5 amps. Calculate the resistance of the deice boot.

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

$$R = \frac{28 \text{ volts}}{6.5 \text{ amps}}$$

$$R = 4.31\Omega$$

Example 3
A taxi light has a resistance of 4.9Ω and a total current of 2.85 amps. Calculate the system voltage.

$E = I \times R$

$E = 2.85 \times 4.9\Omega$

E = 14 volts

Whenever troubleshooting aircraft electrical circuits, it is always valuable to consider Ohm's Law. A good understanding of the relationship between resistance and current flow can help one determine if a circuit contains an open or a short. Remembering that a low resistance means increased current can help explain why circuit breakers pop or fuses blow. In almost all cases, aircraft loads are wired in parallel to each other; therefore, there is a constant voltage supplied to all loads and the current flow through a load is a function of that load's resistance.

Figure 9-2 illustrates several ways of using Ohm's Law for the calculation of current, voltage, and resistance.

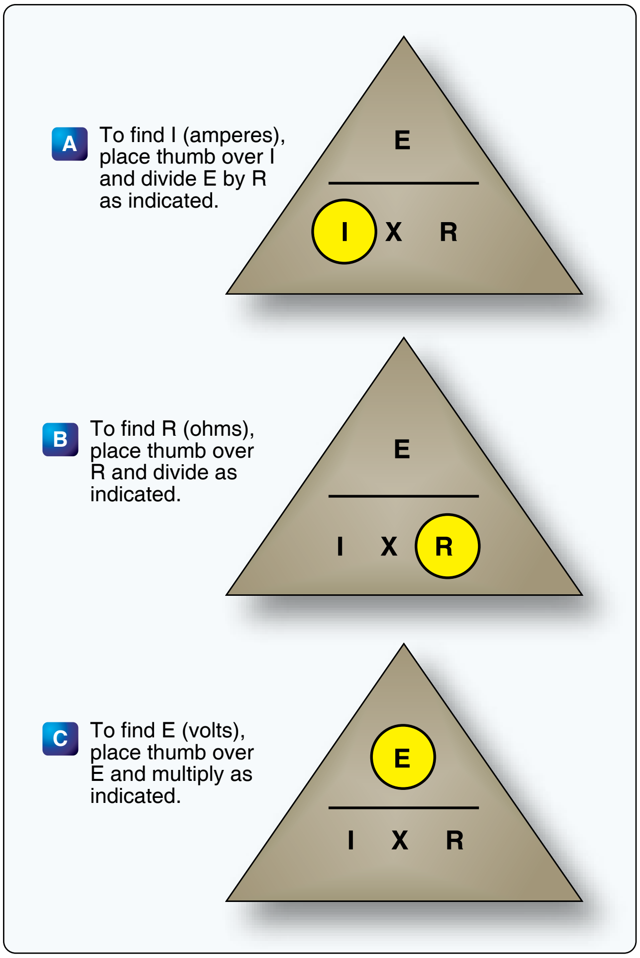


Figure 9-2. *Ohm's Law chart.*

Current

Electrical current is the movement of electrons. This electron movement is referred to as current, flow, or current flow. In practical terms, this movement of electrons must take place within a conductor (wire). Current is typically measured in amps. The symbol for current is I and the symbol for amps is A.

The current flow is actually the movement of the free electrons found within conductors. Common conductors include copper, silver, aluminum, and gold. The term "free electron" describes a condition in some atoms where the outer electrons are loosely bound to their parent atom. These loosely bound electrons are easily motivated to move in a given direction when an external source, such as a battery, is applied to the circuit. These electrons are attracted to the positive terminal of the battery, while the negative terminal is the source of the electrons. So, the measure of current is actually the number of electrons moving through a conductor in a given amount of time.

The internationally accepted unit for current is the ampere (A). One ampere (A) of current is equivalent to 1 coulomb (C) of charge passing through a conductor in 1 second. One coulomb of charge equals 6.28×10^{18} electrons. Obviously, the unit of amperes is a much more convenient term to use than coulombs. The unit of coulombs is simply too small to be practical.

When current flow is in one direction, it is called direct current (DC). Later in the text, the form of current that periodically oscillates back and forth within the circuit is discussed. The present discussion is concerned only with the use of DC. It should be noted that as with the movement of any mass, electron movement (current flow) only occurs when there is a force present to push the electrons. This force is commonly called voltage (described in more detail in the next section). When a voltage is applied across the conductor, an electromotive force creates an electric field within the conductor, and a current is established. The electrons do not move in a straight direction, but undergo repeated collisions with other nearby atoms within a conductor. These collisions usually knock other free electrons from their atoms, and these electrons move on toward the positive end of the conductor with an average velocity called the drift velocity, which is relatively low speed. To understand the nearly instantaneous speed of the effect of the current, it is helpful to visualize a long tube filled with steel balls. *[Figure 9-3]*

It can be seen that a ball introduced in one end of the tube, which represents the conductor, immediately causes a ball to be emitted at the opposite end of the tube. Thus, electric

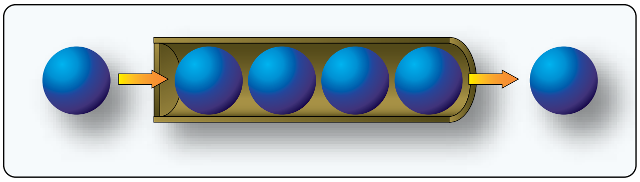


Figure 9-3. *Electron flow.*

current can be viewed as instantaneous, even though it is the result of a relatively slow drift of electrons.

Conventional Current Theory & Electron Theory

There are two competing schools of thought regarding the flow of electricity. The two explanations are the conventional current theory and the electron theory. Both theories describe the movement of electrons through a conductor. They simply explain the direction current moves. Typically during troubleshooting or the connection of electrical circuits, the use of either theory can be applied as long as it is used consistently. The Federal Aviation Administration (FAA) officially defines current flow using electron theory (negative to positive).

The conventional current theory was initially advanced by Benjamin Franklin, who reasoned that current flowed out of a positive source into a negative source or an area that lacked an abundance of charge. The notation assigned to the electric charges was positive (+) for the abundance of charge and negative (−) for a lack of charge. It then seemed natural to visualize the flow of current as being from the positive (+) to the negative (−). Later discoveries were made that proved that just the opposite is true. Electron theory describes what actually happens in the case of an abundance of electrons flowing out of the negative (−) source to an area that lacks electrons or the positive (+) source. Both conventional flow and electron flow are used in industry.

Electromotive Force (Voltage)

Voltage is most easily described as electrical pressure force. It is the electromotive force (EMF), or the push or pressure from one end of the conductor to the other, that ultimately moves the electrons. The symbol for EMF is the capital letter E. EMF is always measured between two points and voltage is considered a value between two points. For example, across the terminals of the typical aircraft battery, voltage can be measured as the potential difference of 12 volts or 24 volts. That is to say that between the two terminal posts of the battery, there is a voltage available to push current through a circuit. Free electrons in the negative terminal of the battery move toward the excessive number of positive charges in the positive terminal. The net result is a flow or current through a conductor. There cannot be a flow in a conductor unless there is an applied voltage from a battery, generator, or ground power unit. The potential difference, or the voltage across any two points in an electrical system, can be determined by:

$$V_1 - V_2 = V_{Drop}$$

Example

The voltage at one point is 14 volts. The voltage at a second point in the circuit is 12.1 volts. To calculate the voltage drop, use the formula above to get a total voltage drop of 1.9 volts.

Figure 9-4 illustrates the flow of electrons of electric current. Two interconnected water tanks demonstrate that when a difference of pressure exists between the two tanks, water flows until the two tanks are equalized. *Figure 9-4* shows the level of water in tank A to be at a higher level, reading 10 pounds per square inch (psi) (higher potential energy), than the water level in tank B, reading 2 psi (lower potential energy). Between the two tanks, there is 8 psi potential difference. If the valve in the interconnecting line between the tanks is opened, water flows from tank A into tank B until the level of water (potential energy) of both tanks is equalized. It is important to note that it was not the pressure in tank A that caused the water to flow; rather, it was the difference in pressure between tank A and tank B that caused the flow.

This comparison illustrates the principle that electrons move, when a path is available, from a point of excess electrons (higher potential energy) to a point deficient in electrons (lower potential energy). The force that causes this movement is the potential difference in electrical energy between the two points. This force is called the electrical pressure (voltage), the potential difference, or the electromotive force (electron moving force).

Resistance

The two fundamental properties of current and voltage are related by a third property known as resistance. In any electrical circuit, when voltage is applied to it, a current results. The resistance of the conductor determines the amount of current that flows under the given voltage. In general, the greater the circuit resistance, the less the current.

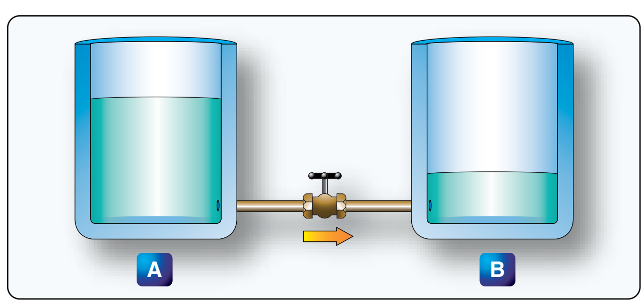


Figure 9-4. *Difference of pressure.*

If the resistance is reduced, then the current will increase. This relation is linear in nature and is known as Ohm's Law. An example would be if the resistance of a circuit is doubled, and the voltage is held constant, then the current through the resistor is cut in half.

There is no distinct dividing line between conductors and insulators; under the proper conditions, all types of material conduct some current. Materials offering a resistance to current flow midway between the best conductors and the poorest conductors (insulators) are sometimes referred to as semiconductors and find their greatest application in the field of transistors.

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

Factors Affecting Resistance

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

The resistance of a metallic conductor is directly proportional to its length. The longer the length of a given size of wire, the greater the resistance. *Figure 9-5* shows two wire conductors of different lengths. If 1 volt of electrical pressure is applied across the two ends of the conductor that is 1 foot in length and the resistance to the movement of free electrons is assumed to be 1 ohm, the current flow is limited to 1 ampere. If the same size conductor is doubled in length, the same electrons set in motion by the 1 volt applied now find twice the resistance.

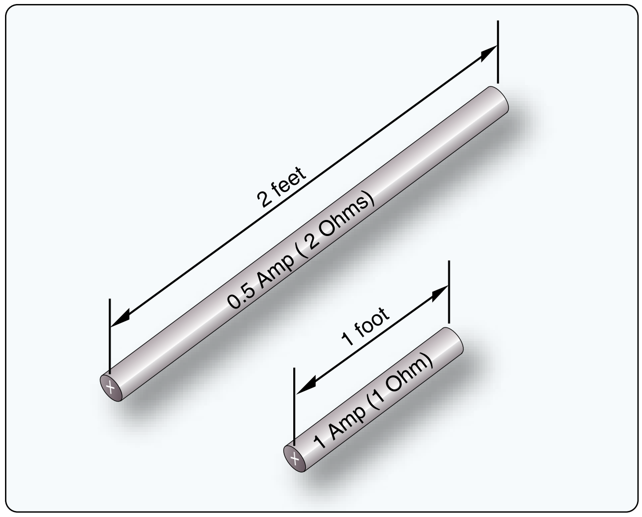


Figure 9-5. *Resistance varies with length of conductor.*

Electromagnetic Generation of Power

Electrical energy can be produced through a number of methods. Common methods include the use of light, pressure, heat, chemical, and electromagnetic induction. Of these processes, electromagnetic induction is most responsible for the generation of the majority of the electrical power used by humans. Virtually all mechanical devices (generators and alternators) that produce electrical power employ the process of electromagnetic induction. The use of light, pressure, heat, and chemical sources for electrical power is found on aircraft but produce a minimal amount of all the electrical power consumed during a typical flight.

In brief, light can produce electricity using a solar cell (photovoltaic cell). These cells contain a certain chemical that converts light energy into voltage/current.

Using pressure to generate electrical power is commonly known as the piezoelectric effect. The piezoelectric effect (piezo or piez taken from Greek: to press; pressure; to squeeze) is a result of the application of mechanical pressure on a dielectric or nonconducting crystal.

Chemical energy can be converted into electricity, most commonly in the form of a battery. A primary battery produces electricity using two different metals in a chemical solution like alkaline electrolyte. A chemical reaction exists between the metals which frees more electrons in one metal than in the other.

Heat used to produce electricity creates the thermoelectric effect. When a device called a thermocouple is subjected to heat, a voltage is produced. A thermocouple is a junction between two different metals that produces a voltage related to a temperature difference. If the thermocouple is connected to a complete circuit, a current also flows. Thermocouples are often found on aircraft as part of a temperature monitoring system, such as a cylinder head temperature gauge.

Electromagnetic induction is the process of producing a voltage (EMF) by moving a magnetic field in relationship to a

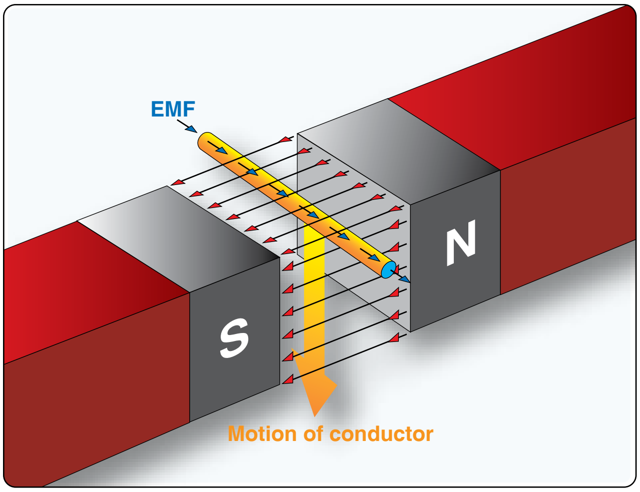


Figure 9-6. *Inducing an EMF in a conductor.*

conductor. As shown in *Figure 9-6,* when a conductor (wire) is moved through a magnetic field, an EMF is produced in the conductor. If a complete circuit is connected to the conductor, the voltage also produces a current flow.

One single conductor does not produce significant voltage/current via electromagnetic induction. *[Figure 9-6]* In practice, instead of a single wire, a coil of wire is moved through the magnetic field of a strong magnet. This produces a greater electrical output. In many cases, the magnetic field is created by using a powerful electromagnet. This allows for the production of a greater voltage/current due to the stronger magnetic field produced by the electromagnet when compared to an ordinary magnet.

Please note that this text often refers to voltage/current in regards to electrical power. Remember voltage (electrical pressure) must be present to produce a current (electron flow). Hence, the output energy generated through the process of electromagnetic induction always consists of voltage. Current also results when a complete circuit is connected to that voltage. Electrical power is produced when there is both electrical pressure E (EMF) and current (I). Power = Current × Voltage ($P = I \times E$)

It is the relative motion between a conductor and a magnetic field that causes current to flow in the conductor. Either the conductor or magnet can be moving or stationary. When a magnet and its field are moved through a coiled conductor, as shown in *Figure 9-7*, a DC voltage with a specific polarity is produced. The polarity of this voltage depends on the direction in which the magnet is moved and the position of the north and south poles of the magnetic field. The generator left-hand rule can be used to determine the direction of current flow within the conductor. *[Figure 9-8]* Of course, the direction of current flow is a function of the polarity of

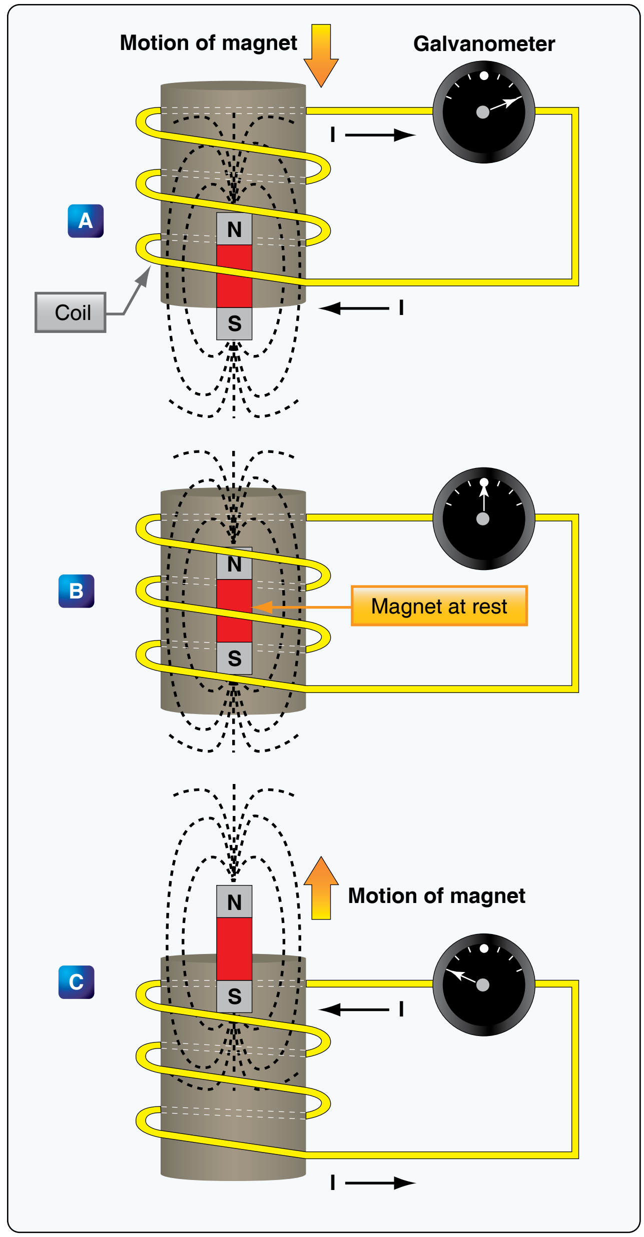


Figure 9-7. *Inducing a current flow.*

the voltage induced in to the conductor.

In practice, producing voltage/current using the process of electromagnetic induction requires a rotating machine. Generally speaking, on all aircraft, a generator or alternator employs the principles of electromagnetic induction to create electrical power for the aircraft. Either the magnetic field can rotate or the conductor can rotate. *[Figure 9-9]* The rotating component is driven by a mechanical device, such as an aircraft engine.

During the process of electromagnetic induction, the value of the induced voltage/current depends on three basic factors:

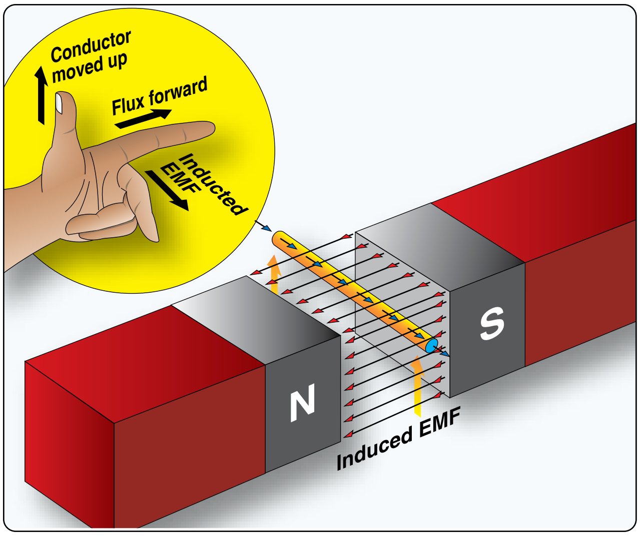


Figure 9-8. *An application of the generator left-hand rule.*

1. Number of turns in the conductor coil (more loops equals greater induced voltage).
2. Strength of the electromagnet (the stronger the magnetic field, the greater the induced voltage).
3. Speed of rotation of the conductor or magnet (the faster the rotation, the greater the induced voltage).

Figure 9-10 illustrates the basics of a rotating machine used to produce voltage. The simple generating device consists of a rotating loop, marked A and B, placed between two magnetic poles, north (N) and south (S). The ends of the loop are connected to two metal slip rings (collector rings), C1 and C2. Current is taken from the collector rings by brushes. If the loop is considered as separate wires, A and B, and the left-hand rule for generators is applied, then it can be observed that as wire B moves up across the field, a voltage is induced that causes the current to flow toward the reader. As wire A moves down across the field, a voltage is induced that causes the current to flow away from the reader. When the wires are formed into a loop, the voltages induced in the two sides of the loop are combined. Therefore, for explanatory purposes, the action of either conductor, A or B, while rotating in the magnetic field is similar to the action of the loop.

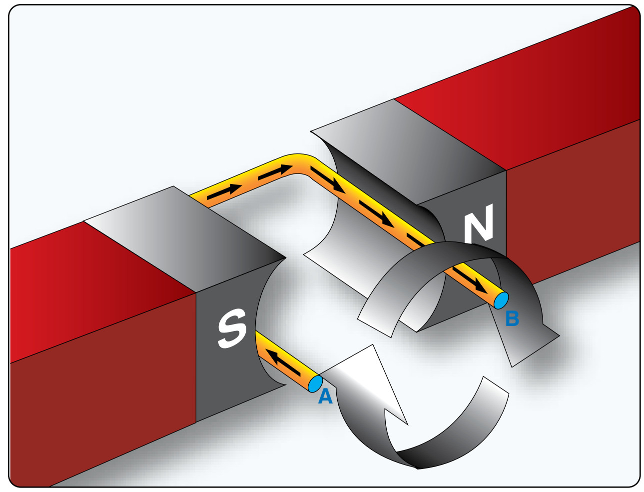


Figure 9-9. *Voltage induced in a loop.*

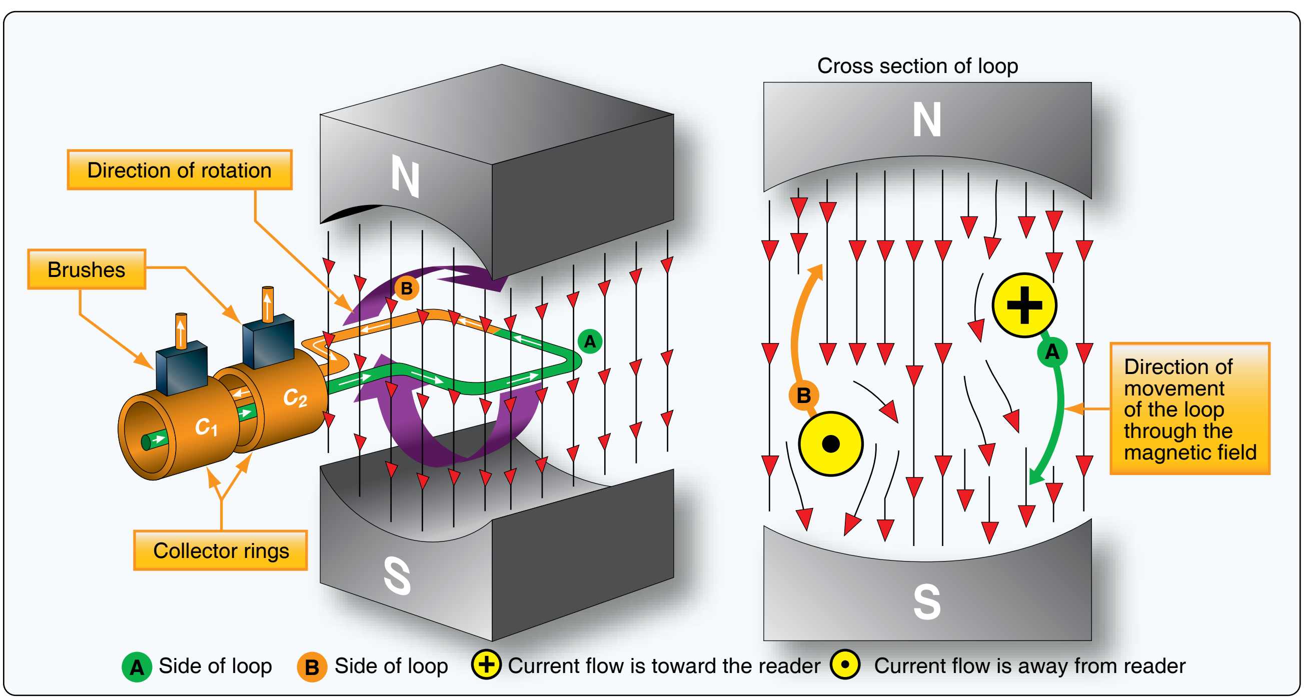


Figure 9-10. *Simple generator.*

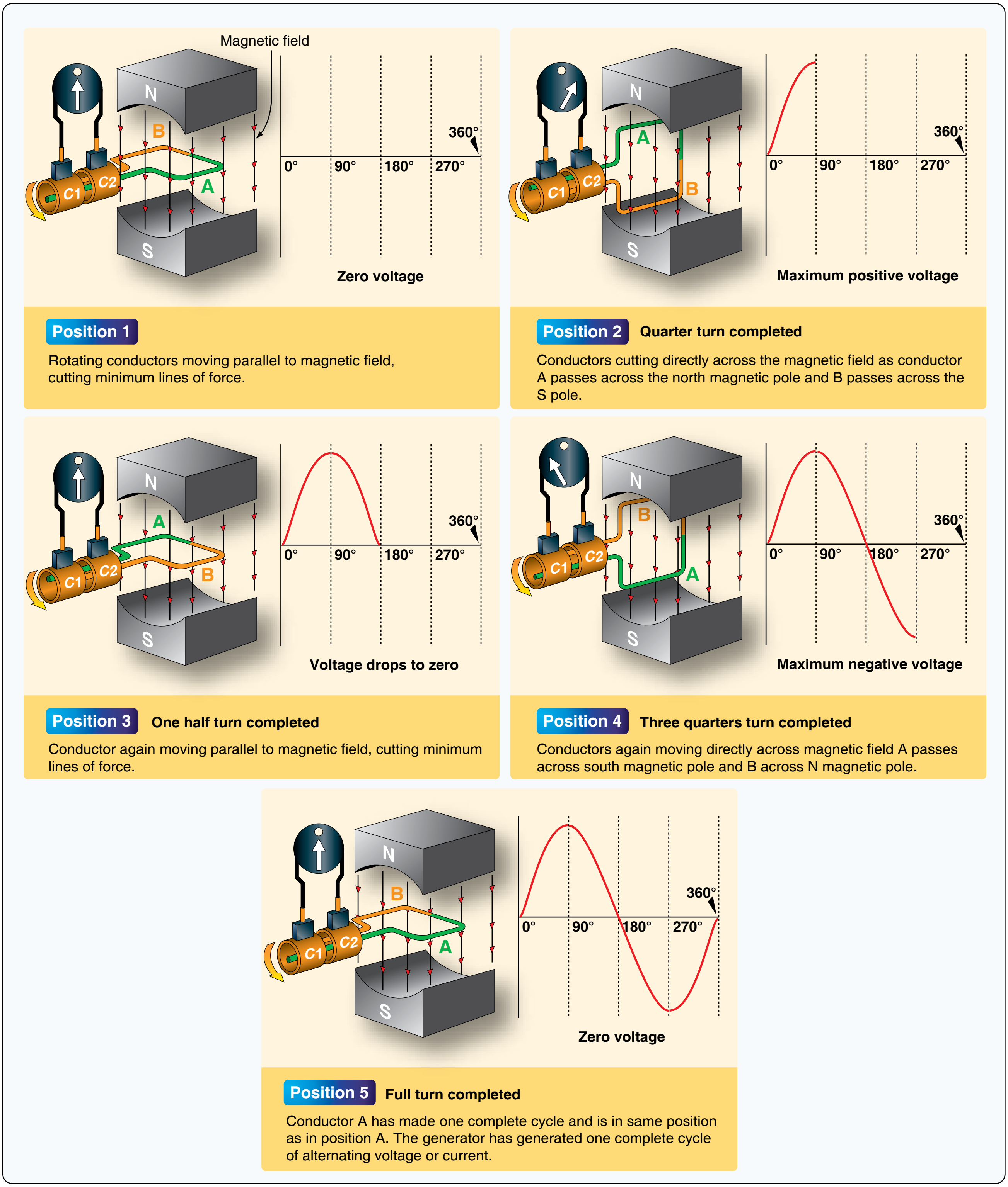


Figure 9-11. *Generation of a sine wave.*

Figure 9-11 illustrates the generation of alternating current (AC) with a simple loop conductor rotating in a magnetic field. As it is rotated in a counterclockwise direction, varying voltages are induced in the conductive loop.

Position 1

The conductor A moves parallel to the lines of force. Since it cuts no lines of force, the induced voltage is zero. As the conductor advances from position 1 to position 2, the induced voltage gradually increases.

Position 2
The conductor is now moving in a direction perpendicular to the flux and cuts a maximum number of lines of force; therefore, a maximum voltage is induced. As the conductor moves beyond position 2, it cuts a decreasing amount of flux, and the induced voltage decreases.

Position 3
At this point, the conductor has made half a revolution and again moves parallel to the lines of force, and no voltage is induced in the conductor. As the A conductor passes position 3, the direction of induced voltage now reverses since the A conductor is moving downward, cutting flux in the opposite direction. As the A conductor moves across the south pole, the induced voltage gradually increases in a negative direction until it reaches position 4.

Position 4
Like position 2, the conductor is again moving perpendicular to the flux and generates a maximum negative voltage. From position 4 to position 5, the induced voltage gradually decreases until the voltage is zero, and the conductor and wave are ready to start another cycle.

Position 5
The curve shown at position 5 is called a sine wave. It represents the polarity and the magnitude of the instantaneous values of the voltages generated. The horizontal baseline is divided into degrees, or time, and the vertical distance above or below the baseline represents the value of voltage at each particular point in the rotation of the loop.

The specific operating principles of both alternators and generators as they apply to aircraft is presented later in this text.

Alternating Current (AC) Introduction

Alternating current (AC) electrical systems are found on most multi-engine, high performance turbine powered aircraft and transport category aircraft. AC is the same type of electricity used in industry and to power our homes. Direct current (DC) is used on systems that must be compatible with battery power, such as on light aircraft and automobiles. There are many benefits of AC power when selected over DC power for aircraft electrical systems.

AC can be transmitted over long distances more readily and more economically than DC, since AC voltages can be increased or decreased by means of transformers. Because more and more units are being operated electrically in airplanes, the power requirements are such that a number of advantages can be realized by using AC (especially with large transport category aircraft). Space and weight can be saved since AC devices, especially motors, are smaller and simpler than DC devices. In most AC motors, no brushes are required, and they require less maintenance than DC motors. Circuit breakers operate satisfactorily under loads at high altitudes in an AC system, whereas arcing is so excessive on DC systems that circuit breakers must be replaced frequently. Finally, most airplanes using a 24-volt DC system have special equipment that requires a certain amount of 400 cycle AC current. For these aircraft, a unit called an inverter is used to change DC to AC. Inverters are discussed later in this book.

AC is constantly changing in value and polarity, or as the name implies, alternating. *Figure 9-12* shows a graphic comparison of DC and AC. The polarity of DC never changes, and the polarity and voltage constantly change in AC. It should also be noted that the AC cycle repeats at given intervals. With AC, both voltage and current start at zero, increase, reach a peak, then decrease and reverse polarity. If one is to graph this concept, it becomes easy to see the alternating wave form. This wave form is typically referred to as a sine wave.

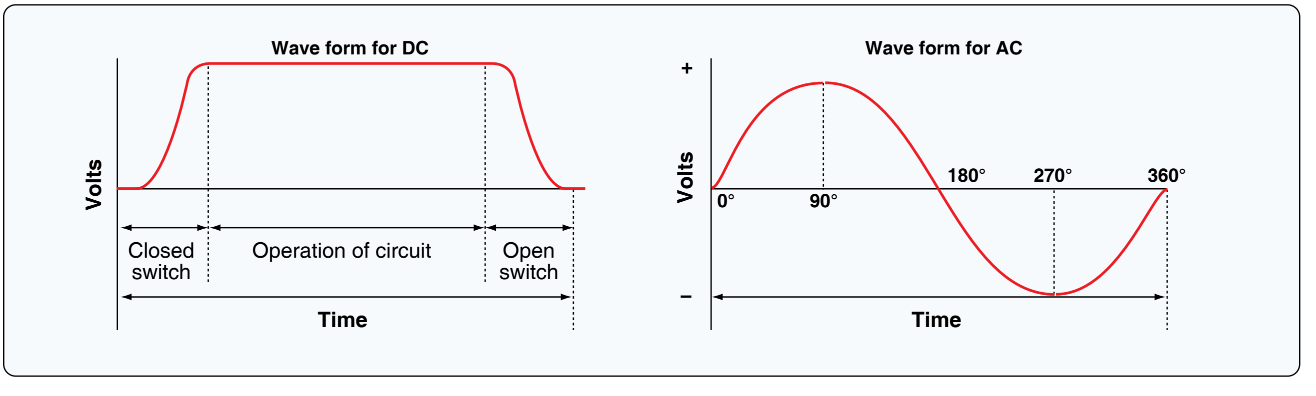


Figure 9-12. *DC and AC voltage curves.*

Definitions

Values of AC

There are three values of AC that apply to both voltage and current. These values help to define the sine wave and are called instantaneous, peak, and effective. It should be noted that during the discussion of these terms, the text refers to voltage. But remember, the values apply to voltage and current in all AC circuits.

Instantaneous

An instantaneous voltage is the value at any instant in time along the AC wave. The sine wave represents a series of these values. The instantaneous value of the voltage varies from zero at 0° to maximum at 90°, back to zero at 180°, to maximum in the opposite direction at 270°, and to zero again at 360°. Any point on the sine wave is considered the instantaneous value of voltage.

Peak

The peak value is the largest instantaneous value, often referred to as the maximum value. The largest single positive value occurs after a certain period of time when the sine wave reaches 90°, and the largest single negative value occurs when the wave reaches 270°. Although important in the understanding of the AC sine wave, peak values are seldom used by aircraft technicians.

Effective

The effective values for voltage are always less than the peak (maximum) values of the sine wave and approximate DC voltage of the same value. For example, an AC circuit of 24 volts and 2 amps should produce the same heat through a resistor as a DC circuit of 24 volts and 2 amps. The effective value is also known as the root mean square, or RMS value, which refers to the mathematical process by which the value is derived.

Most AC meters display the effective value of the AC. In almost all cases, the voltage and current ratings of a system or component are given in effective values. In other words, the industry ratings are based on effective values. Peak and instantaneous values, used only in very limited situations, would be stated as such. In the study of AC, any values given for current or voltage are assumed to be effective values unless otherwise specified. In practice, only the effective values of voltage and current are used.

The effective value is equal to .707 times the peak (maximum) value. Conversely, the peak value is 1.41 times the effective value. Thus, the 110 volt value given for AC is only 0.707 of the peak voltage of this supply. The maximum voltage is approximately 155 volts (110 × 1.41 = 155 volts maximum).

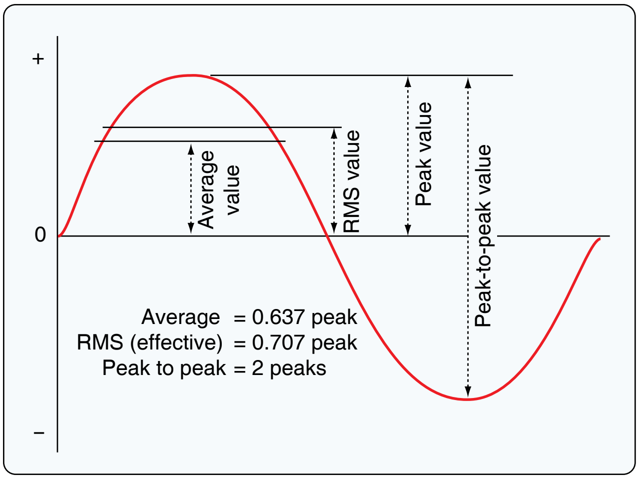


Figure 9-13. *Values of AC.*

How often the AC waveform repeats is known as the AC frequency. The frequency is typically measured in cycles per second (CPS) or hertz (Hz). One Hz equals one CPS. The time it takes for the sine wave to complete one cycle is known as period (P). Period is a value or time period and typically measured in seconds, milliseconds, or microseconds. It should be noted that the time period of a cycle can change from one system to another; it is always said that the cycle completes in 360° (related to the 360° of rotation of an AC alternator). *[Figure 9-13]*

Cycle Defined

A cycle is a completion of a pattern. Whenever a voltage or current passes through a series of changes, returns to the starting point, and then repeats the same series of changes, the series is called a cycle. When the voltage values are graphed, as in *Figure 9-14,* the complete AC cycle is displayed. One complete cycle is often referred to as the sine wave and said to be 360°. It is typical to start the sine wave where the voltage is zero. The voltage then increases to a

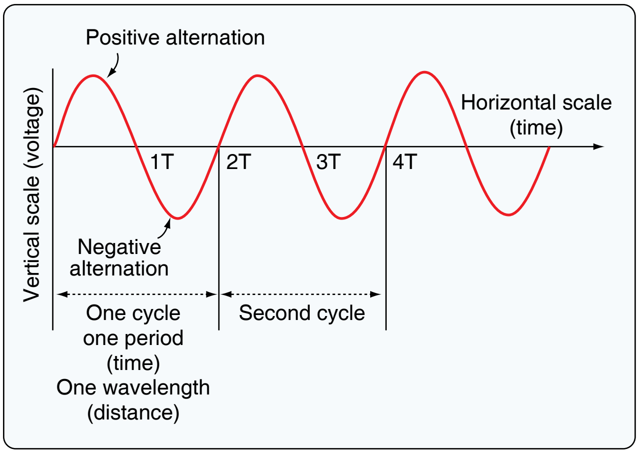


Figure 9-14. *Cycle of voltage.*

maximum positive value, decreases to a value of zero, then increases to a maximum negative value, and again decreases to zero. The cycle repeats until the voltage is no longer available. There are two alternations in a complete cycle: the positive alternation and the negative. It should be noted that the polarity of the voltage reverses for each half cycle. Therefore, during the positive half cycle, the electron flow is considered to be in one direction; during the negative half cycle, the electrons reverse direction and flow the opposite way through the circuit.

Frequency Defined

The frequency is the number of cycles of AC per second (CPS). The standard unit of frequency measurement is the Hz. *[Figure 9-15]* In a generator, the voltage and current pass through a complete cycle of values each time a coil or conductor passes under a north and south pole of the magnet. The number of cycles for each revolution of the coil or conductor is equal to the number of pairs of poles. The frequency, then, is equal to the number of cycles in one revolution multiplied by the number of revolutions per second.

Period Defined

The time required for a sine wave to complete one full cycle is called a period (P). A period is typically measured in seconds, milliseconds, or microseconds. *[Figure 9-14]* The period of a sine wave is inversely proportional to the frequency. That is to say that the higher the frequency, the shorter the period. The mathematical relationship between frequency and period is given as:

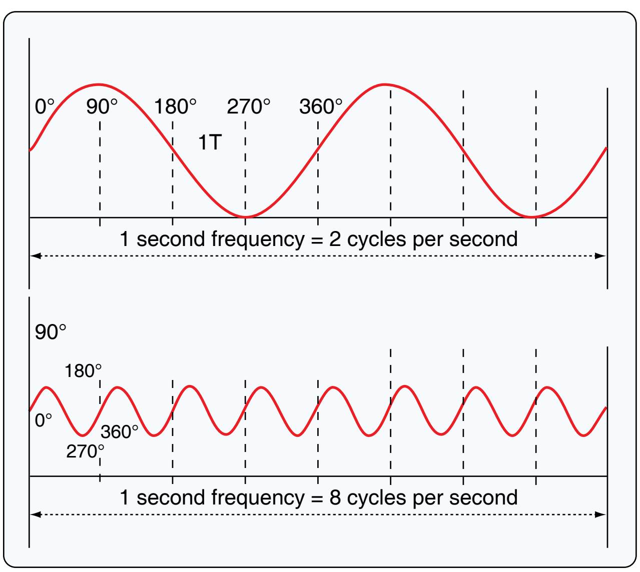


Figure 9-15. *Frequency in cycles per second.*

Period

$$P = \frac{1}{f}$$

Frequency

$$F = \frac{1}{P}$$

Wavelength Defined

The distance that a waveform travels during a period is commonly referred to as a wavelength and is indicated by the Greek letter lambda (λ). Wavelength is related to frequency by the formula:

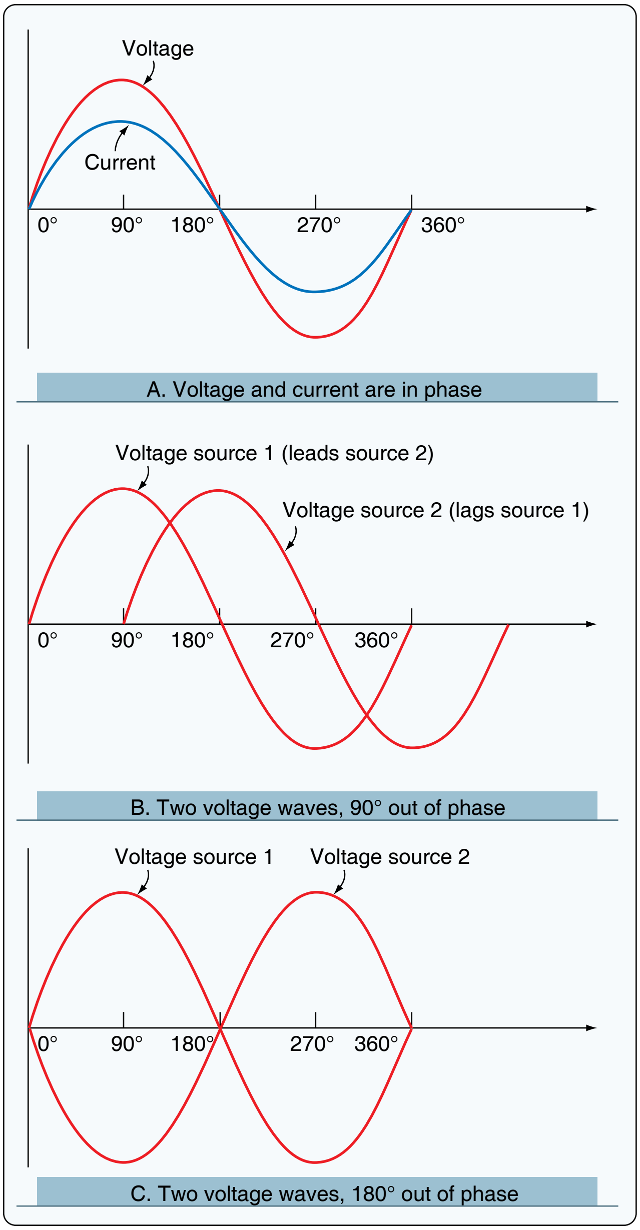
$$\frac{\text{wave speed}}{\text{frequency}} = \text{wavelength}$$

The higher the frequency is, the shorter the wavelength is. The measurement of wavelength is taken from one point on the waveform to a corresponding point on the next waveform. *[Figure 9-14]* Since wavelength is a distance, common units of measure include meters, centimeters, millimeters, or nanometers. For example, a sound wave of frequency 20 Hz would have wavelength of 17 meters and a visible red light wave of $4.3 \times 10\ -12$ Hz would have a wavelength of roughly 700 nanometers. Keep in mind that the actual wavelength depends on the media through which the waveform must travel.

Phase Relationships

Phase is the relationship between two sine waves, typically measured in angular degrees. For example, if there are two different alternators producing power, it would be easy to compare their individual sine waves and determine their phase relationship. In *Figure 9-16B*, there is a 90° phase difference between the two voltage waveforms. A phase relationship can be between any two sine waves. The phase relationship can be measured between two voltages of different alternators or the current and voltage produced by the same alternator.

Figure 9-16A shows a voltage signal and a current signal superimposed on the same time axis. Notice that when the voltage increases in the positive alternation that the current also increases. When the voltage reaches its peak value, so does the current. Both waveforms then reverse and decrease back to a zero magnitude, then proceed in the same manner in the negative direction as they did in the positive direction. When two waves are exactly in step with each other, they are said to be in phase. To be in phase, the two waveforms must go through their maximum and minimum points at the same time and in the same direction.



A. Voltage and current are in phase

B. Two voltage waves, 90° out of phase

C. Two voltage waves, 180° out of phase

Figure 9-16. *In-phase and out-of-phase conditions.*

When two waveforms go through their maximum and minimum points at different times, a phase difference exists between the two. In this case, the two waveforms are said to be out of phase with each other. The terms lead and lag are often used to describe the phase difference between waveforms. The waveform that reaches its maximum or minimum value first is said to lead the other waveform. *Figure 9-16B* shows this relationship. On the other hand, the second waveform is said to be lagging the first source. When a waveform is said to be leading or lagging, the difference in degrees is usually stated. If the two waveforms differ by 360°, they are said to be in phase with each other. If there is a 180° difference between the two signals, then they are still out of phase even though they are both reaching their minimum and maximum values at the same time. *[Figure 9-16C]*

Opposition to Current Flow of AC

There are three factors that can create an opposition to the flow of electrons (current) in an AC circuit. Resistance, similar to resistance of DC circuits, is measured in ohms and has a direct influence on AC regardless of frequency. Inductive reactance and capacitive reactance, on the other hand, oppose current flow only in AC circuits, not in DC circuits. Since AC constantly changes direction and intensity, inductors and capacitors may also create an opposition to current flow in AC circuits. It should also be noted that inductive reactance and capacitive reactance may create a phase shift between the voltage and current in an AC circuit. Whenever analyzing an AC circuit, it is very important to consider the resistance, inductive reactance, and the capacitive reactance. All three have an effect on the current of that circuit.

Resistance

As mentioned, resistance creates an opposition to current in an AC circuit similar to the resistance of a DC circuit. The current through a resistive portion of an AC circuit is inversely proportional to the resistance and directly proportional to the voltage applied to that circuit or portion of the circuit. The equations $I = E / R$ & $E = I \times R$ show how current is related to both voltage and resistance. It should be noted that resistance in an AC circuit does not create a phase shift between voltage and current.

Figure 9-17 shows how a circuit of 10 ohms allows 11.5 amps of current flow through an AC resistive circuit of 115 volts.

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

$$I = \frac{115V}{10\Omega}$$

$$I = 11.5 \text{ amps}$$

Inductive Reactance

When moving a magnet through a coil of wire, a voltage is induced across the coil. If a complete circuit is provided, then a current will also be induced. The amount of induced voltage is directly proportional to the rate of change of the magnetic field with respect to the coil. Conversely, current flowing through a coil of wire produces a magnetic field. When this wire is formed into a coil, it then becomes a basic inductor.

The primary effect of a coil is its property to oppose any change in current through it. This property is called inductance. When current flows through any conductor, a magnetic field starts to expand from the center of the wire. As the lines of magnetic

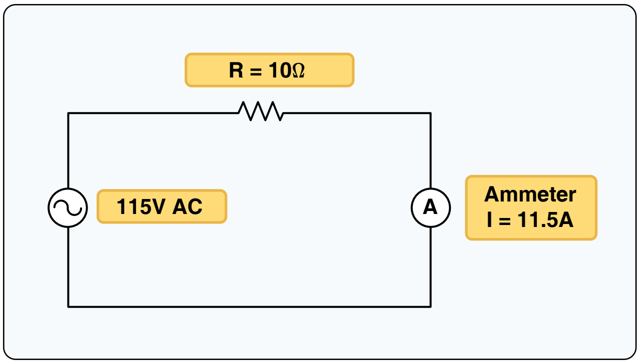


Figure 9-17. *Resistance.*

force grow outward through the conductor, they induce an EMF in the conductor itself. The induced voltage is always in the direction opposite to the direction of the applied current flow. The effects of this countering EMF are to oppose the applied current. This effect is only a temporary condition. Once the current reaches a steady value in the conductor, the lines of magnetic force are no longer expanding and the countering EMF is no longer present. Since AC is constantly changing in value, the inductance repeats in a cycle always opposite the applied voltage. It should be noted that the unit of measure for inductance is the henry (H).

The physical factors that affect inductance are:

1. Number of turns—doubling the number of turns in a coil produces a field twice as strong if the same current is used. As a general rule, the inductance varies with the square of the number of turns.
2. Cross-sectional area of the coil—the inductance of a coil increases directly as the cross-sectional area of the core increases. Doubling the radius of a coil increases the inductance by a factor of four.
3. Length of a coil—doubling the length of a coil, while keeping the same number of turns, reduces inductance by one-half.
4. Core material around which the coil is formed—coils are wound on either magnetic or nonmagnetic materials. Some nonmagnetic materials include air, copper, plastic, and glass. Magnetic materials include nickel, iron, steel, and cobalt, which have a permeability that provides a better path for the magnetic lines of force and permit a stronger magnetic field.

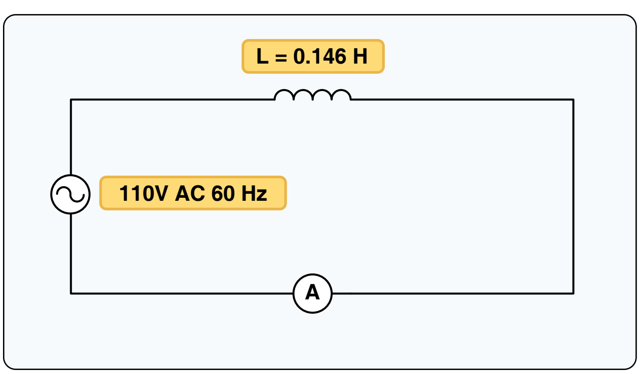


Figure 9-18. *AC circuit containing inductance.*

Since AC is in a constant state of change, the magnetic fields within an inductor are also continuously changing and create an inducted voltage/current. This induced voltage opposes the applied voltage and is known as the counter EMF. This opposition is called inductive reactance, symbolized by X_L, and is measured in ohms. This characteristic of the inductor may also create a phase shift between voltage and current of the circuit. The phase shift created by inductive reactance always causes voltage to lead current. That is, the voltage of an inductive circuit reaches its peak values before the current reaches peak values. Additional discussions related to phase shift are presented later in this chapter.

Inductance is the property of a circuit to oppose any change in current and is measured in henries. Inductive reactance is a measure of how much the countering EMF in the circuit opposes the applied current. The inductive reactance of a component is directly proportional to the inductance of the component and the applied frequency to the circuit. By increasing either the inductance or applied frequency, the inductive reactance likewise increases and presents more opposition to current in the circuit. This relationship is given as $X_L = 2\pi fL$ Where X_L = inductive reactance in ohms, L = inductance in henries, f = frequency in cycles per second, and $\pi = 3.1416$.

In *Figure 9-18*, an AC series circuit is shown in which the inductance is 0.146 henry and the voltage is 110 volts at a frequency of 60 cycles per second. Inductive reactance is determined by the following method.

$$X_L = 2\pi \times f \times L$$

$$X_L = 6.28 \times 60 \times 0.146$$

$$X_L = 55\Omega$$

In AC series circuits, inductive reactance is added like resistances in series in a DC circuit. *[Figure 9-19]* The total reactance in the illustrated circuit equals the sum of the individual reactances.

$$X_L = X_{L1} + X_{L2}$$

$$X_L = 10\Omega + 15\Omega$$

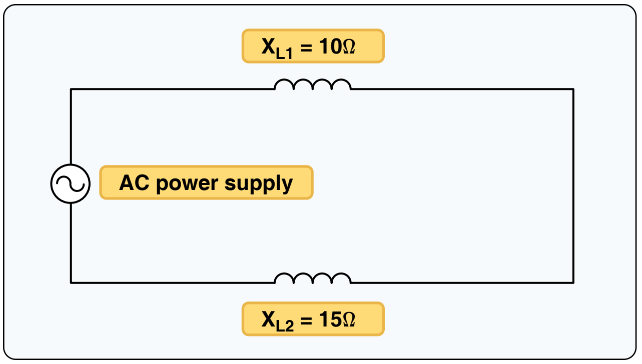


Figure 9-19. *Inductances in series.*

$X_{LT} = 25\Omega$

The total reactance of inductors connected in parallel is found the same way as the total resistance in a parallel circuit. *[Figure 9-20]* Thus, the total reactance of inductances connected in parallel, as shown, is expressed as:

$$X_{LT} = \cfrac{1}{\cfrac{1}{X_{L1}} + \cfrac{1}{X_{L2}} + \cfrac{1}{X_{L3}}}$$

$$X_{LT} = \cfrac{1}{\cfrac{1}{15} + \cfrac{1}{15} + \cfrac{1}{15}}$$

$X_{LT} = 5\Omega$

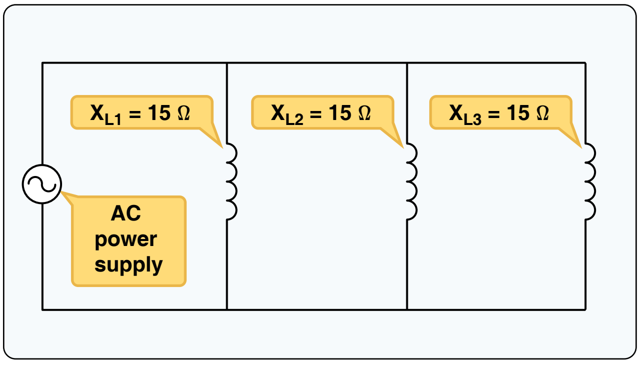


Figure 9-20. *Inductances in parallel.*

Capacitive Reactance

Capacitance is the ability of a body to hold an electric charge. In general, a capacitor is constructed of two parallel plates separated by an insulator. The insulator is commonly called the dielectric. The capacitor's plates have the ability to store electrons when charged by a voltage source. The capacitor discharges when the applied voltage is no longer present and the capacitor is connected to a current path. In an electrical circuit, a capacitor serves as a reservoir or storehouse for electricity.

The basic unit of capacitance is the farad and is given by the letter F. By definition, one farad is one coulomb of charge stored with one volt across the plates of the capacitor. In practical terms, one farad is a large amount of capacitance. Typically, in electronics, much smaller units are used. The two more common smaller units are the microfarad (μF), which is 10^{-6} farad and the picofarad (pF), which is 10^{-12} farad.

Capacitance is a function of the physical properties of the capacitor:

1. The capacitance of parallel plates is directly proportional to their area. A larger plate area produces a larger capacitance, and a smaller area produces less capacitance. If we double the area of the plates, there is room for twice as much charge.
2. The capacitance of parallel plates is inversely proportional to the distance between the plates.
3. The dielectric material effects the capacitance of parallel plates. The dielectric constant of a vacuum is defined as 1, and that of air is very close to 1. These values are used as a reference, and all other materials have values relative to that of air (vacuum).

When an AC is applied in the circuit, the charge on the plates constantly changes. *[Figure 9-21]* This means that electricity must flow first from Y clockwise around to X, then from X counterclockwise around to Y, then from Y clockwise around to X, and so on. Although no current flows through the insulator between the plates of the capacitor, it constantly flows in the remainder of the circuit between X and Y. As this current alternates to and from the capacitor, a certain time lag is created. When a capacitor charges or discharges through a resistance, a certain amount of time is required for a full

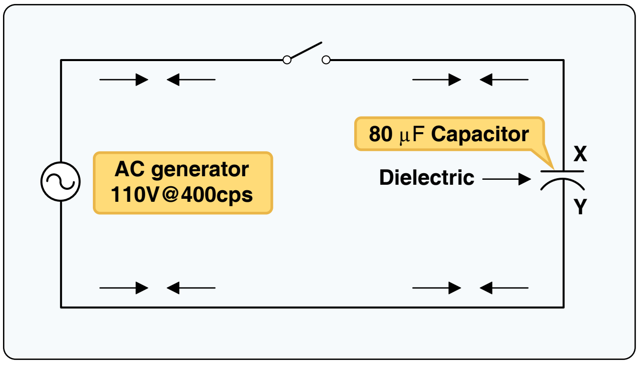


Figure 9-21. *Capacitor in an AC circuit.*

charge or discharge. The voltage across the capacitor does not change instantaneously. The rate of charging or discharging is determined by the time constant of the circuit. This rate of charge and discharge creates an opposition to current flow in AC circuits known as capacitive reactance. Capacitive reactance is symbolized by X_C and is measured in ohms. This characteristic of a capacitor may also create a phase shift between voltage and current of the circuit. The phase shift created by capacitive reactance always causes current to lead voltage. That is, the current of a capacitive circuit reaches its peak values before the voltage reaches peak values.

Capacitive reactance is a measure of how much the capacitive circuit opposes the applied current flow. Capacitive reactance is measured in ohms. The capacitive reactance of a circuit is indirectly proportional to the capacitance of the circuit and the applied frequency to the circuit. By increasing either the capacitance or applied frequency, the capacitive reactance decreases, and vice versa. This relationship is given as:

$$X_C = \frac{1}{2\pi fC}$$

Where: X_C = capacitive reactance in ohms, C = capacitance in farads, f = frequency in cycles per second, and $\pi = 3.1416$.

In *Figure 9-21,* a series circuit is shown in which the applied voltage is 110 volts at 400 cps, and the capacitance of a condenser is 80 mf. Find the capacitive reactance and the current flow.

To find the capacitive reactance, the following equation:

$$X_C = \frac{1}{2\pi fC}$$

First, the capacitance, 80 µf, is changed to farads by dividing 80 by 1,000,000, since 1 million microfarads is equal to 1 farad. This quotient equals 0.000080 farad. This is substituted in the equation:

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{1}{2\pi(400)(0.000080)}$$

$$X_C = 4.97\Omega$$

Impedance

The total opposition to current flow in an AC circuit is known as impedance and is represented by the letter Z. The combined effects of resistance, inductive reactance, and capacitive

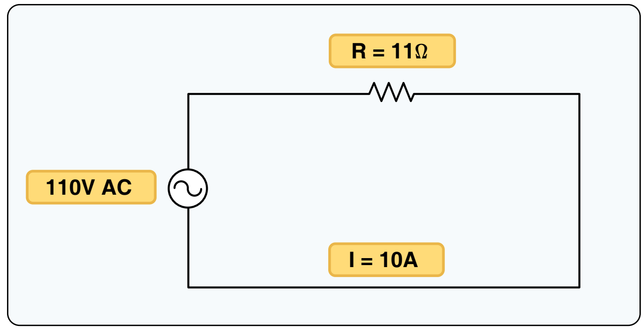


Figure 9-22. *Ohm's Law applies to AC circuit only when circuit consists of resistance only. Impedance (Z) = Resistance (R).*

reactance make up impedance (the total opposition to current flow in an AC circuit). In order to accurately calculate voltage and current in AC circuits, the effect of inductance and capacitance along with resistance must be considered. Impedance is measured in ohms.

The rules and equations for DC circuits apply to AC circuits only when that circuit contains resistance alone and no inductance or capacitance. In both series and parallel circuits, if an AC circuit consists of resistance only, the value of the impedance is the same as the resistance, and Ohm's Law for an AC circuit, I = E/Z, is exactly the same as for a DC circuit. *Figure 9-22* illustrates a series circuit containing a heater element with 11 ohms resistance connected across a 110-volt source. To find how much current flows if 110 volts AC is applied, the following example is solved:

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

$$I = \frac{110V}{11\Omega}$$

I = 10 amps

If there are two resistance values in parallel connected to an

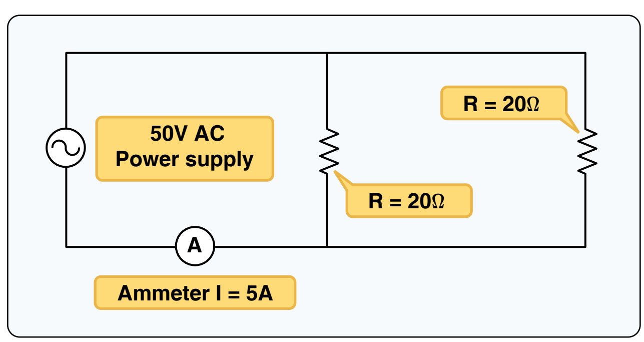


Figure 9-23. *Two resistance values in parallel connected to an AC voltage. Impedance is equal to the total resistance of the circuit.*

AC voltage, as seen in *Figure 9-23,* impedance is equal to the total resistance of the circuit. Once again, the calculations would be handled the same as if it were a DC circuit and the following would apply:

$$R_T = \cfrac{1}{\cfrac{1}{R_1} + \cfrac{1}{R_2}}$$

$$R_T = \cfrac{1}{\cfrac{1}{20} + \cfrac{1}{20}}$$

$R_T = 10\Omega$

Since this is a pure resistive circuit $R_T = Z$ (Resistance = Impedance)

$Z_T = R_T$

$Z_T = 10\Omega$

To determine the current flow in the circuit use the equation:

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

$$I = \frac{50V}{10\Omega}$$

$I = 5$ amps

Impedance is the total opposition to current flow in an AC circuit. If a circuit has inductance or capacitance, one must take into consideration resistance (R), inductive reactance (X_L), and/or capacitive reactance (X_C) to determine impedance (Z). In this case, Z does not equal R_T. Resistance and reactance (inductive or capacitive) cannot be added directly, but they can be considered as two forces acting at right angles to each other. Thus, the relation between resistance, reactance, and impedance may be illustrated by a right triangle. *[Figure 9-24]* Since these quantities may be related to the sides of a right triangle, the formula for finding the impedance can be found using the Pythagorean Theorem. It states that the square of the hypotenuse is equal to the sum of the squares of the other two sides. Thus, the value of any side of a right triangle can be found if the other two sides are known.

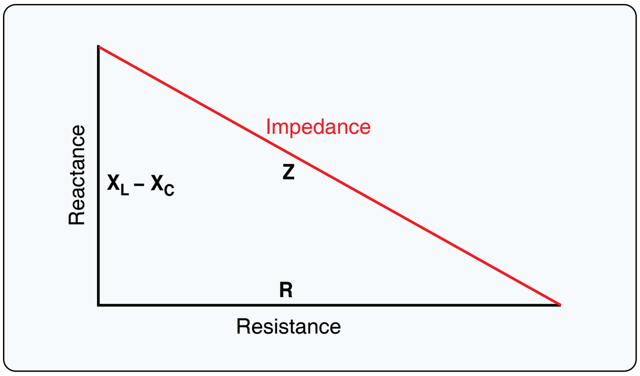


Figure 9-24. *Impedance triangle.*

In practical terms, if a series AC circuit contains resistance and inductance, as shown in *Figure 9-25*, the relation between the sides can be stated as:

$Z^2 = R^2 + (X_L - X_C)^2$

The square root of both sides of the equation gives:

$Z = \sqrt{R^2 + (X_L - X_C)^2}$

This formula can be used to determine the impedance when the values of inductive reactance and resistance are known. It can be modified to solve for impedance in circuits containing capacitive reactance and resistance by substituting X_C in the formula in place of X_L. In circuits containing resistance with both inductive and capacitive reactance, the reactances can be combined; but because their effects in the circuit are exactly opposite, they are combined by subtraction (the smaller number is always subtracted from the larger):

$Z = X_L - X_C$

or

$X = X_C - X_L$

Figure 9-25 shows example 1. Here, a series circuit containing a resistor and an inductor are connected to a source of 110 volts at 60 cycles per second. The resistive element is a simple measuring 6 ohms, and the inductive element is a coil with an inductance of 0.021 henry. What is the value of the impedance and the current through the circuit?

Solution:
First, the inductive reactance of the coil is computed:

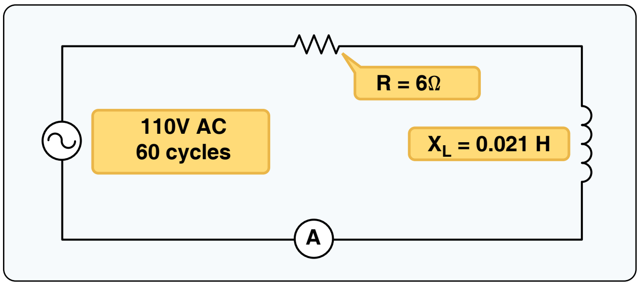


Figure 9-25. *A circuit containing resistance and inductance.*

$X_L = 2\pi \times f \times L$

$X_L = 6.28 \times 60 \times 0.021$

$X_L = 8$ ohms inductive reactance

Next, the total impedance is computed:

$$Z = \sqrt{R^2 + X_L^2}$$

$$Z = \sqrt{6^2 + 8^2}$$

$$Z = \sqrt{36 + 64}$$

$$Z = \sqrt{100}$$

$$Z = 10\Omega$$

Remember when making calculations for Z always use inductive reactance not inductance, and use capacitive reactance, not capacitance.

Once impedance is found, the total current can be calculated.

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

$$I = \frac{110V}{10\Omega}$$

$I = 11$ amps

Since this circuit is resistive and inductive, there is a phase shift where voltage leads current.

Example 2 is a series circuit illustrated in which a capacitor of 200 µf is connected in series with a 10 ohm resistor. *[Figure 9-26]* What is the value of the impedance, the current flow, and the voltage drop across the resistor?

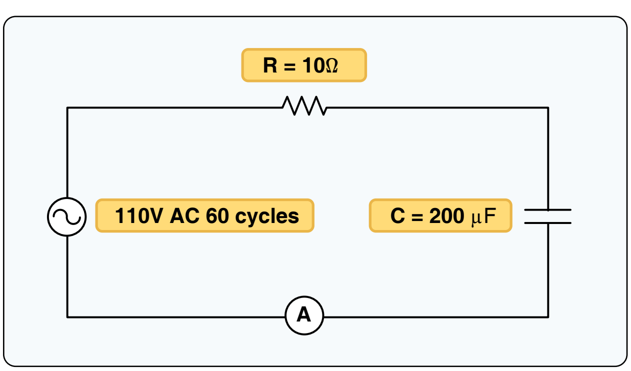


Figure 9-26. *A circuit containing resistance and capacitance.*

Solution:
First, the capacitance is changed from microfarads to farads. Since 1 million microfarads equal 1 farad, then 200 µf = 0.000200 farads.

Next solve for capacitive reactance:

$$X_C = \frac{1}{2\pi fC}$$

$$X_C = \frac{1}{2\pi(60)(.00020)}$$

$$X_C = \frac{1}{0.07536}$$

$$X_C = 13\Omega$$

To find the impedance,

$$Z = \sqrt{R^2 + X_C^2}$$

$$Z = \sqrt{10^2 + 13^2}$$

$$Z = 16.4\Omega$$

Since this circuit is resistive and capacitive, there is a phase shift where current leads voltage:

To find the current:

$$I_T = \frac{E}{Z}$$

$$I_T = \frac{110V}{6.4\Omega}$$

$I_T = 6.7$ amps

To find the voltage drop across the resistor (E_R):

$E_R = I \times R$

$E_R = 6.7A \times 10\Omega$

$E_R = 67$ volts

To find the voltage drop over the capacitor (E_C):

$E_C = I \times X_C$

$E_C = 6.7A \times 13\Omega$

$E_C = 86.1$ volts

The sum of these two voltages does not equal the applied voltage, since the current leads the voltage. Use the following formula to find the applied voltage:

$$E = \sqrt{(E_R)^2 + (E_C)2}$$

$$E = \sqrt{67^2 + 86.1^2}$$

$$E = \sqrt{4{,}489 + 7{,}413}$$

$$E = \sqrt{11{,}902}$$

$E = 110$ volts

When the circuit contains resistance, inductance, and capacitance, the following equation is used to find the impedance.

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

Example 3: What is the impedance of a series circuit consisting of a capacitor with a capacitive reactance of 7 ohms, an inductor with an inductive reactance of 10 ohms, and a resistor with a resistance of 4 ohms? *[Figure 9-27]*

Solution:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$Z = \sqrt{4^2 + (10 - 7)^2}$$

$$Z = \sqrt{25}$$

$$Z = 5\Omega$$

To find total current:

$$I_T = \frac{E_T}{Z}$$

$$I_T = \frac{110V}{5\Omega}$$

$I_T = 22$ amps

Remember that inductive and capacitive reactances can cause a phase shift between voltage and current. In this example, inductive reactance is larger than capacitive reactance, so the voltage leads current.

It should be noted that since inductive reactance, capacitive reactance, and resistance affect each other at right angles, the voltage drops of any series AC circuit should be added using vector addition. *Figure 9-28* shows the voltage drops over the series AC circuit described in example 3 above.

To calculate the individual voltage drops, simply use the equations:

$$E_R = I \times R$$

$$E_{X_L} = I \times X_L$$

$$E_{X_C} = I \times X_C$$

To determine the total applied voltage for the circuit, each individual voltage drop must be added using vector addition.

$$E_T = \sqrt{E_R^2 + (E_L - E_C)^2}$$

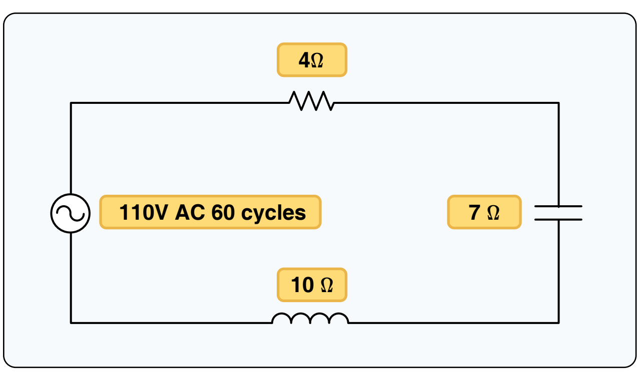


Figure 9-27. *A circuit containing resistance, inductance, and capacitance.*

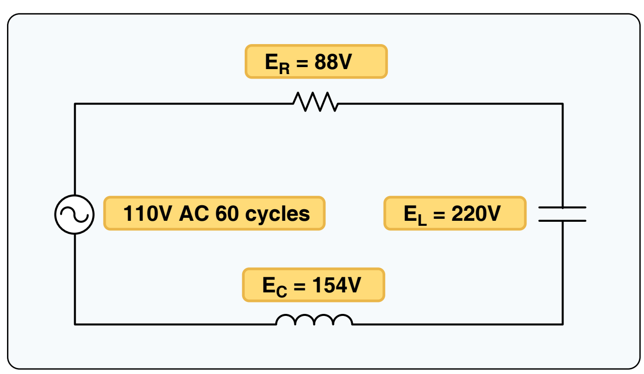


Figure 9-28. *Voltage drops.*

$$E_T = \sqrt{88^2 + (220 - 154)^2}$$

$$E_T = \sqrt{88^2 + 66^2}$$

$$E_T = \sqrt{12{,}100}$$

$$E_T = 110 \text{ volts}$$

Parallel AC Circuits

When solving parallel AC circuits, one must also use a derivative of the Pythagorean Theorem. The equation for finding impedance in an AC circuit is as follows:

$$Z = \sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}$$

To determine the total impedance of the parallel circuit shown in *Figure 9-29*, one would first determine the capacitive and inductive reactances. (Remember to convert microfarads to farads.)

$$X_L = 2\pi FL$$

$$X_L = 2\pi(400)(0.02)$$

$$X_L = 50\Omega$$

$$X_C = \frac{1}{2\pi FC}$$

$$100\mu f = 0.0001F$$

$$X_C = \frac{1}{2\pi(400)(0.0001)}$$

$$X_C = 4\Omega$$

Next, the impedance can be found:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}}$$

$$Z = \frac{1}{\sqrt{\left(\frac{1}{50}\right)^2 + \left(\frac{1}{50} - \frac{1}{4}\right)^2}}$$

$$Z = \frac{1}{\sqrt{(.02)^2 + (.02 - .25)^2}}$$

$$Z = \frac{1}{\sqrt{.0004 + .0529}}$$

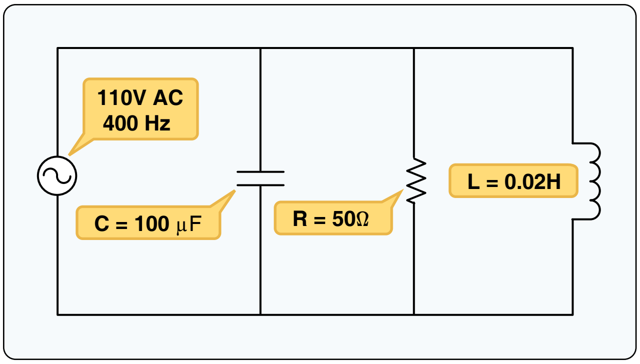


Figure 9-29. *Total impedance of parallel circuit.*

$$Z = \frac{1}{.23}$$

$$Z = 4.33\Omega$$

To determine the current flow in the circuit:

$$I_T = \frac{E_T}{Z}$$

$$I_T = \frac{100V}{4.33\Omega}$$

$$I_T = 23.09 \text{ amps}$$

To determine the current flow through each parallel path of the circuit, calculate I_R, I_L, and I_C.

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

$$I_R = \frac{100V}{50\Omega}$$

$$I_R = 2 \text{ amps}$$

$$I_L = \frac{E}{X_L}$$

$$I_L = \frac{100V}{50\Omega}$$

$$I_L = 2 \text{ amps}$$

$$I_C = \frac{E}{X_C}$$

$$I_C = \frac{100V}{4\Omega}$$

$I_C = 25$ amps

It should be noted that the total current flow of parallel circuits is found by using vector addition of the individual current flows as follows:

$$I_T = \sqrt{I_R^2 + (I_L - I_C)^2}$$

$$I_T = \sqrt{2^2 + (2 - 25)^2}$$

$$I_T = \sqrt{2^2 + 23^2}$$

$$I_T = \sqrt{4 + 529}$$

$$I_T = \sqrt{533}$$

$I_T = 23$ amps

Power in AC Circuits

Since voltage and current determine power, there are similarities in the power consumed by both AC and DC circuits. In AC however, current is a function of both the resistance and the reactance of the circuit. The power consumed by any AC circuit is a function of the applied voltage and both circuit's resistance and reactance. AC circuits have two distinct types of power, one created by the resistance of the circuit and one created by the reactance of the circuit.

True Power

True power of any AC circuit is commonly referred to as the working power of the circuit. True power is the power consumed by the resistance portion of the circuit and is measured in watts (W). True power is symbolized by the letter P and is indicated by any wattmeter in the circuit. True power is calculated by the formula:

$P = I^2 \times Z$

Apparent Power

Apparent power in an AC circuit is sometimes referred to as the reactive power of a circuit. Apparent power is the power consumed by the entire circuit, including both the resistance and the reactance. Apparent power is symbolized by the letter S and is measured in volt-amps (VA). Apparent power is a product of the effective voltage multiplied by the effective current. Apparent power is calculated by the formula:

$S = I^2 \times Z$

Power Factor

As seen in *Figure 9-30,* the resistive power and the reactive power effect the circuit at right angles to each other. The power factor in an AC circuit is created by this right angle effect.

Power factor can be defined as the mathematical difference between true power and apparent power. Power factor (PF) is a ratio and always a measurement between 0 and 100. The power factor is directly related to the phase shift of a circuit. The greater the phase shift of a circuit the lower the power factor. For example, an AC circuit that is purely inductive (contains reactance only and no resistance) has a phase shift of 90° and a power factor of 0.0. An AC circuit that is purely resistive (has no reactance) has a phase shift of 0 and a power factor of 100. Power factor is calculated by using the following formula:

$$PF = \frac{\text{True Power (Watts)}}{\text{Apparent Power (VA)}} \times 100$$

Example of calculating PF: *Figure 9-31* shows an AC load connected to a 50 volt power supply. The current draw of the circuit is 5 amps and the total resistance of the circuit is 8 ohms. Determine the true power, the apparent power, and the power factor for this circuit.

Solution:

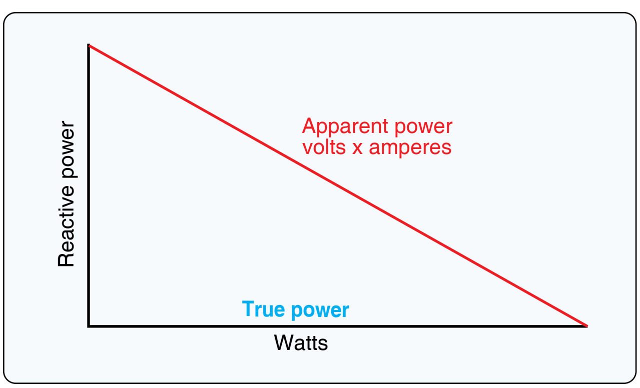


Figure 9-30. *Power relations in AC circuit.*

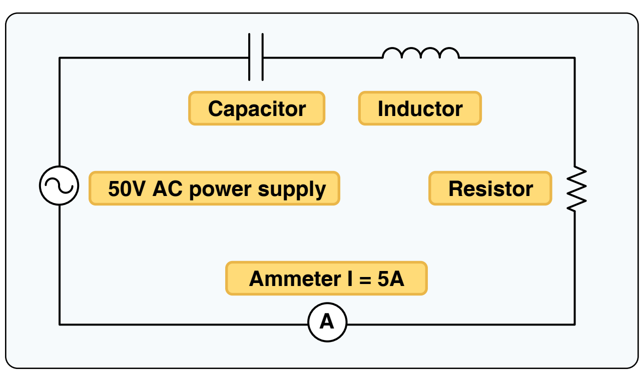


Figure 9-31. *AC load connected to a 50-volt power supply.*

$$P = I^2 \times R$$

$$P = 5^2 \times 8$$

$$P = 200 \text{ Watts}$$

$$S = E \times I$$

$$S = 50 \times 5$$

$$S = 250\text{VA}$$

$$PF = \frac{TP}{S} \times 100$$

$$PF = \frac{200}{250} \times 100$$

$$PF = 80$$

Power factor can also be represented as a percentage. Using a percentage to show power factor, the circuit in the previous example would have a power factor of 80 percent.

It should be noted that a low power factor is undesirable. Circuits with a lower power factor create excess load on the power supply and produce inefficiency in the system. Aircraft AC alternators must typically operate with a power factor between 90 percent and 100 percent. It is therefore very important to carefully consider power factor when designing the aircraft electrical system.

Aircraft Batteries

Aircraft batteries are used for many functions (e.g., ground power, emergency power, improving DC bus stability, and fault clearing). Most small private aircraft use lead-acid batteries. Most commercial and corporate aircraft use nickel-cadmium (NiCd) batteries. However, other lead acid types of batteries are becoming available, such as the valve-regulated lead-acid (VRLA) batteries. The battery best suited for a particular application depends on the relative importance of several characteristics, such as weight, cost, volume, service or shelf life, discharge rate, maintenance, and charging rate. Any change of battery type may be considered a major alteration.

Types of Batteries

Aircraft batteries are usually identified by the material used for the plates. The two most common types of battery used are lead-acid and NiCd batteries.

Lead-Acid Batteries

Dry Charged Cell Lead-Acid Batteries

Dry charged cell lead-acid batteries, also known as flooded or wet batteries, are assembled with electrodes (plates) that have been fully charged and dried. The electrolyte is added to the battery when it is placed in service, and battery life begins when the electrolyte is added. An aircraft storage battery consists of 6 or 12 lead-acid cells connected in series. The open circuit voltage of the 6 cell battery is approximately 12 volts, and the open circuit voltage of the 12-cell battery is approximately 24 volts. Open circuit voltage is the voltage of the battery when it is not connected to a load. When flooded (vented) batteries are on charge, the oxygen generated at the positive plates escapes from the cell. Concurrently, at the negative plates, hydrogen is generated from water and escapes from the cell. The overall result is the gassing of the cells and water loss. Therefore, flooded cells require periodic water replenishment. *[Figure 9-32]*

Valve-Regulated Lead-Acid (VRLA) Batteries

VRLA batteries contain all electrolyte absorbed in glass-mat

Figure 9-32. *Lead-acid battery installation.*

Figure 9-33. *Valve-regulated lead-acid battery (sealed battery).*

separators with no free electrolyte and are sometimes referred to as sealed batteries. *[Figure 9-33]* The electrochemical reactions for VRLA batteries are the same as flooded batteries, except for the gas recombination mechanism that is predominant in VRLA batteries. These types of battery are used in general aviation and turbine powered aircraft and are sometimes authorized replacements for NiCd batteries.

When VRLA batteries are on charge, oxygen combines chemically with the lead at the negative plates in the presence of H_2SO_4 to form lead sulfate and water. This oxygen recombination suppresses the generation of hydrogen at the negative plates. Overall, there is no water loss during charging. A very small quantity of water may be lost as a result of self-discharge reactions; however, such loss is so small that no provisions are made for water replenishment. The battery cells have a pressure relief safety valve that may vent if the battery is overcharged.

NiCd Batteries

A NiCd battery consists of a metallic box, usually stainless steel, plastic-coated steel, painted steel, or titanium containing a number of individual cells. *[Figure 9-34]* These cells are connected in series to obtain 12 volts or 24 volts. The cells are connected by highly conductive nickel copper links. Inside the battery box, the cells are held in place by partitions, liners, spacers, and a cover assembly. The battery has a ventilation system to allow the escape of the gases produced during an overcharge condition and provide cooling during normal operation.

NiCd cells installed in an aircraft battery are typical of the vented cell type. The vented cells have a vent or low pressure release valve that releases any generated oxygen and hydrogen gases when overcharged or discharged rapidly. This also means the battery is not normally damaged by excessive rates of overcharge, discharge, or even negative charge. The cells are rechargeable and deliver a voltage of 1.2 volts during discharge.

Figure 9-34. *NiCd battery installation.*

Aircraft that are outfitted with NiCd batteries typically have a fault protection system that monitors the condition of the battery. The battery charger is the unit that monitors the condition of the battery and the following conditions are monitored:

1. Overheat condition,
2. Low temperature condition (below –40 °F),
3. Cell imbalance,
4. Open circuit, and
5. Shorted circuit.

If the battery charger finds a fault, it turns off and sends a fault signal to the Electrical Load Management System (ELMS).

NiCd batteries are capable of performing to their rated capacity when the ambient temperature of the battery is in the range of approximately 60–90 °F. An increase or decrease in temperature from this range results in reduced capacity. NiCd batteries have a ventilation system to control the temperature of the battery. A combination of high battery temperature (in excess of 160 °F) and overcharging can lead to a condition called thermal runaway. *[Figure 9-35]* The temperature of the battery has to be constantly monitored to ensure safe operation. Thermal runaway can result in a NiCd chemical fire and/or explosion of the NiCd battery under recharge by a constant-voltage source and is due to cyclical, ever-increasing temperature and charging current. One or more shorted cells or an existing high temperature and low charge can produce the following cyclical sequence of events:

1. Excessive current,
2. Increased temperature,

Figure 9-35. *Thermal runaway damage.*

3. Decreased cell(s) resistance,
4. Further increased current, and
5. Further increased temperature.

This does not become a self-sustaining thermal-chemical action if the constant-voltage charging source is removed before the battery temperature is in excess of 160 °F.

Capacity

Capacity is measured quantitatively in ampere-hours delivered at a specified discharge rate to a specified cut-off voltage at room temperature. The cut-off voltage is 1.0 volt per cell. Battery available capacity depends upon several factors including such items as:

1. Cell design (cell geometry, plate thickness, hardware, and terminal design govern performance under specific usage conditions of temperature, discharge rate, etc.).
2. Discharge rate (high current rates yield less capacity than low rates).
3. Temperature (capacity and voltage levels decrease as battery temperature moves away from the 60 °F (16 °C) to 90 °F (32 °C) range toward the high and low extremes).
4. Charge rate (higher charge rates generally yield greater capacity).

Aircraft Battery Ratings by Specification

The one-hour rate is the rate of discharge a battery can endure for 1 hour with the battery voltage at or above 1.67 volts per cell, or 20 volts for a 24-volt lead-acid battery, or 10 volts for a 12-volt lead-acid battery. The one-hour capacity, measured in ampere hours (Ah), is the product of the discharge rate and time (in hours) to the specified end voltage.

The emergency rate is the total essential load, measured in amperes, required to support the essential bus for 30 minutes. This is the rate of discharge a battery can endure for 30 minutes with the battery voltage at or above 1.67 volts per cell, or 20 volts for a 24 volt lead-acid battery, or 10 volts for a 12 volt lead-acid battery.

Storing & Servicing Facilities

Separate facilities for storing and/or servicing flooded electrolyte lead-acid and NiCd batteries must be maintained. Introduction of acid electrolyte into alkaline electrolyte causes permanent damage to vented (flooded electrolyte) NiCd batteries and vice versa. However, batteries that are sealed can be charged and capacity checked in the same area. Because the electrolyte in a valve-regulated lead-acid battery is absorbed in the separators and porous plates, it cannot contaminate a NiCd battery even when they are serviced in the same area.

Warning: It is extremely dangerous to store or service lead-acid and NiCd batteries in the same area. Introduction of acid electrolytes into alkaline electrolyte destroys the NiCd, and vice versa.

Battery Freezing

Discharged lead-acid batteries exposed to cold temperatures are subject to plate damage due to freezing of the electrolyte. To prevent freezing damage, maintain each cell's specific gravity at 1.275 or, for sealed lead-acid batteries, check open circuit voltage. *[Figure 9-36]* NiCd battery electrolyte is not as susceptible to freezing because no appreciable chemical change takes place between the charged and discharged states. However, the electrolyte freezes at approximately –75 °F.

Note: Only a load check determines overall battery condition.

Temperature Correction

U.S.-manufactured lead-acid batteries are considered fully charged when the specific gravity reading is between 1.275 and 1.300. A ⅓ discharged battery reads about 1.240 and a ⅔ discharged battery shows a specific gravity reading of about 1.200 when tested by a hydrometer at an electrolyte temperature of 80 °F. However, to determine precise specific gravity readings, a temperature correction should be applied to the hydrometer indication. *[Figure 9-37]* As an example, for a hydrometer reading of 1.260 and electrolyte temperature of 40 °F, the corrected specific gravity reading of the electrolyte is 1.244.

Battery Charging

Operation of aircraft batteries beyond their ambient temperature or charging voltage limits can result in excessive cell temperatures leading to electrolyte boiling, rapid

Specific Gravity	Freezing Point		State of Charge (SOC) for Sealed Lead-Acid Batteries at 70°		
	°C	°F	SOC	12 volt	24 volt
1.300	–70	–95	100%	12.9	25.8
1.275	–62	–80	75%	12.7	25.4
1.250	–52	–62	50%	12.4	24.8
1.225	–37	–35	25%	12.0	24.0
1.200	–26	–16			
1.175	–20	–04			
1.150	–15	+05			
1.125	–10	+13			
1.100	–08	+19			

Figure 9-36. *Lead-acid battery electrolyte freezing points.*

Electrolyte Temperature		Points to Subtract From or Add to Specific Gravity Readings
°C	°F	12 volt
+60	+140	+0.024
+55	+130	+0.020
+49	+120	+0.016
+43	+110	+0.012
+38	+100	+0.008
+33	+90	+0.004
+27	+80	0
+23	+70	–0.004
+15	+60	–0.008
+10	+50	–0.012
+05	+40	–0.016
–02	+30	–0.020
–07	+20	–0.024
–13	+10	–0.028
–18	0	–0.032
–23	–10	–0.036
–28	–20	–0.040
–35	–30	–0.044

Figure 9-37. *Sulfuric acid temperature correction.*

deterioration of the cells, and battery failure. The relationship between maximum charging voltage and the number of cells in the battery is also significant. This determines (for a given ambient temperature and state of charge) the rate at which energy is absorbed as heat within the battery. For lead-acid batteries, the voltage per cell must not exceed 2.35 volts. In the case of NiCd batteries, the charging voltage limit varies with design and construction. Values of 1.4 and 1.5 volts per cell are generally used. In all cases, follow the recommendations of the battery manufacturer.

Constant Voltage (CV) Charging

The battery charging system in an airplane is of the constant voltage type. An engine-driven generator, capable of supplying the required voltage, is connected through the aircraft electrical system directly to the battery. A battery switch is incorporated in the system so that the battery may be disconnected when the airplane is not in operation.

The voltage of the generator is accurately controlled by means of a voltage regulator connected in the field circuit of the generator. For a 12-volt system, the voltage of the generator is adjusted to approximately 14.25. On 24-volt systems, the adjustment should be between 28 and 28.5 volts. When these conditions exist, the initial charging current through the battery is high. As the state of charge increases, the battery voltage also increases, causing the current to taper down. When the battery is fully charged, its voltage is almost equal to the generator voltage, and very little current flows into the battery. When the charging current is low, the battery may remain connected to the generator without damage.

When using a constant-voltage system in a battery shop, a voltage regulator that automatically maintains a constant voltage is incorporated in the system. A higher capacity battery (e.g., 42 Ah) has a lower resistance than a lower capacity battery (e.g., 33 Ah). Hence, a high-capacity battery draws a higher charging current than a low-capacity battery when both are in the same state of charge and when the charging voltages are equal. The constant voltage method is the preferred charging method for lead-acid batteries.

Constant Current (CC) Charging

Constant current charging is the most convenient for charging batteries outside the airplane because several batteries of varying voltages may be charged at once on the same system. A constant current charging system usually consists of a rectifier to change the normal AC supply to DC. A transformer is used to reduce the available 110-volt or 220-volt AC supply to the desired level before it is passed through the rectifier. If a constant current charging system is used, multiple batteries may be connected in series, provided that the charging current is kept at such a level that the battery does not overheat or gas excessively.

The constant current charging method is the preferred method for charging NiCd batteries. Typically, a NiCd battery is constant current charged at a rate of 1CA until all the cells have reached at least 1.55V. Another charge cycle follows at 0.1CA, again until all cells have reached 1.55V. The charge is finished with an overcharge or top-up charge, typically for not less than 4 hours at a rate of 0.1CA. The purpose of the overcharge is to expel as much, if not all the gases collected on the electrodes, hydrogen on the anode, and oxygen on the cathode; some of these gases recombine to form water that, in turn, raises the electrolyte level to its highest level after which it is safe to adjust the electrolyte levels. During the overcharge or top-up charge, the cell voltages go beyond 1.6V and then slowly start to drop. No cell should rise above 1.71V (dry cell) or drop below 1.55V (gas barrier broken).

Charging is done with vent caps loosened or open. A stuck vent might increase the pressure in the cell. It also allows for refilling of water to correct levels before the end of the top-up charge while the charge current is still on. However, cells should be closed again as soon as the vents have been cleaned and checked since carbon dioxide dissolved from outside air carbonates the cells and ages the battery.

Battery Maintenance

Battery inspection and maintenance procedures vary with the type of chemical technology and the type of physical construction. Always follow the battery manufacturer's approved procedures. Battery performance at any time in a given application depends upon the battery's age, state of health, state of charge, and mechanical integrity, which you can determine according to the following:

- To determine the life and age of the battery, record the install date of the battery on the battery. During normal battery maintenance, battery age must be documented either in the aircraft maintenance log or in the shop maintenance log.
- Lead-acid battery state of health may be determined by duration of service interval (in the case of vented batteries), by environmental factors (such as excessive heat or cold), and by observed electrolyte leakage (as evidenced by corrosion of wiring and connectors or accumulation of powdered salts). If the battery needs to be refilled often, with no evidence of external leakage, this may indicate a poor state of the battery, the battery charging system, or an overcharge condition.
- Use a hydrometer to determine the specific gravity of the lead-acid battery electrolyte, which is the weight of the electrolyte compared to the weight of pure water. Take care to ensure the electrolyte is returned to the cell from which it was extracted. When a specific gravity difference of 0.050 or more exists between cells of a battery, the battery is approaching the end of its useful life and replacement should be considered. Electrolyte level may be adjusted by the addition of distilled water. Do not add electrolyte.
- Battery state of charge is determined by the cumulative effect of charging and discharging the battery. In a normal electrical charging system, the aircraft generator or alternator restores a battery to full charge during a flight of 1 hour to 90 minutes.
- Proper mechanical integrity involves the absence of any physical damage, as well as assurance that hardware is correctly installed and the battery is properly connected. Battery and battery compartment venting system tubes, nipples, and attachments, when required, provide a means of avoiding the potential buildup of explosive gases, and should be checked periodically to ensure that they are securely connected and oriented in accordance with the maintenance manual's installation procedures. Always follow procedures approved for the specific aircraft and battery system to ensure that the battery system is capable of delivering specified performance.

Battery & Charger Characteristics

The following information is provided to acquaint the user with characteristics of the more common aircraft battery and battery charger types. *[Figure 9-38]* Products may vary from these descriptions due to different applications of available technology. Consult the manufacturer for specific performance data.

Figure 9-38. *Battery charger.*

Note: Never connect a lead-acid battery to a charger, unless properly serviced.

Lead-Acid Batteries

Lead-acid vented batteries have a two volt nominal cell voltage. Batteries are constructed so that individual cells cannot be removed. Occasional addition of water is required to replace water loss due to overcharging in normal service. Batteries that become fully discharged may not accept recharge. Lead-acid sealed batteries are similar in most respects to lead-acid vented batteries, but do not require the addition of water.

The lead-acid battery is economical and has extensive application but is heavier than an equivalent performance battery of another type. The battery is capable of a high rate of discharge and low-temperature performance. However, maintaining a high rate of discharge for a period of time usually warps the cell plates, shorting out the battery. Its electrolyte has a moderate specific gravity, and state of charge can be checked with a hydrometer.

Lead-acid batteries are usually charged by regulated DC voltage sources. This allows maximum accumulation of charge in the early part of recharging.

NiCd Batteries

NiCd vented batteries have a 1.2-volt nominal cell voltage. Occasional addition of distilled water is required to replace water loss due to overcharging in normal service. Cause of failure is usually shorting or weakening of a cell. After replacing the bad cell with a good cell, the battery's life can be extended for 5 or more years. Full discharge is not harmful to this type of battery.